Strong Interaction Shift and Width of the 1s Level in Pionic Hydrogen

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The $3p$-$1s$ x-ray line of pionic hydrogen was measured with a reflecting bent crystal spectrometer. The strong interaction energy level shift and the total decay width of the $1s$ state, obtained from the transition energy and the linewidth, are $\varepsilon_{1s} = -7.127 \pm 0.028(\text{stat}) \pm 0.036(\text{syst})$ eV (attractive) and $\Gamma_{1s} = 0.97 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$ eV. The corresponding hadronic πN s-wave scattering lengths for elastic scattering and single charge exchange are $a^h_{\pi^- p \to \pi^- p} = 0.0885 \pm 0.0009 m_\pi^{-1}$ and $a^h_{\pi^- p \to \pi^0 n} = -0.136 \pm 0.010 m_\pi^{-1}$.

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The pionic hydrogen atom offers the unique possibility to study the pion-nucleon interaction at zero energy. With a precise measurement of the energy and the line shape of a pionic K x-ray line, one can determine the energy level shift ε_{1s} and broadening Γ_{1s} of the ground state induced by the strong interaction. In this paper we report results from a new measurement of the 2.9 keV x-ray line from the $3p$-$1s$ transition in pionic hydrogen; results obtained with deuterium are published separately [1]. The difference between the measured energy and the calculated electromagnetic transition energy gives the strong interaction shift $\varepsilon_{1s} = -(E^{\text{meas}}_{3p\text{-}1s} - E^{\text{el mag}}_{3p\text{-}1s})$, and the deconvolution of the measured line profile with the instrumental resolution function yields the linewidth $\Gamma_{3p\text{-}1s}$. The linewidth is determined (apart from a small Doppler broadening) by the total decay width Γ_{1s} of the $1s$ state induced by the nuclear capture processes $\pi^- p \to \pi^0 n$ and $\pi^- p \to \gamma n$. The two measured quantities allow a direct determination of the two independent hadronic πN s-wave scattering lengths, without the need of an extrapolation of the scattering amplitudes to zero energy. Deser-type formulas relate ε_{1s} and Γ_{1s} to the elastic and charge exchange scattering lengths of an isospin symmetric strong interaction [2,3]:

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

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

Here E_{1s} is the electromagnetic binding energy of the $1s$ level, r_B the Bohr radius, and q the c.m. momentum of the π^0; $\delta_\varepsilon, \delta_\Gamma$ are corrections for electromagnetic and mass splitting effects [3]. The total decay width Γ_{1s} is corrected with the Panofsky ratio $P = 1.546 \pm 0.009$ [4] to obtain the partial width from the charge exchange reaction $\pi^- p \to \pi^0 n$, which is related to the scattering length $a^h_{\pi^- p \to \pi^0 n}$. In a first step of the experiment a precision of 5% had been reached for the shift: $\varepsilon_{1s} = -7.12 \pm 0.32$ eV [5]. The width has never been measured so far.

A detailed description of the experiment is given in Ref. [6]. The schematic layout of the experiment in the πE5 beam at the Paul Scherrer Institut (PSI) is shown in Fig. 1. The spectrometer consisted of three main parts: the pion stop target mounted in the center of the cyclotron trap [7], the bent quartz crystals mounted on a turntable and placed in a temperature stabilized (± 0.1 °C) aluminum box, and the position sensitive CCD (charge coupled device) x-ray detector mounted on an XY table. A target, crystals, and an x-ray detector were located on a Rowland circle with a diameter of 235 cm. The three parts were connected with flexible plastic tubes filled with helium to reduce the absorption of the 2.9 keV x rays.

The principle of the wavelength (energy) measurement was to measure the Bragg angle *difference* between a calibration line (wavelength standard) and the pionic hydrogen line. As a wavelength standard, the electronic $K\alpha_1$ line of argon was used because its energy is well known and close to the energy of the pionic hydrogen $K\beta$ transition. The argon $K\alpha$ doublet was recently remeasured at NIST (National Institute of Standards and Technology), and the energy of the $K\alpha_1$ peak was determined with a precision of 6 ppm: $E_{\text{Ar}}(K\alpha_1) = 2957.685 \pm 0.019$ eV [8]. For a calibration measurement the target cell was filled with argon gas with a pressure

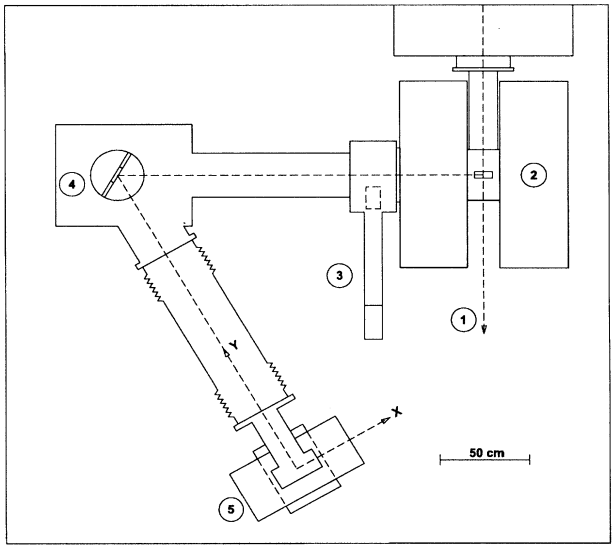

FIG. 1. Schematic layout: (1) beam direction, (2) cyclotron trap with target cell, (3) movable argon source for the stability monitoring, (4) turntable with crystal assembly, and (5) XY table with CCD x-ray detectors.

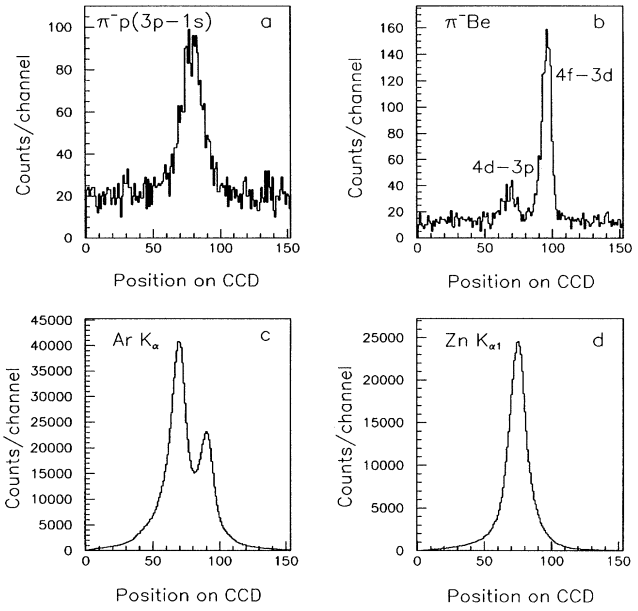

FIG. 2. Measured x-ray lines: (a) Pionic hydrogen line. (b) With the pionic beryllium line, the instrumental resolution function was measured. (c) The electronic argon $K\alpha$ line was used as a wavelength standard. (d) The energy calibration was cross checked with the zinc $K\alpha_1$ line, measured in third order.

of 0.1 bar and illuminated with an x-ray tube to produce fluorescent $K\alpha$ x rays. The crystals were oriented to reflect the argon x rays emitted from the target cell under the Bragg angle $\vartheta_{\mathrm{Ar}} = 58.6°$, and the CCDs were positioned at the argon focus. Figure 2(c) shows a measured argon calibration line; as a cross-check of the energy calibration the $K\alpha_1$ line of zinc was measured in third order [Fig. 2(d)]. For the measurement of the pionic hydrogen transition the crystals were rotated with the turntable by an angle $t = \vartheta_{\mathrm{Ar}} - \vartheta_{\pi^- p}$, so that they reflected the pionic hydrogen x rays from the target cell under the *expected* Bragg angle $\vartheta_{\pi^- p}$ of $\approx 61.0°$; the CCDs were moved with the XY table from the argon focus to the position of the pionic hydrogen focus. Figure 2(a) shows the measured pionic hydrogen line. From the measured X and Y coordinates of the pionic hydrogen line (relative to the position of the argon calibration line) and the rotation angle t, the Bragg angle difference $\Delta\vartheta$ between the argon calibration line and the pionic hydrogen line was obtained. With the known Bragg angle of the calibration line and the measured angle difference $\Delta\vartheta$ the wavelength of the transition can be calculated with Bragg's law.

Because of the very low x-ray energy and event rate, focusing crystals had to be used in reflecting mode [9]. The crystal assembly consisted of six cylindrically bent quartz (110) crystals [lattice spacing $d = 2.45668(20)$ Å at 20 °C] in Johann geometry, arranged in two planes [6]; each crystal was 96 mm wide and 55 mm high. The three crystals of a plane were aligned such that their reflexes were projected on top of each other at the detector plane. The whole crystal assembly was mounted on a turntable, which was equipped with an angle encoder with a precision of 1 arc sec (corresponding to an energy uncertainty of 8 meV) over a full turn. During the experiment the turntable had to be rotated by 4° only.

An array of four CCDs (with a total number of about 3.6×10^6 pixels) was used as x-ray detector. Each CCD was approximately 26 mm high and 17 mm wide and consisted of 770×1152 pixels with a size of 22.5 μm $\times$ 22.5 μm. The CCDs were operated at a temperature of -120 °C to reduce the thermal noise charge accumulated during a typical exposure time of 30 min for a pionic hydrogen run. The signature for a good pionic x-ray event was a single pixel hit with a deposited energy of 2.9 keV. The good two-dimensional spatial resolution of the CCDs, together with the good intrinsic energy resolution of 150 eV (FWHM) at 2.9 keV, was crucial for the selection of a clean sample of pionic x-ray events out of a vast background [10].

In liquid (or high pressure) hydrogen the yield of the radiative $\pi^- p(3p\text{-}1s)$ transition is strongly suppressed because of Stark mixing of the angular momentum states occurring during a collision of an excited $\pi^- p$ atom with a (much larger) normal hydrogen atom. For this reason saturated hydrogen vapor at a pressure of 1 bar (temperature of 20.4 K) was used, corresponding to a density of $\sim 15\rho_{\mathrm{STP}}$. The yield of the radiative $\pi^- p(3p\text{-}1s)$ transition at this density is about 3.4%

[11]. To increase the pion stop rate in the low density hydrogen the cyclotron trap was used. About 10% of the pions injected into the trap (approximately 10^8 π^-/s at a momentum of 85 MeV/c) stopped in the hydrogen gas.

The instrumental resolution function was measured directly with the pionic Be($4f$-$3d$) transition; it has a very small natural linewidth and an energy which is only 42 eV smaller than the energy of the pionic hydrogen transition. For this measurement the gas target cell was replaced by a beryllium target, which consisted of eight 20 μm thick Be foils, approximating the homogeneous material distribution of the gas target. Figure 2(b) shows the measured beryllium line.

To monitor the stability of the spectrometer, an argon chamber could be moved into the x-ray path (see Fig. 1). The $K\alpha$ line was measured twice a day with high statistics.

Figure 2 shows the measured x-ray lines. The event rate in the pionic x-ray lines was about 5/h for hydrogen and beryllium, the total number of collected events is 1906 ± 83 in the hydrogen line and 1416 ± 49 in the beryllium line. From the π^-Be($4f$-$3d$) line an instrumental resolution of 0.66 ± 0.03 eV (FWHM) is obtained. Assuming that the angular resolution of the spectrometer is constant over the small energy interval between the pionic hydrogen and beryllium lines, a width of $\Gamma_{3p-1s} = 1.02 \pm 0.10(\text{stat})$ eV for the deconvoluted hydrogen line is obtained. A 5% correction is applied to this width to account for a potential Doppler broadening (due to Coulomb deexcitation of the pionic atoms [12]), and a 5% systematic error due to the uncertainty of this Doppler broadening is added to the statistical width error of 10%. The total decay width of the $1s$ state then becomes $\Gamma_{1s} = 0.97 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$ eV.

The measured energy, the calculated electromagnetic transition energy [3], and the corresponding strong interaction shift of the $1s$ state are given in Table I (the shift and width of the $3p$ state are negligible). Inserting ε_{1s} and Γ_{1s} into Eqs. (1) and (2) and correcting the elastic scattering length by $\delta_\varepsilon = -(2.1 \pm 0.5)\%$ and the charge exchange scattering length by $\delta_\Gamma = -(1.3 \pm 0.5)\%$ for electromagnetic and mass splitting effects [3], one gets the hadronic s-wave scattering lengths

$$a^h_{\pi^- p \to \pi^- p} = (0.0885 \pm 0.0009) m_\pi^{-1}, \quad (3)$$

$$a^h_{\pi^- p \to \pi^0 n} = (-0.136 \pm 0.010) m_\pi^{-1}. \quad (4)$$

They are related to the isoscalar (b_0) and isovector (b_1) scattering lengths and to the scattering lengths a_1 and a_3 for total isospin 1/2 and 3/2, respectively, by $a^h_{\pi^- p \to \pi^- p} = b_0 - b_1 = \frac{1}{3}(2a_1 + a_3)$ and $a^h_{\pi^- p \to \pi^0 n} = \sqrt{2} b_1 = \frac{\sqrt{2}}{3}(a_3 - a_1)$. Figure 3 shows the constraints on b_0 and b_1 imposed by the values of Eqs. (3) and (4). Also shown in Fig. 3 is the nearly horizontal band derived from the real part of the $\pi^- d$ scattering length [1] and the calculations of Thomas and Landau [14], which relate $\text{Re}a_{\pi^- d}$ to the elementary πN scattering lengths. The width of this band ($\pm 1\sigma$) is dominated by theoretical uncertainties. The deuterium band is in contradiction to the Karlsruhe-Helsinki (KH) πN s-wave scattering lengths [15], which were derived from data collected before 1980. Deviations from the KH values were also observed in recent low energy πN scattering experiments (see, e.g., [16] and references therein).

If isospin would be an exact symmetry (and if we assume that the calculations of Thomas and Landau are complete), all constraints from the three independently analyzed reactions of Fig. 3 should have a common intersection. Conversely, if isospin symmetry is broken, constraints from more than two independent processes would, in general, be incompatible [17]. Gibbs *et al.* [18] reported isospin breaking effects beyond Coulomb and mass splitting corrections for the πN elastic and single charge exchange reactions above threshold. Inspection of Fig. 3 shows that with our present accuracy, the three constraints are still compatible with isospin symmetry. In order to improve the constraint on b_1, more data have been collected in a new experiment.

Recently, Bernard, Kaiser, and Meissner have calculated the isovector scattering length b_1 within the

TABLE I. Measured and calculated (electromagnetic) $3p$-$1s$ transition energy [3,13] and deduced strong interaction shift of the $1s$ state.

	Energy (eV)
E^{meas}_{3p-1s}	2885.935 ± 0.028(stat) ± 0.035(syst)
E^{calc}_{3p-1s}	
Point nucleus (Klein-Gordon)	2875.715 ± 0.008
Vacuum polarization (Uehling potential)	3.235 ± 0.001
Finite size (proton and pion)	−0.102 ± 0.003
Relativistic recoil effect and magnetic moment of the proton	−0.047 ± 0.000
Higher order corrections	0.011 ± 0.003
Electromagnetic transition energy	2878.812 ± 0.008
Shift from recoil of $\pi^- p$ atom	−0.004
Strong interaction shift ε_{1s}	−7.127 ± 0.028(stat) ± 0.036(syst)

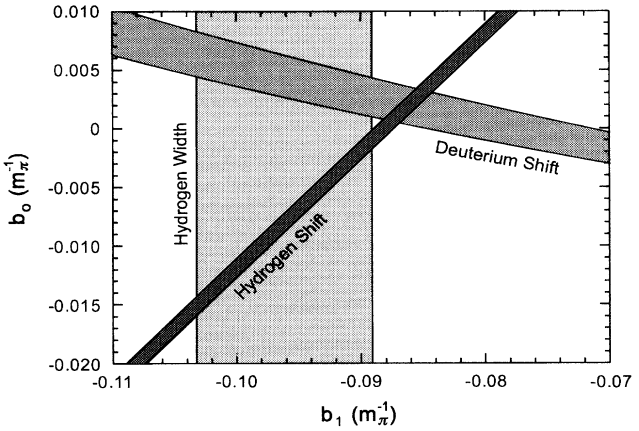

FIG. 3. Constraints on the scattering lengths b_0 and b_1 imposed by the measured strong interaction shift and width of the $1s$ state of pionic hydrogen and the $1s$ shift of pionic deuterium [1].

framework of heavy baryon chiral perturbation theory, improving the early current algebra prediction of Weinberg [19]. To order m_π^4 their prediction is $-0.096 m_\pi^{-1} \leq b_1 \leq -0.088 m_\pi^{-1}$ [20]. This is consistent with our experimental values.

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