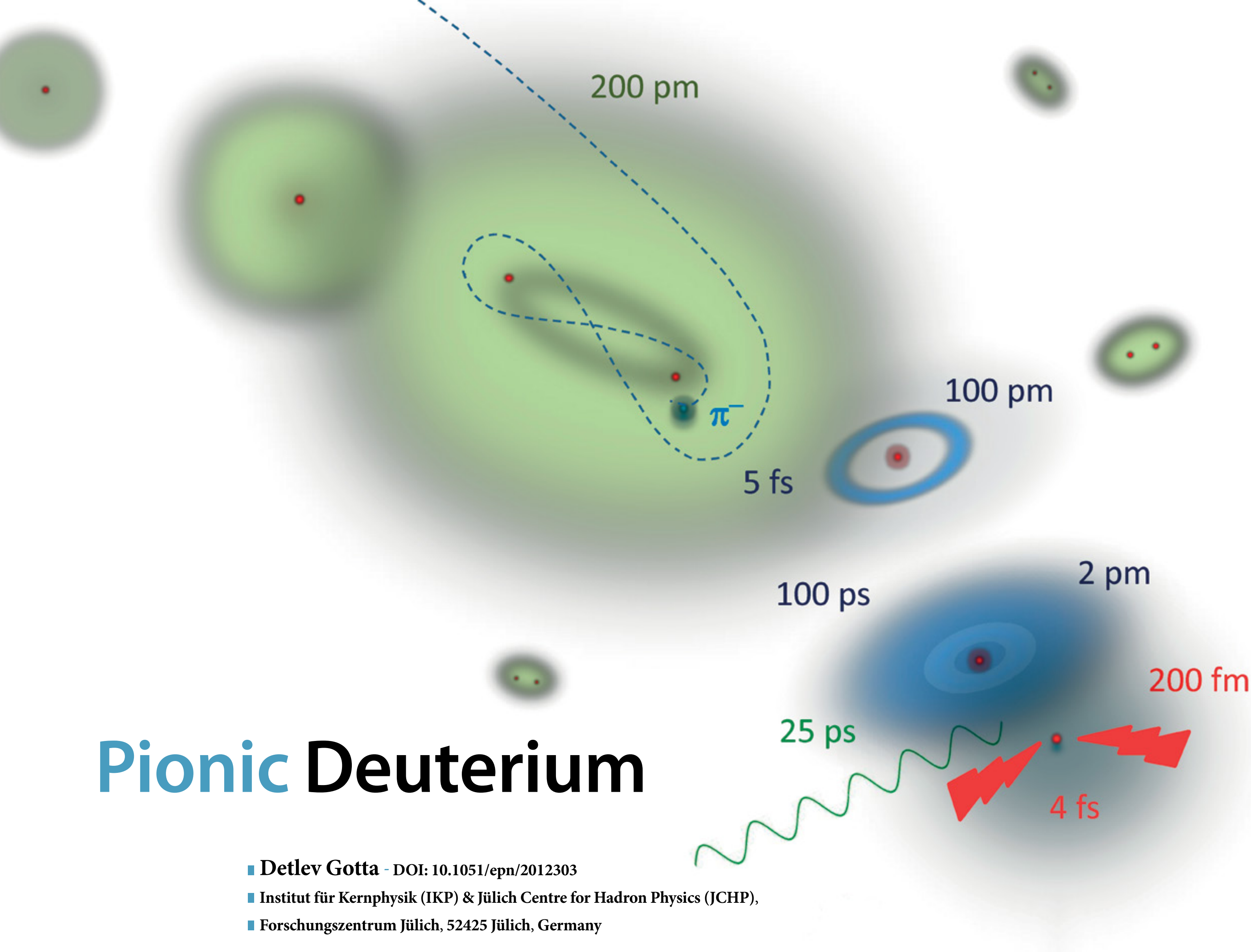

Pionic Deuterium

Detlev Gotta - DOI: 10.1051/epn/2012303
Institut für Kernphysik (IKP) & Jülich Centre for Hadron Physics (JCHP),
Forschungszentrum Jülich, 52425 Jülich, Germany

Atoms formed after Coulomb capture of negatively charged pions rapidly develop to nuclear dimensions and eventually decay by strong interaction. The strong force affects energy and line width of X-rays emitted during a de-excitation cascade which allows precise measurements of hadronic quantities by means of crystal spectrometers. Pionic deuterium - involving the lightest composite nucleus - constitutes a bridge between particle and nuclear physics.

▲ Length and time scales of pion capture at a deuterium molecule, subsequent de-excitation cascade, and nuclear decay

The close relation between particle and nuclear physics is evident from prediction and discovery of mesons (medium heavy particles) mediating the short-range nuclear force. The lightest one – the pion – though 270 times heavier than an electron is still light on the typical nuclear scale of 1 GeV/c^2, and its interaction with the nucleon is a corner-stone in understanding the nuclear force.

The description is based on quantum chromodynamics (QCD), where elementary particles and forces are quarks and gluons which, however, are not realised as individual particles in nature (confinement). Nevertheless, symmetries of QCD determine properties of the directly accessible, but composite, strongly interacting particles (hadrons) – the mesons, nucleons as well as nuclei. Effective field theories like chiral perturbation theory (χPT) - the modern low-energy approach of QCD - exploit chiral symmetry founded on the small masses of the light quarks u, d and s. In a perturbative approach, where order parameters are momenta, pion mass, and fine structure constant α, strong and electromagnetic interactions are treated on the same footing [1-4].

Exotic atoms

The existence of negatively charged muons (a "heavy" electron), mesons, and antiprotons suggested immediately the formation of atomic systems with a nucleus $A(Z,N)$ by eliminating electrons (Box 1). Such **exotic atoms** were predicted in the late 1940s and verified experimentally soon after at accelerator facilities. Later on, systematic and high-statistics precision studies became possible at meson factories and dedicated low-energy antiproton storage rings.

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Exotic atoms are created as highly excited systems. During an atomic cascade, de-excitation occurs among others by Auger electron and X-ray emission, which allows a variety of studies [5]:

- mass and spin of the captured particle,
- nuclear moments (from muonic atoms),
- test of bound-state quantum electrodynamics,
- behaviour of excited many-electron systems,
- muon catalyzed fusion, and
- the strong force at low energies by measuring shift and broadening of low-lying atomic levels.

Exotic hydrogen plays an outstanding role as it directly probes the elementary hadron-proton system and - using isotopes - additionally the interaction with the neutron.

Pion-nucleon scattering

Neglecting the electric charge, (almost) identical strong interaction properties of proton and neutron led to the concept of isospin symmetry. Nowadays, it is identified with the (approximate) symmetry of u and d quarks building up the nucleons.

In terms of isospin, three pions $\pi \equiv (\pi^{\pm,0})$ and two nucleons $N \equiv (p,n)$ combine (analogue to spins) to 1/2 and 3/2 states. Therefore, in the limit of isospin invariance two different scattering lengths $a_{\pi N}$ are sufficient to determine all $\pi N \to \pi N$ reactions. For experimentally important channels, isospin conservation and charge symmetry yield

$a_{\pi^- p \to \pi^- p} - a_{\pi^+ p \to \pi^+ p} = -\sqrt{2} \cdot a_{\pi^- p \to \pi^0 n}$ and

$a_{\pi^+ p \to \pi^+ p} = a_{\pi^- n \to \pi^- n}$.

In pionic hydrogen (πH), energy shift ε and level broadening Γ of the atomic ground state 1s can be attributed to the elementary processes elastic and charge exchange scattering, respectively [6]:

$\varepsilon_{1s}(\pi H) \propto a_{\pi^- p \to \pi^- p} + \ldots$

$\Gamma_{1s}(\pi H) \propto (a_{\pi^- p \to \pi^0 n})^2 + \ldots$

For pionic deuterium, the shift is due to the coherent sum of proton and neutron scattering

$\varepsilon_{1s}(\pi D) \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + \ldots$

Ellipses stand for the strong (owing to the different mass of u and d quark) and the electromagnetic isospin symmetry violation.

Isospin and charge-symmetry breaking corrections are quantifiable consistently by the methods of χPT [6]. Multiple scattering and nuclear structure effects, as occurring in the case of πD, are well under control [9].Hence, $\varepsilon_{1s}(\pi D)$ constitutes a decisive constraint on the scattering lengths as obtained from πH, particularly, as chiral symmetry requires one of the isospin amplitudes - the isoscalar scattering length $a^+ \equiv a_{\pi^- p \to \pi^- p} + a_{\pi^+ p \to \pi^+ p}$ - to vanish in leading order [1,2]. In other words, the $\pi^- p$ and $\pi^+ p$

> **Exotic atoms allow 'scattering experiments' at relative energy 'zero'**

BOX 1: CHARACTERISTICS OF EXOTIC ATOMS

Slowed down to kinetic energies of a few eV, negatively charged muons, pions, kaons, or antiprotons (x-) are captured in the Coulomb field of a nucleus A(Z,N) at approximately the outmost electron (e) shells. Due to the large mass ratio m_x / m_e , the subsequent quantum cascade starts from highly excited atomic states. For example, in pionic hydrogen and antiprotonic xenon, initial principle quantum numbers n are distributed around 16 and 200, respectively, occupying there most of the possible angular momentum states ℓ.

The mass dependence of binding energies E_n and radii $r_{n\ell}$ reveals the dimensions of such atoms:

$E_n = \mu c^2 \alpha^2 Z^2 / n^2$

$r_{n\ell} = R_B \cdot [3n^2 - \ell(\ell+1)]/2.$

Exotic-atom Bohr radii $R_B = \hbar c / \mu c^2 \alpha Z$ range from about 50 to 3 fm for Z=1 to 82 (μ denotes the reduced mass of particle and nucleus). Binding energies increase - compared to electronic atoms - to a few keV for exotic hydrogen (Z=1) up to MeV for heavy nuclei like lead (Z=82).

De-excitation cascade

In medium and high Z atoms, de-excitation is very fast mainly due to internal processes. It proceeds at the fs scale preferentially by Auger electron emission in the upper and X-radiation in the lower part of the cascade. Collisional effects, *e.g.*, electron refilling may occur in dense media.

By contrast, the exotic hydrogen cascade, assumed to develop within a few 100 ps, is dominated by collisional de-excitation already at low densities. The electrically neutral x^-H system penetrates deeply into the electron cloud of neighbouring atoms, where the nuclear Coulomb field induces an s-state admixture in higher ℓ states. Consequently, for strongly interacting particles the atomic cascade depletes because of inelastic nuclear reactions from the beginning and X-ray yields depend strongly on density. In pionic hydrogen and deuterium, typical yields are a few per cent for Lyman series (Fig. 1).

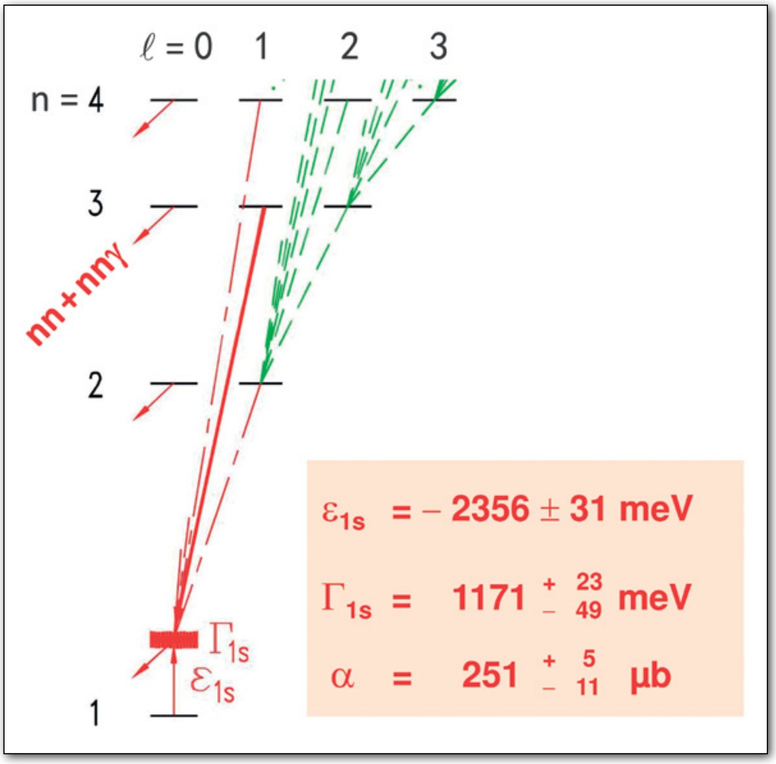
Strong-interaction effects

The small distances enhance significantly the overlap of the wave function of orbiting particle and nucleus. In hadronic atoms - systems formed with pions, kaons, or antiprotons - the nuclear force contributes to the binding energy observable as an X-ray line shift ε. Nuclear reactions reduce the life time Δt of low-lying atomic states which manifests itself in an additional line broadening Γ according to the uncertainty relation $\Gamma \cdot \Delta t \approx \hbar$.

The shift is attributed in leading order to elastic hadron-nucleus scattering and the broadening accounts for inelastic nuclear reactions. In this way, for atomic s-states, ε_{ns} and Γ_{ns} measure real and imaginary part of the effective complex hadron-nucleus scattering length $a_{\pi A}$ [10]

$$\varepsilon_{ns} - \frac{i\Gamma_{ns}}{2} = -\frac{4}{n} \cdot \frac{E_n}{R_b} \cdot a_{\pi A}$$

Atomic binding energies are well below the typical hadronic scale of 1 GeV. Hence, exotic atoms constitute a laboratory for "scattering experiments" at relative energy "zero" without the need to extrapolate cross section data.



▲ **FIG. 1: Low-lying atomic levels in pionic deuterium and recent experimental results [7]. The shift ε_{1s} is obtained by comparing the measured X-ray energy with the (calculated) pure electromagnetic value. The broadening Γ_{1s} is extracted from the line shape. The small (negative) value for $\varepsilon_{1s}(\pi D)$ is a consequence of chiral symmetry resulting in a minor repulsive interaction. For comparison, latest results given for pionic hydrogen are $\varepsilon_{1s}(\pi H) = +7120 \pm 11$ meV (indicating the strongly attractive $\pi^- p$ interaction) and $\Gamma_{1s}(\pi H) = 823 \pm 19$ meV [8].**

interaction is of identical magnitude but opposite in sign.

Deviation from zero of a^+ measures the extent of chiral symmetry breaking, which is linked to the nucleon's mass and strangeness content [4]. Obviously, in the limit of charge symmetry, the leading order of $\varepsilon_{1s}(\pi D)$ is given by a^+.

In πN reactions involving charged pions, isospin breaking effects are calculated to be a few per cent only. In the case of $\varepsilon_{1s}(\pi D)$, however, they were predicted to contribute outstanding 40% because of the smallness of a^+ [11]. Verification via πD and πH precision experiments [7,8] constitutes an important success within the framework of χPT [9].

Pion production and absorption

For pion absorption, $\pi NN \to NN$, energy-momentum conservation requires at least A=2 nuclei. In πD, as charge exchange is suppressed by isospin conservation, the level broadening $\Gamma_{1s}(\pi D)$ is **not** generated by πN scattering, in contrast to the πH case. $\Gamma_{1s}(\pi D)$ is dominated by true absorption $\pi^- d \to nn$. About 25% of the decays are due to radiative capture $\pi^- d \to nn\gamma$.

Exploiting time reversal invariance and charge symmetry, *i.e.*, assuming for matrix elements $|A_{\pi^- d \to nn}| = |A_{\pi^+ d \to pp}|$, the broadening measures the s-wave pion production strength α [7]:

$\Gamma_{1s}(\pi D) \propto |A_{pp \to \pi + d}|^2 \propto \alpha$.

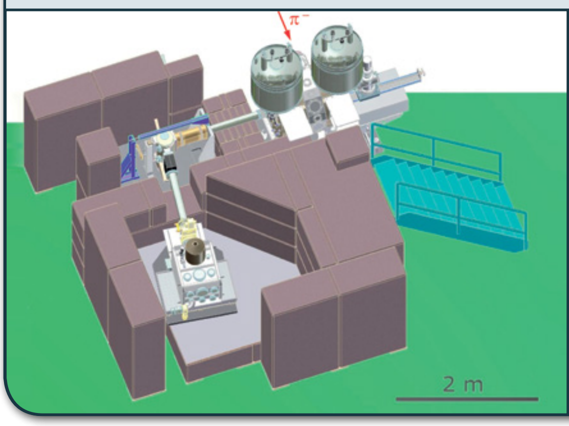
Given that exchange of virtual pions essentially contributes to nuclear binding, α constitutes an important quantity in the description of nuclei in terms of elementary processes [12].

Experimental approach

High-intensity and low-energy pion beams of up to several 10^8 pions per second are available at the meson factory of the Paul Scherrer Institut [13]. Exotic atom formation was optimized by means of the cyclotron trap [14], a superconducting split coil magnet, which winds up the range curve of the particle beam in order to achieve an X-ray source of suitable extensions for the crystal spectrometer. In this way, the stop density at pion beams is enhanced by about a factor of 200 compared to a linear arrangement. A gas cell, cooled to 25K to increase the D_2 density, defines the stop volume.

The crystal spectrometer was set up with a spherically bent Bragg crystal and charge-coupled devices (**CCDs**) for X-ray detection. Count rates are a few tens per hour

BOX 2: A JOHANN-TYPE SET-UP FOR EXOTIC-ATOM X-RAY SPECTROSCOPY



Crystal spectrometer set up at the low-energy beam line of the Paul Scherrer Institut. Pions are stopped in the cyclotron trap (upper right with its liquid helium reservoirs). The Bragg crystal is mounted inside a vacuum chamber (upper left). The diffracted X-rays are detected with the CCD array (bottom left). The massive concrete shielding (roof not displayed) suppresses substantially beam-induced background.

Johann-type set-ups allow a simultaneous measurement of an angle (*i.e.*, an energy) interval according to the extensions of X-ray source and detector in the direction of dispersion – indispensable in low-rate applications like ultimate resolution spectroscopy of exotic atoms [5].

for the Lyman β transition $\pi D(3p\text{-}1s)$, which is very low compared to dedicated X-ray facilities like synchrotron light sources. X-ray source, Bragg crystal, and detector are part of a vacuum system to keep absorption losses small (Box 2).

X-rays from the $\pi D(3p\text{-}1s)$ transition are diffracted in 1. order under the same Bragg angle as gallium $K\alpha_2$ X-radiation in 3. order providing the energy calibration (Fig. 2). The fluorescence radiation was excited by means of an X-ray tube from a GaAs sheet installed inside the gas cell, which allowed alternating measurements of πD and Ga X-rays without any mechanical change.

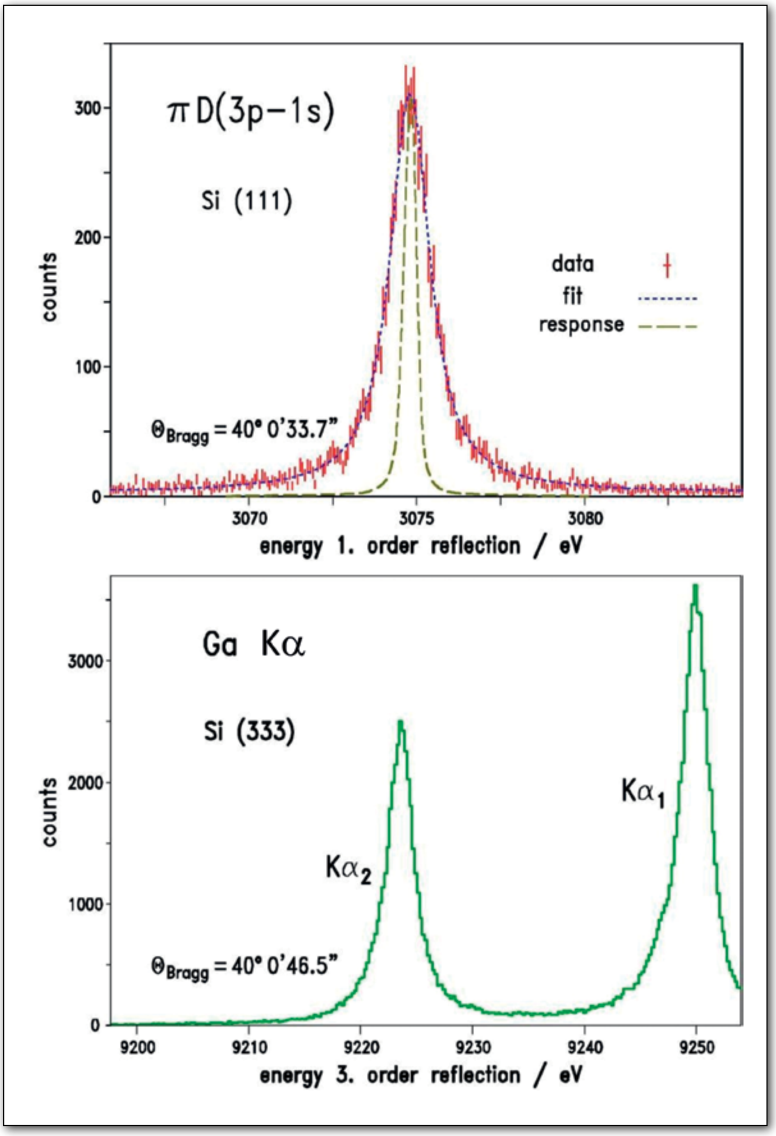
Fluorescence X-rays are inapplicable to calibrate resolution functions because of their complex line shape, and nuclear γ-rays are not available in the few keV range. Therefore, as a novel approach the spectrometer response was determined by using X-rays from highly charged ions [15].

The ions were produced at high rate in an electron-cyclotron resonance source, usually taken to provide ion beams. Such ions are proven to be slow by means of optical spectroscopy, ensuring Doppler broadening to be small.

In particular suited are the very narrow M1 transitions. For helium-like argon, the energy coincides within 25 eV with the one of the $\pi D(3p\text{-}1s)$ transition.

Summary

X-ray spectroscopy of exotic atoms by crystal spectrometers as a precision tool to determine low-energy **QCD** parameters has been developed continuously to exploit the increase in performance of modern accelerator facilities. The experimental accuracy has reached the per cent level or better, which coincides with recent theoretical achievements within the frame work of effective field theories. ■



▲ **FIG. 2:** $\pi D(3p\text{-}1s)$ transition (top) and $Ga\ K\alpha_2$ calibration line (bottom) measured in 1. and 3. order, respectively, using a spherically bent silicon crystal cut along the 111 plane (from [7]). The spectrometer resolution (narrow peak - top) was determined with X-rays from helium-like argon to be 436 ± 3 meV (FWHM). This value is close to the theoretical limit of 403 meV as calculated from intrinsic crystal properties and aberrations owing to the setup geometry.

About the Author

Study of physics and PhD (1981) at University of Karlsruhe (TH). Research on pion-nuclear physics and exotic atoms. Since 1986 at IKP of the Research Centre Juelich. Spokesperson collaborations "Antiprotonic Hydrogen" (LEAR/CERN), "Pion Mass" and "Pionic Hydrogen" (PSI/former SIN). Professor for experimental physics at University of Cologne.

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