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Pionic hydrogen and friends

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Abstract Pion-nucleon scattering lengths are directly related to the ground-state level shift and broadening in pionic hydrogen as well as to the pionic deuterium level shift. The level broadening in deuterium measures the strength of pion threshold-production in proton-proton reactions. However, collisional processes during the atomic de-excitation cascade

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considerably complicate the analysis of X-ray line shapes in order to extract the hadronic broadening. Therefore, additionally the purely electromagnetic twin system muonic hydrogen was studied. Results of these experiments performed at PSI by using a high-resolution crystal spectrometer are discussed in the context with a new analysis approach for the hadronic broadening.

Keywords Exotic atoms · X-ray spectrometer · Pion-nucleon scattering

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1 Introduction

Ultimate resolution X-ray spectroscopy enables the precise determination of line energies and line shapes of X-rays emitted during the de-excitation cascade of exotic atoms [1]. In pionic hydrogen (πH), the main goal of the measurement is to extract from the strong-interaction shift ϵ_{1s} and broadening Γ_{1s} of the ground state $1s$ accurate results for the elastic pion-nucleon scattering lengths $a_{\pi^-p \rightarrow \pi^-p}$ and $a_{\pi^-p \rightarrow \pi^0n}$. All pion-nucleon scattering lengths may be expressed by only two pure strong-interaction quantities, the isoscalar and isovector scattering length a^+ and a^- . They are related to $\epsilon_{1s}^{\pi H}$ and $\Gamma_{1s}^{\pi H}$ by [2–4]

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^-p \rightarrow \pi^-p} = a^+ + a^- + \dots \quad (1)$$

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^-p \rightarrow \pi^0n})^2 \propto (a^-)^2 + \dots \quad (2)$$

Dots indicate corrections due to strong and electromagnetic effects. Recent discussions on these corrections may be found for field theoretical and for phenomenological approaches in refs. [5] and refs. [6–8], respectively.

The ground-state level shift $\epsilon_{1s}^{\pi D}$ in pionic deuterium (πD) provides a mandatory constraint on the πH data. It is proportional to the real part of the complex pion-deuteron scattering length $a_{\pi D}$, which can be traced back to coherent scattering on the proton and the neutron. The leading term reads

$$\epsilon_{1s}^{\pi D} \propto \text{Re } a_{\pi D} = a_{\pi^-p \rightarrow \pi^-p} + a_{\pi^-n \rightarrow \pi^-n} + \dots = 2a^+ + \dots \quad (3)$$

Here, in addition (substantial) corrections are necessary due to multiple scattering and absorption [9–11].

The πD level broadening $\Gamma_{1s}^{\pi D}$ provides information on different processes, because it originates from true absorption $\pi^-d \rightarrow nn$ and radiative capture $\pi^-d \rightarrow nn\gamma$. Hence, when exploiting detailed balance, $\Gamma_{1s}^{\pi D}$ measures the s-wave pion-production strength α on isospin zero nucleon pairs [12–14]:

$$\Gamma_{1s}^{\pi D} \propto \text{Im } a_{\pi D} \propto \alpha. \quad (4)$$

In order to extract the parameter α , the exotic-atom method involves significantly smaller systematic uncertainties than the extrapolation of cross-sections to threshold because of the absence of normalisation and Coulomb interference problems. The parameter α is subject to field theoretical calculations [15, 16].

A major challenge is to quantify the line broadening stemming from Coulomb de-excitation, which constitutes a non-radiative transition occurring during the collision of exotic hydrogen with atoms of the target [17]. The de-excitation energy is transferred

into kinetic energy of the collision partners, which causes X-rays to be Doppler broadened when emitted during subsequent transitions. Elastic scattering, on the other hand, decelerates such fast atoms.

The new approach of this experiment was to measure (i) different ground-state transitions ($\pi\text{H}(2p-1s)$, $\pi\text{H}(3p-1s)$, and $\pi\text{H}(4p-1s)$), (ii) to explore the density dependence of the atomic cascade and (iii) to study additionally the twin system muonic hydrogen (μH), where the Doppler broadening dominates the line width because of the absence of the hadronic interaction [18]. The variety of the cascade information available for the various conditions should allow a decisive comparison with theoretical predictions for a possible improvement on the Doppler correction.

A thorough analysis reveals the problems inherent to least square fitting when quantifying the Doppler-broadening correction in order to determine the hadronic contribution. In such fits, a bias occurs and the procedure to estimate the corresponding errors is not well defined. Therefore, also an analysis based on the Bayesian approach has been started. It is bias free and provides statistical and systematic errors of this multiparameter problem on equal footing.

2 Experiment

The experiment was performed at the high-intensity low-energy pion beam line πE5 of the Paul Scherrer Institut (PSI) [18]. Pions were stopped in the center of the cyclotron trap in a cylindrical gas cell, where the densities of H_2 and D_2 gas were adjusted by means of a cooling finger. Muonic hydrogen is formed when muons originating from the decay of slow pions are also stopped inside the gas cell.

X-rays emitted after pionic-atom formation were measured by using a Johann-type Bragg spectrometer equipped with spherically bent silicon and quartz crystals (Figs. 1 and 2 - left). As X-ray detector, an array of charge-coupled devices was used. The experimental setup is described in detail in refs. [14, 19].

3 Results

3.1 Doppler broadening

Theoretical predictions for kinetic energy distributions of μH and πH atoms have been provided within the framework of the Extended Standard Cascade Model (ESCM [20]) [20–22]. So far, for πD no such prediction exists.

In the case of the $\mu\text{H}(3p-1s)$ transition, two high-energetic components were identified at about 24 and 55 eV which correspond to the $(5-4)$ and $(4-3)$ Coulomb de-excitation transitions [23]. About 2/3 of the intensity were found to be collected in a low-energetic component (≤ 4 eV) representing the non-accelerated or moderated atoms. It was found to be sufficient to model the three identified kinetic-energy components by narrow energy intervals of 2–4 eV width, each.

Also in the πH case, high-energetic components are doubtlessly present. The relative intensity varies between about 25 % and 50 % with uncertainties of the order of 25 %.

For πD , the Bayes analysis confirmed that any high-energetic component is absent in the $\pi\text{D}(3p-1s)$ transition at the level of 10 % relative intensity or more [13, 14, 24]. This is clearly contrary to the case of μH and πH .

Fig. 1 Measured spectra of pionic hydrogen (left) [19] and deuterium (right) [13, 14]. The narrow line represents the spectrometer resolution

Fig. 2 Measured spectrum of muonic hydrogen [23] (left). The narrow lines represent the spectrometer resolution. Result from the Bayes analysis of the high-energetic components contributing to Doppler broadening of the $\mu H(3p-1s)$ transition (right) [24]

Noteworthy, that results for the kinetic-energy components for position and intensity both from the χ^2 analysis and the Bayesian approach are consistent to a large extent (Fig. 2 - right). The Bayesian approach, however, shows clearly the uncertainties for the fit parameters, in particular for $\Gamma_{1s}^{\pi H}$ and the intensities of high-energetic components. They must be assumed to be about a factor of two larger than suggested from χ^2 minimization.

3.2 Hadronic broadening

Inspired by the result for muonic hydrogen, the kinetic energy distribution is modeled by a low-energy component and up to 4 high-energetic contributions corresponding to possible Coulomb de-excitation transitions. The width of these individual components was chosen to 2–4 eV each. Again, the results of χ^2 analysis and Bayesian approach are not contradictory, but the latter method reveals the uncertainty owing to statistics and systematics (Fig. 3).

Six data sets for πH (2 per transition) have been analysed yielding for the hadronic broadening values from 750 to 900 meV with a central value at 850 meV. From the probability distributions obtained with the Bayes analyses a (preliminary) combined result is extracted (Table 1). The uncertainty is about a factor of two larger than the one obtained from the usual averaging of the fit results. However, it contains already the full systematics.

Fig. 3 Probability distributions for the hadronic width $\Gamma_{1s}^{\pi H}$ in pionic hydrogen for the six analysed data sets. All distributions overlap around 850 meV

Table 1 Results for the strong-interaction effects in pionic hydrogen and deuterium

	$\epsilon_{1s} / \text{meV}$		Γ_{1s} / meV	$\alpha / \mu\text{b}$	
πH	7086 ± 10	[19]	850^{+40}_{-50}	preliminary result of Bayes analyses	
πD	-2356 ± 31	[14]	1171^{+23}_{-49}	[13, 14]	251^{+5}_{-11} [13, 14]

The result for $\epsilon_{1s}^{\pi H}$ is in good agreement with the one from the previous precision measurement taking into account the new calculation for the electromagnetic transition energy [26]

Noteworthy, that no bias occurs with the Bayesian method. The magnitude of such a possible bias for $\Gamma_{1s}^{\pi H}$ in the χ^2 analysis has been identified by means of Monte-Carlo simulations and amounts up to 30 meV [25].

For pionic deuterium, the $\pi\text{D}(3p - 1s)$ transition was measured. The asymmetry of the error (Table 1) is mainly due to the upper limit of 10 % for a Doppler-broadening contribution [13, 14].

3.3 Hadronic shift

In total, seven data sets were used for the determination of the hadronic shift $\epsilon_{1s}^{\pi H}$ using both $\pi\text{H}(3p - 1s)$ and $\pi\text{H}(4p - 1s)$ transitions [19]. In contrast to earlier experiments [27–30] — using the argon $K\alpha$ fluorescence lines — in five cases the pionic-atom transitions $\pi\text{O}(6h - 5g)$ and $\pi\text{Be}(4f - 3d)$ served as energy calibration lines. In this way, the contribution to

the error from the uncertainty of the pion mass cancels in leading order. The accuracy is limited mainly by statistics.

In the two other cases, as for πD , zinc or gallium $K\alpha$ fluorescence radiation was used which served for πH mainly as a stability check. Here, the uncertainty is basically limited by the accuracy given for the energy of the fluorescence line. Therefore, calibration using fluorescence X-rays is inferior to the pionic-atom method by a factor 2 to 5. The weighted average results in an improvement of about four compared to the previous precision experiment.

4 Summary

Various transitions and calibration approaches yield consistent results for the hadronic shift in pionic hydrogen reaching an accuracy in the per mille range. The extraction of both isospin scattering length a^+ and a^- becomes already feasible when combining with the precise result for the shift in pionic deuterium. The relative errors for the individual isospin scattering lengths, however, are significantly larger than the ones for $\epsilon_{1s}^{\pi H}$ and $\epsilon_{1s}^{\pi D}$ because of the uncertainties based on the presently poor knowledge of low-energy constants [5, 10, 11].

The accuracy of the measured strong-interaction broadening in pionic hydrogen and deuterium is limited to a few per cent by Doppler broadening. Hence, the constraint on a^+ and a^- is restrictive only at about the level provided by the two shift results. Progress may come from forthcoming cascade calculations, which provide improved kinetic energy distributions to be used as constraints in the line shape analysis.

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