Pionic atom research

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Precision experiments on pionic–atom X–rays became possible by high–flux beams, e. g., at the Paul-Scherrer-Institut (PSI) and modern techniques in preparing suitable experimental conditions. These are the cyclotron trap to achieve high stop densities in dilute gases, cryogenic targets, high luminosity and high resolution crystal spectrometers as well as large area and high–rate capable pixel detectors build up from Charge–Coupled Devices (CCDs)[1, 2]. The measuring program covers the study of pionic hydrogen isotopes [3] and other light systems[4].

The study of the strong–interaction effects in pionic hydrogen yields the pion–nucleon scattering lengths a^+ and a^- from the hadronic shift ε_{1s} and broadening Γ_{1s} of the atomic ground state. Moreover, Γ_{1s} is directly connected to the pion–nucleon coupling constant $f^2_{\pi N}$. The recent results of the experiment reach a precision of 0.2% for ε_{1s} and, preliminary, of 3-4% for Γ_{1s}. Final goal is an uncertainty of about 1% for Γ_{1s}, which corresponds to 0.5% for $f^2_{\pi N}$. Such a precision then allows for a decisive test of the methods of Chiral Perturbation Theory, which is the low–energy approach of QCD. The new pionic hydrogen experiment profits from a significantly improved peak–to–background ratio and statistics. Three different transitions have been measured and the target density was varied over a pressure range of 200. This served to disentangle the effects of *Coulomb deexcitation*, where deexcitation energy is transferred into kinetic energy of the colliding πH system and other hydrogen atoms of the target, leading to a Doppler broadening of the X–ray transitions. The hadronic width is now constrained to lower values than obtained from previous experiments having an accuracy of 7%.

Because of the large uncertainty of Γ_{1s}, at present ε_{1s} from πD must be used to determine a^+, a^-, and $f^2_{\pi N}$ facing nontrivial 3–body corrections. In order to achieve Γ_{1s} at the 1% level, a better knowledge of the effects from *Coulomb deexcitation* is indispensable. Therefore, as a next step *Coulomb deexcitation* will be measured precisely in muonic hydrogen, where the hadronic broadening is absent. This, however, reqiures a better knowledge of the crystal resolution function as well. For that reason, an Electron–Cylotron–Resonance Ion Trap to produce hydrogen and heliumlike few electron systems has been set up [5]. High X–ray yields were obtained by using the superconducting magnet of the cyclotron trap itself to generate a strong mirror field. The observation of the narrow M1 transition $2^3S_1 \rightarrow 1^1S_0$ in heliumlike argon yielded already a precise crystal response for the first series of measurements and led to the discovery of a noticable *Coulomb explosion* in CH_4 [6].

A new value for the charged pion mass m_π results from a simultaneous measurement of pionic nitrogen and muonic oxygen X–rays. This measurement exploits the knowledge of the positive muon mass to 0.05ppm [7], which assuming CPT invariance, serves by measuring the $\mu O(5g-4f)$ transition as an ultimate energy calibration at 4 keV. Limitations of this method are due to the rather small μO count rate as compared to our previous calibration with Cu X–rays [8] and the significant Doppler broadening of the πN and μO transitions caused by *Coulomb explosion*. It originates from acceleration of the ions by Coulomb repulsion when the molecule breaks up and has been proven by a dedicated measurement to be much larger than anticipated [9]. Finally a precision of about 1.5ppm will be obtained for m_π from the $\pi N/\mu O$ comparison.

A line broadening from *Coulomb explosion* is principally excluded in exotic atoms formed with noble gases. In a few cases transitions with sufficient yields are available in the medium part of the atomic cascade, where the exotic atom is a true hydrogenlike system. Here, energy determination is not obscured from any screening effects due to remaining electrons and, hence, usable as X–ray standard in the few keV range. As a first example titanium fluorescence radiation was calibrated with the new standard [10].

Table 1: Recent measurements on light pionic atoms by the PION MASS and PIONIC HYDROGEN collaborations.

	transition	measured quantity	physical quantity
πH	(2p–1s)	Γ_{1s}	$a^-, g_{\pi N}$
	(3p–1s)	$\varepsilon_{1s}, \Gamma_{1s}$	$a^+, a^-, f^2_{\pi N}$
	(4p–1s)	Γ_{1s}	$a^-, f^2_{\pi N}$
πD	(2p–1s)	ε_{1s}	a^+
		Γ_{1s}	$\pi NN_{I=0} \rightarrow NN$
$\pi N/\mu O$	(5g–4)	energy difference	m_π
		line broadening	*Coulomb expl.*
πNe	(5g–4f)	X–ray standard	*QED tests*
Ar^{16+}	M1	crystal response	*Coulomb deex.*
		few–body systems	*QED tests*

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