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/c², 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.
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 $\pi = (\pi^+\pi^-\pi^0)$ and two nucleons $N = (p,n)$ combine (analogous 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 $\pi N$ scattering reactions. For experimentally important channels, isospin conservation and charge symmetry yield $a_{\pi^- p} - a_{\pi^- n} = -\sqrt{2}a_{\pi^- p} a_{\pi^- n}$ and $a_{\pi^- p} a_{\pi^- n} = a_{\pi^- n} a_{\pi^- p}$.

In pionic hydrogen ($\pi H$), energy shift $\epsilon$ and level broadening $\Gamma$ of the atomic ground state 1s can be attributed to the elementary processes elastic and charge exchange scattering, respectively [6]:

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

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

For pionic deuterium, the shift is due to the coherent sum of proton and neutron scattering $\epsilon_{1s} (\pi D) \propto a_{\pi^- p} a_{\pi^- n} + a_{\pi^- n} a_{\pi^- n} + \ldots$

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 $\chi PT$ [6]. Multiple scattering and nuclear structure effects, as occurring in the case of $\pi D$, are well under control [9]. Hence, $\epsilon_{1s}(\pi D)$ constitutes a decisive constraint on the scattering lengths as obtained from $\pi H$, particularly, as chiral symmetry requires one of the isospin amplitudes - the isoscalar scattering length $a' = a_{\pi^- p} a_{\pi^- n} + a_{\pi^- n} a_{\pi^- n} - \ldots$ - to vanish in leading order [1,2]. In other words, the $\pi^- p$ and $\pi^- n$

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

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**BOX 1: CHARACTERISTICS OF EXOTIC ATOMS**

Slowed down to kinetic energies of a few eV, negatively charged muons, pions, kaons, or antiprotons ($\bar{x}$) 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 $m_\mu / m_e$, 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 $\ell$.

The mass dependence of binding energies $E_n$ and radii $r_n$ reveals the dimensions of such atoms:

$$E_n = \mu c^2 a^2 Z^2 / n^l$$

$$r_n = R_0 (3n^2 - 6\ell + 1) / 2.$$ Exotic-atom Bohr radii $R_0 = \hbar c / \mu c^2 a Z$ range from about 50 to 3 fm for $Z = 1$ to 82 ($\mu$ 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 predominantly by Auger electron emission in the upper and X-radiation in the lower part of the cascade. Collisions 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 neighboring atoms, where the nuclear Coulomb field induces an $s$-state admixture in higher $\ell$ 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 $\epsilon$. Nuclear reactions reduce the life time $\Delta t$ of low-lying atomic states which manifests itself in an additional line broadening $\Gamma$ according to the uncertainty relation $\Gamma \Delta t = \hbar$.

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, $\epsilon_{ns}$ and $\Gamma_{ns}$ measure real and imaginary part of the effective complex hadron-nucleus scattering length $a_{nh}$ [10]

$$\frac{\Gamma_{ns}}{E_{nm} - 2 \epsilon_{ns}} = \frac{4}{n} \frac{E_{nm}}{\epsilon_{ns}} a_{nh}$$

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.
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 \( \pi N \) 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 \( \pi D \) and \( \pi H \) precision experiments \([7,8]\) constitutes an important success within the framework of \( \chi PT \) \([9]\).

**Pion production and absorption**

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

Exploiting time reversal invariance and charge symmetry, i.e., assuming for matrix elements \( |A_{\pi d \rightarrow nn}| = |A_{\pi d \rightarrow pp}| \), the broadening measures the s-wave pion production strength \( \alpha \) \([7]\):

\[
\Gamma_{1s}(\pi D) \propto |A_{\pi d \rightarrow nn}|^2 \propto \alpha^2.
\]

Given that exchange of virtual pions essentially contributes to nuclear binding, \( \alpha \) 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.
for the Lyman β transition \( \pi D(3p-1s) \), 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 \( \pi D(3p-1s) \) transition are diffracted in 1. order under the same Bragg angle as gallium \( K\alpha \) 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 \( \pi D \) 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 \( \gamma \)-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 \( \pi D(3p-1s) \) 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.

**About the Author**


**References**