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PIONIC HYDROGEN

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The new pionic hydrogen experiment at PSI aims at a determination of the strong interaction ground state shift and width of the pionic hydrogen atom with the final goal to extract isospin separated scattering lengths with accuracies on the percent level. Its achievements compared to previous efforts are indicated and the inherent difficulties of the experimantal approach as well as the chosen solutions are discussed. First results are presented.

Keywords: Pion-nucleon interaction; scattering lengths; X-ray spectroscopy.

1. Introduction

The measurement of X-ray transitions feeding the ground–state in pionic hydrogen allows to determine the isoscalar and isovector scattering lengths a^+ and a^-, which describe the πN s–wave interaction at threshold. The scattering lengths of the elastic channel $a_{\pi^- p} \to a_{\pi^- p}$ and the charge–exchange reaction $a_{\pi^- p} \to a_{\pi^0 n}$ are related to the strong–interaction shift ϵ_{1s} and broadening Γ_{1s} by Deser–type formulae [1,2].

$$\frac{\epsilon_{1s}}{B_{1s}} = -\frac{4}{r_B}\, a_{\pi^- p \to \pi^- p}(1+\delta_\epsilon) \tag{1}$$

$$\frac{\Gamma_{1s}}{B_{1s}} = 8\frac{q_0}{r_B}(1+\frac{1}{P})[a_{\pi^- p \to \pi^0 n}(1+\delta_\Gamma)]^2, \tag{2}$$

where $\epsilon_{1s} \propto a^+ + a^-$ and, assuming isospin invariance, $\Gamma_{1s} \propto (a^-)^2$ holds. $q_0 = 0.1421 fm^{-1}$ is the centre–of–mass momentum of the π^0 in the charge–exchange reaction $\pi^- p \to \pi^0 n$ and $P = 1.546 \pm 0.009$ [4] the branching ratio of charge exchange and radiative capture (Panofsky ratio). The new experiment (PSI experiment R–98.01 [3]) aims at an improvement in the shift measurement and in particular at a significant increase in accuracy for Γ_{1s} by about an order of magnitude.

The peculiar features of this method may be summarized as follows:

In comparison with scattering experiments no extrapolation to energy zero is necessary.

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Furthermore, from Γ_{1s} alone the πN coupling constant $f^2_{\pi N}$ is obtained by the Goldberger–Miyazawa–Oehme sum rule [5].

Provided an accuracy in the determination of isospin scattering lengths on the percent level can be achieved the methods of Heavy Baryon χPT can be tested. The predictions of theory are at the moment on the level of several percent. Hence accurate data are well suited to constrain further theoretical development.

Highly accurate scattering lenghts as obtained from pionic hydrogen serve as a basis for comparison of changes of these quantities in nuclear medium [6].

The exotic atom's method has inherent drawbacks as well. In order to achieve the necessary energy resolution a crystal spectrometer must be used which requires a highly intensive source of X-rays together with an especially tailored crystal spectrometer. A sufficient number of pionic hydrogen atoms requires the stopping of negative pions in hydrogen gas with pressures above 3 bar. At such presures the pionic hydrogen atom will interact with neighbouring molecules. Two effects influence the extraction of a strong interaction shift and width with the desired accuracy.

A molecular complex like [(πpp)p]ee may be formed. X-rays which could follow such a complex formation are shifted in energy which first requires a proof that an observed shift is not caused by molecular formation [7,8].

The energy release for the de–excitation step $(\pi p)_{nl} \rightarrow (\pi p)_{n'l'}$ may be converted into kinetic energy of the collision partners $\pi^- p$ and H_2). The velocity increase then leads to a Doppler broadening of subsequent X–ray transitions. This so-called Coulomb de–excitation has been observed directly by measurements of the time–of–flight of neutrons from the charge exchange reaction $\pi^- p \rightarrow \pi^0 n$ [9].

2. Experimental Approach

The new pionic–hydrogen experiment, set up at the high–intensity low–energy pion beam $\pi E5$ of the Paul–Scherrer–Institut, consists of the new cyclotron trap, a cryogenic target, and a Bragg spectrometer equipped with spherically bent crystals and a large–area CCD array[10].

2.1. *Cyclotron trap and spectrometer*

Compared to the preceding experiment of the ETHZ–Neuchatel–PSI [11] collaboration the quality of the experiment could be improved. Now a factor of 6 more pions can be stopped. The use of spherically bent crystals together with bigger CCD detectors[12] provided an additional factor of about 3. A specially tailored shielding reduced the background by one order of magnitude. As an example for the quality of the measurement a spectrum of the $\pi H(3-1)$ transition is shown in Fig. 1.

In the years 2001/2002 the 2p–1s, 3p–1s as well as the 4p–1s transitions had been measured. The 3p–1s transitions had been measured at pressures ranging from several bar (room temperature) up to liquid hydrogen. In total up to 28000 entries had been collected summed over all transitions .

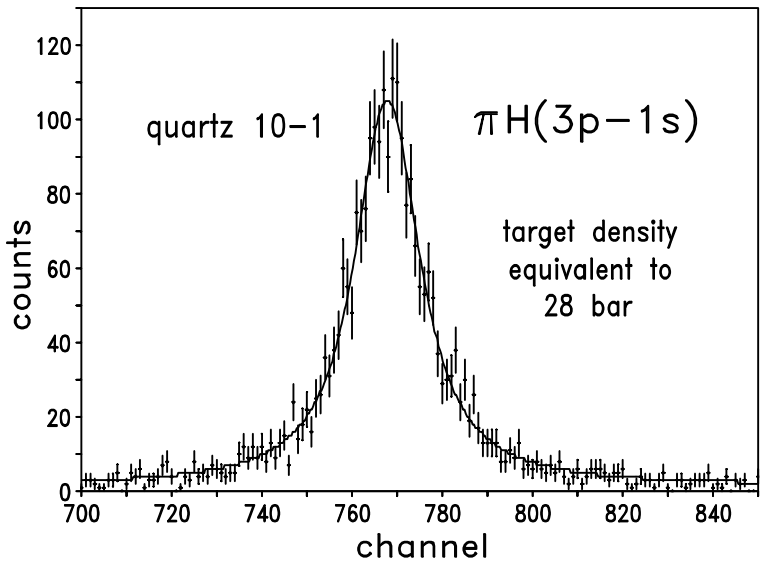

Fig. 1. $\pi H(3-1)$ transition measured at an equivalent density of 28 bar.

2.2. *Energy calibration*

For an accurate extraction of the ground state shift an energy calibration was performed by using the $\pi O(6h-5g)$ transition which is nearby the 3p–1s transition in pionic hydrogen and which is not affected by strong interaction. The transition energy can be calculated to be 2880.506 ± 1 eV. In consequence the shift measurements resulted in an error of less than 1%.

2.3. *Determination of the resolution function*

The determination of the ground state width from a Lorentzian broadening of the transition observed represents a major experimental challenge. The spectrometer's response function which contains a Lorentzian part itself must be determined experimentally. Until recently it had been obtained from narrow pionic–atom transitions [10,11,13] with limited accuracy only. To reach the required accuracy of 1% the calibration measurement should have an intensity of some 10000 events in the line with a peak/background ratio of more than 100:1. For that reason, an Electron–Cyclotron–Resonance Ion Trap (ECRIT) source has been set up to produce helium–like electronic atoms [14].

In such a device few–electron atoms are produced at high rates. Systematic studies using the M1 transitions from helium–like argon, chlorine and sulfur atoms yielded the required characterisation of the resolution function of the Bragg crystals [15] (Fig. 2) at energies corresponding to the 4p–1s, 3p–1s and the 2p–1s transitions.

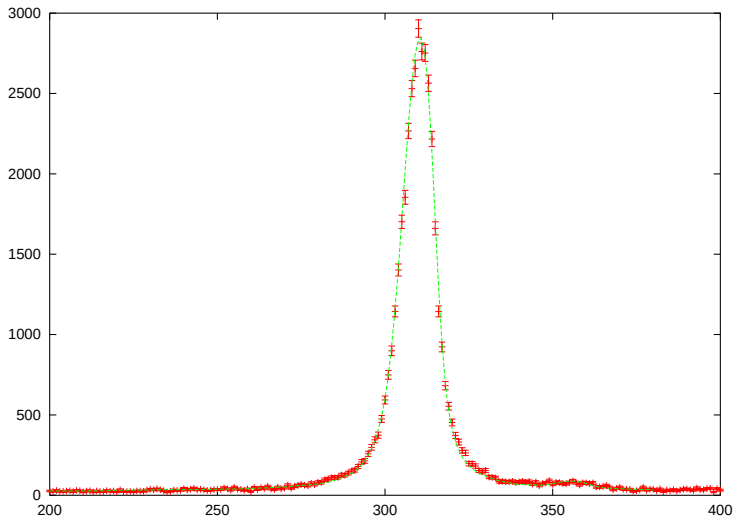

Fig. 2. The energy spectrum (counts/channel against channel number) of He–like sulfur is shown around the region of the M1 transition. A fit based on a well defined response function obtained from X-ray tracking routines allows for an additional Gaussian width as a free parameter. From this procedure the response function of the crystal spectrometer is obtained. The energy of the small satellite line to the right of the main transition from Li–like sulfur is well known and does not influence the quality of the result.

3. First results

3.1. *Transition energy and hadronic shift*

At first, the possibility of radiative de–excitation of the πH atom – when bound into complex molecules formed during collisions $\pi^- p + H_2 \rightarrow [(pp\pi^-)p]ee$ – was studied by searching for a density dependence of the $\pi H(3p-1s)$ transition energy.

A possible pressure shift was excluded experimentally by the observation at different pressures and extrapolating to pressure zero. No density effect was found which is interpreted as the absence of radiative decay from loosly bound molecular states. Consequently, the measured line shift

$$\epsilon_{1s} = +7.120 \pm 0.008 \pm 0.009\ eV \tag{3}$$

can be attributed exclusively to the strong interaction [16]. The first error is due to statistics. The second one contains systematic contributions as are stability, set–up, analysis and the uncertainty for the calculation of the pure electro–magnetic $(3p-1s)$ transition energy to be 2878.808 ± 0.006 eV [17]. Measurements in pionic deuterium lack such a procedure and should not be used to extract a strong interaction shift as long as a similar extrapolation to pressure zero is not performed.

3.2. *Line width and hadronic broadening*

The measured line shape of the pionic hydrogen K transitions is a convolution of a Lorentzian profile according to the natural width Γ_{1s}, the resolution of the crystal spectrometer and in general several contributions to the Doppler width caused by various $n \to n'$ Coulomb transitions. In a first step of evaluation only the response function of the spectrometer as obtained from a calibration with pionic carbon was used for deconvolution. The extracted Lorentzian width (given in meV together with statistical and systematical error) showed for a pressure of 10 bar a significant increase going from $899 \pm 45 \pm 10$ ($4p-1s$) to $1053 \pm 27 \pm 22$ ($3p-1s$) and even more for the $2p-1s$ with a value of $1170 \pm 32 \pm 35$ [16]. This behaviour is attributed to the energy gain available for the acceleration of the pionic–hydrogen which is higher for lower n levels.

Table 1. Extraction of the strong interaction Lorentzian width assuming kinetic energy distributions from Coulomb de–excitation additional to a low energy component less than 1 eV. The weights of the components are left free in the fitting procedure. In case of liquid hydrogen (LH_2) an energy contribution of 30 eV from Stark effect is subtracted. Only the fit error is given.

transition/pressure/crystal	Coulomb steps $n \to n'$	Γ_{1s} meV
$4p-1s$/10b/si 111	$5 \to 4{,}6 \to 5$	812±43
$3p-1s$/10b/si111	$4 \to 3,\ 5 \to 4{,}6 \to 5$	787±41
$2p-1s$/10b/si111	$3 \to 2\ 4 \to 3$	778±40
$3p-1s$/28b/qu10-1	$4 \to 3,\ 5 \to 4$	770±54
$3p-1s/LH_2$/qu10-1	$4 \to 3,\ 5 \to 4$	827±61

Based on the precise knowledge of the spectrometer's resolution function from the ECRIT measurements a more refined evaluation tried to identify various contributions to the line shape from Coulomb de–excitation.

With this procedure the analysis of the three transitions $\pi H(2p{-}1s)$, $\pi H(3p{-}1s)$ and $\pi H(4p-1s)$ at different pressures yielded consistent values for the hadronic broadening independent on transitions and pressures as shown in Table 1. A preliminary result can be given to be $\Gamma_{1s} = 800 \pm 30$ meV.

3.3. *Scattering lengths*

The efforts to improve the accuracy of the scattering lengths face the problem that the linear combination $a^+ + a^-$ to be determined from ϵ_{1s} suffers from the poor knowledge of δ_ϵ (see Eq. 1). The present the correction for ϵ_{1s} is calculated to $\delta_\epsilon = (-7.2 \pm 2.9)\%$ [18]. At present, the experimental accuracy is significantly better than the uncertainty originating from δ_ϵ

A result for the correction δ_Γ of the level broadening Γ_{1s} (see Eq. 2) is expected

in near future [19] allowing to quantify the isovector scattering length.

4. Conclusions and Outlook

The result for ϵ_{1s} from this experiment excludes the influence of molecular states on the level shift at a level of about 0.2%. A similar approach is still missing in the extraction of truly strong interaction shifts in pionic deuterium. Limitations in the extraction of the isospin scattering lengths are given at present by the not precilely known low–energy constant f_1 appearing in second order in the chiral expansion. The more important is the precise determination of the ground state broadening. Here f_1 does not appear in second order, which allows the extraction of the isovector scattering length a^- and the pion–nucleon coupling constant $f^2_{\pi N}$.

A next step is a dedicated measurement of Coulomb de–excitation in muonic hydrogen. Best suited for such an investigation is the $\mu H(3p-1s)$ transition at a density equivalent of 10 bar, where the line yield is about 30% [20]. The μH line width – after deconvolution of the spectrometer response – 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 [21].

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