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PIONIC DEUTERIUM

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Abstract

Data taking of the PIONIC HYDROGEN project has been completed with a high statistics study of the strong–interaction effects in πD by measuring the $K\beta$ X–radiation. The πD hadronic shift will provide a constraint for the πN isospin scattering lengths extracted from the πH measurement. The hadronic width is directly related to pion production at threshold.

1 Introduction

Quantum Chromodynamics (QCD) is today's fundamental microscopic theory of strong interaction. Based on QCD a new framework - Chiral Perturbation Theory (χPT) - gives a theoretical description of the interaction of hadrons at low energies in terms of an expansion in momenta, fine structure constant α and current quark masses [1, 2]. Because relative energies are restricted to the keV range in exotic atoms, they provide an ideal laboratory to study the low-energy meson-baryon interaction without the need of

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any extrapolation to threshold. The strong pion-nucleus s-wave interaction is observed by measuring K X–radiation in pionic atoms as a level shift ϵ_{1s} and broadening Γ_{1s} of the atomic ground state.

Pions and nucleons combine to isospin 1/2 or 3/2 systems. At threshold the πN interaction is then completely described by two amplitudes reducing to two real numbers identified with the s-wave scattering lengths. One may choose the isoscalar and isovector scattering lengths a^+ and a^-. In pionic hydrogen the hadronic shift is in leading order related by Deser-type formula proportional to the sum of the scattering lengths a^+ and a^- and the broadening to a^- [3, 4]. These values have been quantified by the pionic hydrogen experiment [5]. Within the framework of χPT, the corrections to the Deser formula are calculated and in next to leading order of the chiral expansion further low-energy constants appear which are c_1, f_1 and f_2.

The hadronic shift in pionic deuterium [5], when determined to a precision similar to that obtained in pionic hydrogen will provide a constraint for the isoscalar and isovector scattering lengths a^+ and a^-. In addition it allows for the determination of the low-energy constant f_1 for which only dimensional estimates exist. As an outstanding case for charged pion–nucleon interactions, the shift is very sensitive to isospin-breaking corrections owing to the almost complete cancellation of the pion–proton and pion–neutron scattering lengths [6]. Furthermore, the hadronic width is directly related to pion production at threshold. The production reaction $pp \to d\pi^+$ is connected to absorption $d\pi^+ \to pp$ by detailed balance, which in the case of charge symmetry is equal to $d\pi^- \to nn$. These processes will become calculable at the percent level within the framework of χPT in the near future [7].

2 Experimental Approach

The experiment is set up at the high-intensity low-energy pion beam $\pi E5$ at the Paul-Scherrer Institut [8]. It consists of the cyclotron trap II, a cryogenic target, a reflection-type crystal spectrometer equipped with spherically bent crystals and a large-area two-dimensional position-sensitive detector built up from an array of six Charge-Coupled devices (CCDs) for X-ray detection.

After pion injection into the trap the beam is degraded in order to spiral in the magnetic field into a gas-filled target cell. In this way a few % of the incoming pions are stopped forming a concentrated X-ray source. X-rays emitted from the target gas are diffracted by a silicon crystal of 10 cm diameter and 3 m curvature radius. The spherical bending leads to a partial vertical focussing, which increases the count rate. Each CCD has 600 x 600 pixels of 40 μm x 40 μm. The efficiency is maximal around 3.5 keV ($\approx 80\%$)

and, therefore, ideally suited for low energy X-rays.
The energy calibration of the πD (3p-1s) transition (Fig.1) is performed with the precisely known Kα fluorescence radiation of gallium [9], which was excited by means of an X-ray tube. The response function of the spectrometer needed to extract the hadronic broadening was measured with X-rays from He-like Argon (Ar^{16+}) produced in an Electron Cyclotron Resonance Ion Trap (ECRIT) [10].

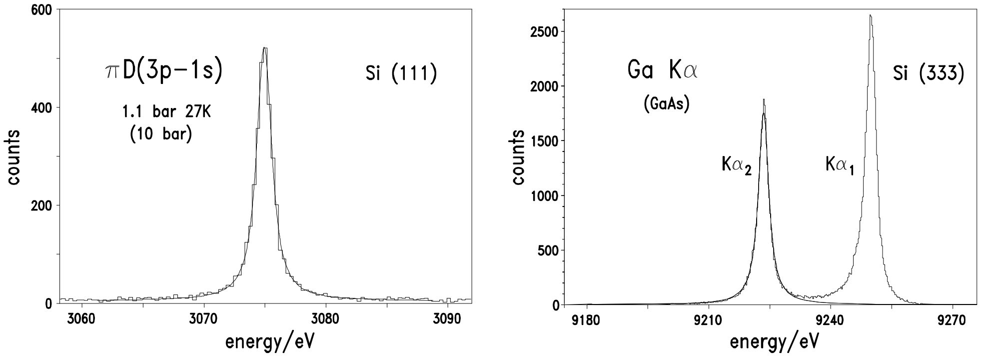

Figure 1: *left: The spectrum of $K\beta$ transition in πD measured with a Si Bragg crystal in first order at a target density equivalent to 10 bar. right: Ga $K\alpha$ doublet measured in third order used for the energy calibration.*

When extracting the hadronic effects, complications arise from processes during the atomic de-excitation cascade, in particular molecular formation [11] and Coulomb de-excitation [12]. In the case of molecular formation like $(\pi D)_{nl} + D_2 \rightarrow [(\pi dd)d]ee$ possible radiative de-excitation out of such complexes leads to an energy shift which alters the extracted hadronic shift. While not observed in πH [8], it is predicted for πD, that the fraction of X-ray emissions increases [11]. If a density dependence is observed, the pure hadronic shift must be obtained from extrapolation to density zero. In the case of Coulomb de-excitation, the energy release for the de-excitation step is converted to kinetic energy: $(\pi^- D)_n + D_2 \rightarrow (\pi^- D)_{n-1} + D + D +$ *kinetic energy*, leading to a Doppler broadening of the line width. Both, molecular formation and Coulomb de-excitation, are scattering processes and depend on the collision rate, i.e., on density. Consequently, the strategy of the experiment was to study the X-ray transitions at different densities.

3 First Results

The actual status of the analysis of the πH data yields the preliminary values $\epsilon_{1s} = +7.120 \pm 0.011\, eV$, $\Gamma_{1s} \approx 823 \pm 19\, meV$ [8].

The πD measurement ended up with nearly 10000 events measured at three different target densities equivalent to 3.5, 10 and 28 bar to be sensitive to effects during the atomic cascade mentioned above.

The most precise experimental values for the strong interaction shift and width in pionic deuterium are reported to be [13] $\epsilon_{1s} = -2468{\pm}55\, meV (\pm 2.2\%)$ and $\Gamma_{1s} = 1193 \pm 129\, meV (\pm 11\%)$. The preanalysis of the new data shows, that it will be possible to extract the hadronic shift and width with an uncertainty of about 0.5% and 4%, respectively, or better.

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