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Precision Measurement of the (3p – 1s) X-Ray Transition in Muonic Hydrogen[1, 2]

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Abstract—The (3p – 1s) X-ray transition to the muonic hydrogen ground state was measured with a high-resolution crystal spectrometer. The assumption of a statistical population of the hyperfine levels of the muonic hydrogen ground state was directly confirmed by the experiment and measured values for the hyperfine splitting can be reported. The measurement supplements studies on line broadening effects induced by Coulomb de-excitation hindering the direct extraction of the pion-nucleon scattering lengths from pionic hydrogen and deuterium X-ray lines.

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1. INTRODUCTION

The measurement of the (3p – 1s) X-ray transition in muonic hydrogen ground state is embedded in a series of measurements on pionic hydrogen and deuterium [1–3]. There, the main goal is to measure with high precision line shift and broadening of Lyman transitions in order to determine the complex pion-nucleon and pion-deuterium scattering lengths.

Besides the strong interaction and the resolution of the apparatus, the line width is affected by Coulomb de-excitation transitions—a non-radiative decay mode occuring in exotic hydrogen atoms during the collision with neighbouring H_2 molecules [4]. The de-excitation energy is converted into kinetic energy of the collision partners, spectral lines originating from subsequently emitted X-rays are Doppler broadened. Muonic hydrogen experiences similar mechanisms during the atomic de-excitation cascade than the pionic atom. Because of the absence of any hadronic broadening, it constitutes an ideal testing ground to study Coulomb de-excitation in order to quantify the corrections necessary in the analysis of the pionic hydrogen line shape [5].

2. EXPERIMENT

The X-ray source is formed by using the cyclotron trap, where pions are slowed down and decay (Fig. 1). About 2% of the decay muons are captured by hydrogen in a cryogenic gas cell filled with H_2 at the center of the trap. The X-rays were reflected in first order by a silicon crystal cut along the (111) plane and bent spherically to a radius of about 3 m. The Bragg crystal's resolution was determined to be (272 ± 5) meV (FWHM) by means of narrow X-ray lines from highly-ionised atoms [6]. As position-sensitive X-ray detector served an array of charge-coupled devices (CCDs) [7].

3. RESULTS

A significant broadening originating from Coulomb de-excitation is observed when comparing the measured line width with the experimental resolution (Fig. 2). An unbiased analysis yielded for a hyperfine splitting of (211 ± 19) meV and a triplet-to-singlet

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[2] The article is published in the original.

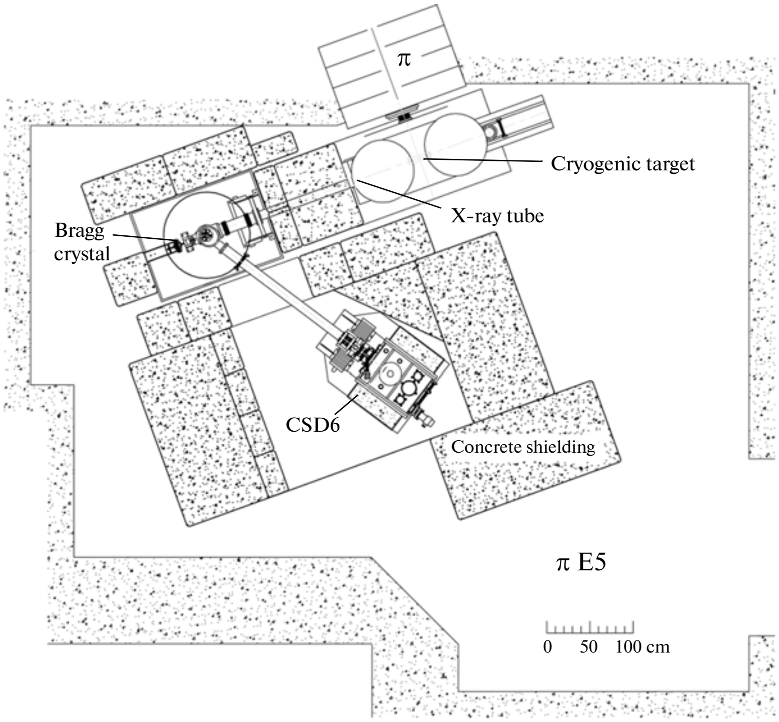

Fig. 1. Set-up at the πE5 channel of the Paul Scherrer Institut (PSI).

population of (3.59 ± 0.51) : 1, in good agreement with the calculated ground-state hyperfine splitting of (182.725 ± 0.062) meV [8] and the expected relative statistical population of 3 : 1.

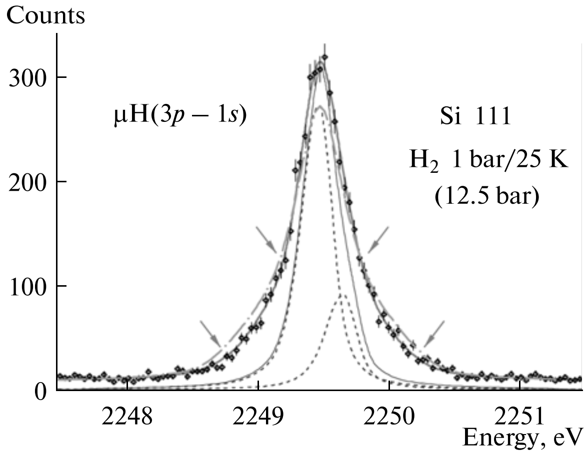

Fig. 2. Measured line shape of the $\mu H(3p - 1s)$ transitions. The narrow structure represents the resolution function of the spectrometer. The arrows indicate the improvement in the description of the line shape by using the most recent cross section calculations.

The experiment triggered a recalculation of atomic cross sections needed to describe the collision processes during the de-excitation cascade [10]. In this way, the kinetic energy distribution of the μH atom can be obtained at the instant of the X-ray emission [9]. The newly calculated cross sections [10] yielded a significantly better description of the line shape pointing to an improved understanding of the cascade processes [5].

4. SUMMARY

The experiment directly confirms the assumption of a statistical population of the hyperfine levels of the muonic hydrogen ground state, which is an important assumption in measurements of the induced pseudoscalar coupling in muon capture by the proton [11]. Measured values for the hyperfine splitting can be reported.

A significant Doppler broadening of the $(3p - 1s)$ line was also found in the case of pionic hydrogen [2], in complete contrast to pionic deuterium [3]. This behavior is not understood at present. Therefore, by implementing the strong interaction the calculation of collision cross sections is being resumed for the pionic hydrogen case to be extended to pionic deuterium.

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