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ANTIPROTONIC ATOMS

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ABSTRACT

The results of five LEAR experiments looking for $\bar{p}$ -atomic X-rays are reviewed. In the $\bar{p}p$ -system, for the first time, transitions to the ground state were observed, and its strong interaction shift and width could be derived. Experiments on heavier atoms produced very accurate data, from which a new best value for the magnetic moment of the antiproton was obtained. Also for the first time, a spin-dependence of the $\bar{p}$ -nucleus interaction was observed.

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Antiprotonic atoms are formed, when a slow antiproton kicks an electron off an atom and is subsequently bound by the Coulomb field of the nucleus. This process can happen on Hydrogen or on all heavier nuclei. The energy levels of an antiprotonic atom are characterized by the main quantum number n and the total angular momentum j . After its capture the antiproton finds itself mainly in states with high n, j -values and then cascades down to states with higher binding energies emitting Auger electrons (low energy cascade transitions) and X-rays. In addition to the electromagnetic force the antiproton feels the strong $\bar{p}$ -nucleon interaction, when its Bohr orbit approaches the nucleus. This strong force gives rise to shifts (ϵ) (compared to the pure QED-case) and natural widths (Γ) which can be measured in the last observable transition of the X-ray spectrum. Only in the case of Hydrogen (Deuterium) the $\bar{p}$ reaches eventually the $1s$ ground state ($2p-1s$ = last observable transition), in heavier atoms the $\bar{p}$ -nucleus annihilation is so strong, that the X-ray cascade ends at higher levels. In $\bar{p}^{16}\text{O}$, e.g., the $4f-3d$ transition is the last observable transition.

The availability of the high-quality low energy $\bar{p}$ -beams at Lear has stimulated a new round of measurements on antiprotonic X-rays the first results of which are reviewed in the following.

1. $\bar{p}$ -Hydrogen (Deuterium)

Measurements on these systems are difficult because of (i) the low energies of the X-rays ($3d-2p$: 1.7 keV; $2p-1s$ = 9 keV) and (ii) the low X-ray yields due to the Day-Snow-Sucher mechanism. It means that a $\bar{p}p(d)$ -system, while it is in energy levels with $n \approx 10-3$, penetrates the strong electric field of a neighbouring Hydrogen-atom, and thus a strong Stark-mixing happens.

This effect mixes atomic levels of the same n -, but different l -quantum numbers, giving rise to an s -or p -state admixture in all states leading to larger than normal annihilation rates from these levels. It is the strongest in liquid Hydrogen (Deuterium) and weakens in gas with decreasing pressure and is responsible for the fact, that the $2p-1s$ X-ray transition is only observable in gaseous Hydrogen.

Three experiments at Lear are looking for $\bar{p}p(d)$ -X-rays using different targets and detectors:

- PS 171 (Asterix collaboration)

Target: 1 atm gas (NTP); Detector: X-ray drift chamber with moderate energy resolution
Tag: Annihilation products and X-ray coincidences

- PS 174 (Birmingham, Rutherford, William and Mary, Nikhef-Collaboration)

Target: Gas (partly low temperature), corresponding to pressures of 10, 2, 0.25 atm
Detector: Si(Li) with NaI-Compton suppression

- PS 175 (Kernforschungszentrum and University, Karlsruhe)

Target: Gas with pressures as low as 60 mbar (Cyclotron-trap: Antiprotons spiralling in a 4.5 T superconducting magnetic field)
Detector: Si(Li) with guard-ring suppression

- X-ray yields (pressure dependence)

All three experiments have identified various members of the X-ray L-series and have determined the absolute yields which are pressure dependent. At NTP the total yield of the L-X-rays is 13% ¹⁾

while it increases to 40% at 60 mbar gas pressure ²⁾. The pressure dependence of the X-ray yields can be well reproduced by appropriate cascade calculations ³⁾, the parameters of which could be determined for the first time.

- Strong interaction effects (ϵ_{1s} , Γ_{1s} , Γ_{2p})

The components of the K-series X-rays have been seen in two experiments until now ^{1,4)}. The yield of the K_{α} -line at NTP, e.g., is down to 2.6% ¹⁾ because of the strong 2p-annihilation width Γ_{2p} which is about 40 meV ^{1,2)}. Recently, Asterix was able to produce pure K_{α} - and L_{α} -lines by requesting coincidences with the respective higher transitions ⁵⁾. The measured shifts (ϵ_{1s}) and widths (Γ_{1s}) range from -500 to -700 eV and 800-1000 eV, respectively. They are compatible with earlier theoretical predictions, but the measurements are not yet accurate enough to allow a selection between the different approaches. However, the large width Γ_{1s} seems to preclude the existence of narrow NN-states very near to the threshold.

2. Heavier $\bar{p}$ -atoms

The X-rays of $\bar{p}^4\text{He}$ -^{1,2,4)} and $\bar{p}^3\text{He}$ -²⁾ atoms have been measured using gaseous targets, while all heavier atom-data were taken on liquid or solid targets. These measurements were performed at Lear from two collaborations:

- PS 176 (Kernforschungszentrum and University, Karlsruhe; University of Basel; Institute for Nuclear Physics, Stockholm; CNR Strasbourg; University of Thessaloniki)
- PS 186 (Technical University, Munich, University of Mississippi)

In short running periods high statistics spectra with excellent peak/background ratios were collected. Up to eight detectors were run simultaneously measuring electromagnetic radiation in the range from 2 keV to 1 GeV and neutrons. The evaluation of the data is still in progress and only some aspects of the measurements are discussed here:

- Magnetic moment of the antiproton

From the fine-structure splitting of the 11-10 X-ray transition of $\bar{p}^{208}\text{Pb}$ a new best value for $\mu_{\bar{p}} = 2.8007(91) \cdot \mu_N$ ⁶⁾ was derived which is two times better than the present world average. Within the errors it is compatible with the CPT-prediction relating μ_p and $\mu_{\bar{p}}$.

- Strong interaction effects

Table I gives a survey on the strong interaction effects measured at Lear:

The widths and shifts of the lower level were derived from an accurate determination of the energies and the natural line widths of the last observable transitions, the width of the upper level using the intensity balance of the X-rays feeding and depopulating the level ¹⁰⁾. In the case of the Mo-isotopes, even a fourth quantity (width of the level below the last observable transition) was measured by taking advantage of a resonance effect between nuclear and atomic levels ^{9,11)}.

The data can be compared with theoretical predictions ¹²⁻¹⁸⁾. Parameterfree analysis using the pp- and pn-amplitudes at threshold,

Table I Strong interaction effects derived from measurements of PS 176/186 ^{7,8,9)}. Also included are the data from PS 171/174/175 ^{1,2,4)} on Hydrogen, Deuterium and Helium. Values with * are still preliminary.

	ϵ_{1s} [eV]	Γ_{1s} [eV]	Γ_{2p} [meV]	
^1H	-500 $\pm$ 300 (PS171) -730 $\pm$ 150 (PS174)	1000* (PS171) 850 $\pm$ 390 (PS174)	$\approx$ 40* (PS175)	
	ϵ_{2p} [eV]	Γ_{2p} [eV]	Γ_{3d} [meV]	
^3He	-17 $\pm$ 4 (PS175)*	25 $\pm$ 8 (PS175)*	2.13 $\pm$ 0.14 (PS175)*	
^4He	-16 $\pm$ 3 (PS175)* -7.4 $\pm$ 5.3 (PS174)	44 $\pm$ 8 (PS175)* 35 $\pm$ 15 (PS174)	2.38 $\pm$ 0.10 (PS175)* 2.4 $\pm$ 0.4 (PS174)	
^6Li	-212 $\pm$ 65 *	685 $\pm$ 160*	$\approx$ 150*	
^7Li	-271 $\pm$ 40 *	745 $\pm$ 120*		
	ϵ_{3d} [eV]	Γ_{3d} [eV]	Γ_{4f} [meV]	
^{14}N	-18 $\pm$ 6	189 $\pm$ 15	275 $\pm$ 25	
^{16}O	-112 $\pm$ 20	495 $\pm$ 45	602 $\pm$ 24)	
^{17}O	-140 $\pm$ 46	540 $\pm$ 150	731 $\pm$ 37)	
^{18}O	-195 $\pm$ 20	640 $\pm$ 40	795 $\pm$ 25)	
^{19}F	-450 $\pm$ 66	1397 $\pm$ 54	3245 $\pm$ 130	
^{23}Na	-2000 $\pm$ 200*	2500 $\pm$ 800	31020 $\pm$ 7020*	
	ϵ_{4f} [eV]	Γ_{4f} [eV]	Γ_{5g} [meV]	
^{40}Ca	-1067 $\pm$ 143*	3576 $\pm$ 403*	34900 $\pm$ 3800*	
	ϵ_{6h} [eV]	Γ_{6h} [eV]	Γ_{7i} [eV]	Γ_{5g} indir. det. via ⁹⁾ nucl.res. [eV]
^{92}Mo	-460 $\pm$ 80 (PS186)	1400 $\pm$ 300(PS186)	19.5 $\pm$ 1.2(PS186)	
^{94}Mo	-640 $\pm$ 220(PS186)	2300 $\pm$ 900(PS186)	68.9 $\pm$ 10.2(PS186)	42500 $\pm$ 9200
^{95}Mo	-740 $\pm$ 120(PS186)	1900 $\pm$ 400(PS186)	28.5 $\pm$ 2.6(PS186)	49900 $\pm$ 19800
^{98}Mo	-550 $\pm$ 160(PS186)	2300 $\pm$ 700(PS186)	47.9 $\pm$ 5.3(PS186)	45100 $\pm$ 10000
	ϵ_{7i} [eV]	Γ_{7i} [eV]	Γ_{8j} [eV]	
^{138}Ba	-350 $\pm$ 150*	1800 $\pm$ 450*		

the nucleon distributions in the nuclear tail and various medium corrections are already available for a few nuclei and reproduce the data within 30%, while phenomenological analysis with one or more adjustable parameters do a similar job, but for the whole range of nuclei measured.

Of particular importance for the determination of as yet still uncertain input parameters, like $f_{\bar{p}n}$ (threshold), ρ_n (nuclear tail), spin dependence of the $\bar{p}$ -nucleus interaction, are the precise measurements on isotopes (e.g. $^{16/17/18}\text{O}$) and the strong interaction effects individually determined for both components of a fine-structure splitted level (^{174}Yb).

- Isotope effects in $^{16/17/18}\text{O}$

Isotope effects have been measured on $^3/4\text{He}$, $^{16/17/18}\text{O}$ and $^{92/94/95/98}\text{Mo}$. They are particularly clear in the case of the Oxygen-isotopes, where the addition of two (one) neutrons gives rise to $8(4)\sigma$ -effects. A proper theoretical treatment of these effects is expected to give insight into the isospin-structure of the low energy $\bar{p}$ -nucleon amplitude.

- Spin-orbit $\bar{p}$ -nucleus interaction

In the case of the $9k-8j$ X-ray transition in ^{174}Yb an individual determination of the shifts and widths of each fine-structure component of the $8j$ -level could be performed for the first time. The shifts and widths are definitely dependent (3σ -effect) on $\vec{L} \cdot \vec{S}$ ($\epsilon_{\uparrow\uparrow} - \epsilon_{\uparrow\downarrow} = (68.0 \pm 25.0)\text{eV}$; $\Gamma_{\uparrow\uparrow} - \Gamma_{\uparrow\downarrow} = (195 \pm 58)\text{eV}$), so that a clear spin-dependence of the $\bar{p}$ -nuclear interaction shows up, which is surprising having in mind the weak spin-dependence of the elastic $\bar{N}N$ -scattering data. A theoretical treatment has to show, if both results are compatible or if the here observed strong spin-effect is due to the annihilation-part of the interaction.

3. Outlook to future measurements

The spectroscopy of $\bar{p}p(d)$ -systems would profit from higher $\bar{p}$ -fluxes, allowing the use of high resolution detectors, like crystal-spectrometers. With high $\bar{p}p$ -densities even the use of optical- or microwave methods could be considered. These detectors would allow the detection of strong interaction effects including FS- and HFS-interaction in levels above the $1s$ -groundstate, the determination of the polarizability of the antiproton and eventual medium range QCD-effects.

Similar statements hold for heavier atoms, where particularly coincidence measurements between atomic X-rays and particles (γ 's) emitted after the $\bar{p}$ -nucleus annihilation are attractive.

Needless to say that high intensity, low energy $\bar{K}$, $\bar{\Sigma}$, $\bar{\Xi}$ -beams from a Kaon-factory would make similar experiments feasible with particles containing strange quarks and thus give further information on the flavour-dependence of quark-interactions.

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