CERN-EP/82-82

24 June 1982

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Invited paper to the
Workshop on Physics at LEAR
With Low-Energy Cooled Antiprotons
9-16 May 1982, Erice, Sicily

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INTRODUCTION

The method of using exotic atoms to study atomic, nuclear, and elementary-particle physics has been a well-established technique for some decades. A multitude of information has been extracted from the X-ray spectra of muonic and hadronic atoms in the past. Detailed reviews of the experimental technique and the evaluation of the data are given elsewhere¹. A compilation of data from hadronic atoms can be found in an earlier paper of the author². In the following the basic properties of exotic atoms, in particular antiprotonic atoms, are recapitulated.

Exotic atoms are hydrogen-like atomic systems. Their level scheme is described in good approximation by the solution of the Dirac equation (Klein-Gordon equation, for mesons) for a point-like nucleus:

$$E_{n,j} = mc^2 \left\{ 1 + \left[\frac{Z\alpha}{n - (j + 1/2) + \sqrt{(j + 1/2)^2 - (Z\alpha)^2}} \right]^2 \right\}^{-1/2} - mc^2 . \quad (1a)$$

In this approximation the energy levels with $\ell = j \pm 1/2$ are degenerated. A more precise formula, which includes vacuum polarization and all relativistic effects of order $(Z\alpha)^4$ is^{3,4)}

$$E_{n,\ell,j} = \frac{mc^2}{2} \left(\frac{Z\alpha}{n} \right)^2 \left\{ 1 + \left(\frac{Z\alpha}{n} \right)^2 \left[\frac{m}{4m_{\bar{p}}} - \frac{3}{4} + \frac{n}{\ell + 1/2} (1 + a_{VP} + a_{\ell j}) \right] \right\}, \quad (1b)$$

which coincides with expansion of Eq. (1a) in $Z\alpha$ for $a_{VP} = 0$ and $a_{\ell j} = (\ell - j)/(\ell + 1/2)$ neglecting the recoil correction factor $m/4m_{\bar{p}}$.

The spin-orbit interaction leads to a splitting of the ℓ -sublevel into doublets. The Dirac equation does not account for the anomalous magnetic moment of the antiproton ($\bar{p}$). For the calculation of the energy splitting of the fine-structure level the full g -factor has to be used and recoil effects⁴ have to be considered. This yields then

$$\Delta E^{LS} = \left(g_0 + 2 \frac{m}{m_{\bar{p}}} g_1 \right) \frac{(Z\alpha)^4}{2n^3} \frac{mc^2}{\ell(\ell+1)}, \quad \ell \neq 0. \quad (2)$$

More detailed calculations, including those for vacuum polarization, are given elsewhere^{4,5}.

Compared to electronic atoms the hyperfine interaction in antiprotonic atoms is small owing to the small magnetic moment of the $\bar{p}$. The energy shift of the atomic levels due to magnetic hyperfine interaction is³, apart from small corrections⁴:

$$E^{HFS} = \frac{mc^2}{2} \alpha g_I \left(\frac{Z\alpha}{n} \right)^3 \frac{f(f+1) - i(i+1) - j(j+1)}{j(j+1)(2\ell+1)}. \quad (3)$$

This yields, for instance, for maximal ℓ and j a splitting between the outermost components of a multiplet:

$$\Delta E^{HFS} = 2mc^2 \alpha g_I \left(\frac{Z\alpha}{n} \right)^3 \begin{cases} \frac{i+1}{4n^2-1} & \text{for } j \leq i \\ \frac{i}{(2n-1)^2} & \text{for } j \geq i. \end{cases} \quad (4)$$

In hadronic atoms the strong interaction adds to the electromagnetic one. Owing to the short-range nature of the strong force, its contribution is only detectable in states where the overlap of the $\bar{p}$ wave function with the nucleus is significant, i.e. in all s -states and low-lying high angular momentum states. Here the strong interaction results in an energy shift of the states and attributes an additional width to the level due to the open $\bar{p}$ annihilation channel.

The standard procedure to calculate the atomic-level energies is to solve the Dirac equation for an extended nucleus with a Hamiltonian containing, apart from the electromagnetic potential and

higher order QED effects such as vacuum polarization, a complex potential for the strong interaction. The latter is only required for the calculation of the energies and the width of low-lying levels.

Antiprotonic atoms are formed when low energetic $\bar{p}$ (several eV to keV) are captured into atomic states. The capture takes place via the emission of an electron. The capture process is not understood in detail, since it involves many unknown parameters such as the $\bar{p}$ energy, its impact parameter, and the electron configuration during capture. Moreover, the physical and the chemical states of the target atom are of importance. However, in a naive picture it is assumed that the $\bar{p}$ is captured into an orbit whose radius is close to that of the electronic 1s state. This corresponds to an initial state with a main quantum number

$$n_{\bar{p}} = \sqrt{\frac{m_{\bar{p}}}{m_e}} n_e^{1s} = 43 . \quad (5)$$

The population of the angular momentum sublevels depends again on the physical and the chemical state of the target atom. However, in most cases a population P of the ℓ -levels according to $P = (2\ell+1)e^{\alpha\ell}$, where α varies between -0.4 and 0.02, can be assumed. From its initial capture into a Rydberg state the $\bar{p}$ cascades down to lower levels by emission of an electron (Auger effect) or by radiative transitions unless the energy can be dissipated by chemical processes. The transition probabilities are

$$W_x = \frac{4\alpha}{3\hbar} \frac{(\Delta E)^3}{(\hbar c)^2} |\langle \psi_f | r | \psi_i \rangle|^2 \quad \text{for radiative transitions} \quad (6)$$

and

$$W_{Au} = \frac{2\pi}{\hbar} |\langle \psi_f \phi_f | \frac{1}{r} | \psi_i \phi_i \rangle|^2 \quad \text{for Auger transitions} . \quad (7)$$

By evaluation of expressions (6) and (7) it becomes clear that the Auger effect dominates in the upper part of the cascade, while radiative transitions take over at low n . In the case where strong absorption is significant, its corresponding width Γ_{str} has to be added to the Auger and radiative widths ($\Gamma_x = \hbar W_x$, $\Gamma_{Au} = \hbar W_{Au}$) to give the total level width

$$\Gamma_{tot} = \Gamma_x + \Gamma_{Au} + \Gamma_{str} . \quad (8)$$

While Γ_x and Γ_{Au} can be calculated to the desired accuracy Γ_{str} or Γ_{tot} has to be determined experimentally. If $\Gamma_{str} \approx \Gamma_{tot}$ it can be measured directly from the line width Γ_ℓ of an X-ray transition to

this level. For $\Gamma_{\text{str}} < \Gamma_x + \Gamma_{\text{Aug}}$ it is derived from the yield Y of an X-ray transition depopulating the level under consideration:

$$Y = \frac{P_n \Gamma_x}{\Gamma_{\text{tot}}}, \quad (9)$$

where the population P_n of this level is found by measuring the intensities $I_{nn'}$ of all feeding X-ray transitions (and correcting for Auger transitions):

$$P_n = \sum_{n'} I_{nn'}. \quad (10)$$

Γ_{str} is then determined by inverting expression (9) and inserting Eq. (8):

$$\Gamma_{\text{str}} = \left(\frac{P_n}{Y} - 1 \right) \Gamma_x - \Gamma_{\text{Aug}}. \quad (11)$$

With these formulae the intensities of transitions can be calculated if the level population is known. In cascade calculations the initial population is determined from a fit to the experimental X-ray intensities. The relative intensities of the three radiative transitions between fine-structure doublets can, however, immediately be given:

$$I_a : I_b : I_c = 1 : (\ell + 2)(2\ell + 3) : \ell(2\ell + 3) \quad (n, \ell) \quad (12)$$

Owing to the triangular shape of the level scheme, the selection rules for the electromagnetic transitions, and the depletion of s-states by absorption, the de-excitation leads to an enhancement of the population of high angular momentum states. Mostly the observed X-ray lines are transitions between high angular momentum states.

On its way through the cascade the $\bar{p}$ finally reaches a state where strong interaction is so large that it is absorbed before it can undergo any further electromagnetic transition. This level, which is a circular orbit in general (i.e. $\ell = n - 1$), is called the last observable level and the feeding X-ray line is called the last observable transition. It appears that the $\bar{p}$ reaches the 1s state only in the case of antiprotonic hydrogen and deuterium. Already

there the 2p-1s transitions are strongly attenuated and about 90% of the $\bar{p}$ are absorbed out of the 2p levels⁶. In $\bar{p}$ -U, for instance, the last observable level has $n = 9$.

The average cascade time for antiprotonic atoms ranges in general from 10^{-9} to 10^{-12} s. However, in dilute gases of light elements, where only a few electrons are available and readily emitted in the initial de-excitation and level mixing is negligible, the cascade time can reach microseconds, because de-excitation can take place only via radiative transitions. This is amplified if the $\bar{p}$ has reached a high circular level from which only a slow transition can take place which changes the main quantum number by one unit.

The $\bar{p}$ absorption proceeds through $\bar{p}$ annihilation on a proton or neutron of the nucleus. It appears that the absorption takes place at the surface of the nucleus and that mostly only one nucleon of the nucleus is directly involved in the absorption process. Depending on the amount of the energy (liberated in the annihilation) which is carried away from the rest of the nucleus, an excited residual nucleus or nuclear fragments are left behind. It might also be possible that in some cases a large part of the annihilation energy will be transferred to the nucleus, creating extreme forms of nuclear or even quark matter⁷.

OBSERVABLES

The basic observables are the energies, line widths, and intensities, of radiative transitions from $\bar{p}$ atoms and of γ -transitions from nuclear fragments. In light atoms the time between capture and annihilation might be measurable directly. For thin targets it should be possible to measure the Auger-electrons, where lines can be attributed to $\bar{p}$ transitions in the upper part of the cascade and the continuous spectrum reflects the atomic capture. Also radiative transitions in the electron cloud taking place while the $\bar{p}$ is bound to the nucleus should be detectable. Spectroscopy of nucleons and light ions emitted after $\bar{p}$ absorption has hardly been investigated, but certainly deserves great attention. Annihilation-pion multiplicities and inclusive spectra of pions and kaons contain valuable information.

EXTRACTABLE INFORMATION

General Aspects

From the energies of $\bar{p}$ X-ray transitions between states, unperturbed by strong interaction, the mass of the $\bar{p}$ can be determined. The magnitude of the fine-structure splitting yields directly the magnetic moment of the $\bar{p}$. If the mass of the $\bar{p}$ is known, its

polarizability can be deduced from eventual shifts of the X-ray energies. Through high-precision energy measurements the validity of the Dirac theory and QED can be tested.

Atomic Physics and Chemical Effects

The measurement of the intensities of radiative transitions allows the reconstruction of the cascade process. Relative intensities for chemically compound targets yield relative capture probabilities and $\bar{p}$ transfer rates from one target atom to the other. The measurement of the cascade time and the Auger-electron spectrum enables a better determination of the initial capture process. This is particularly interesting for the $\bar{p}$ -He system where long atomic lifetimes (some microseconds) are predicted⁸ and where the $\bar{p}$ atomic capture might be considerably influenced by the existence of Coulomb resonances in the $\bar{p}$ eeHe system slightly above threshold⁹. Apart from general interest, a comprehensive understanding of $\bar{p}$ atomic capture and cascade allows deformation of the cascade in a particular way and enhancement of the population of a desired atomic level or the use of atomic spectra for material analysis.

Particle Physics

The energies, line widths, and intensities of X-ray transitions between states where strong interaction is significant can be directly related to the $\bar{p}$ N scattering amplitude or a $\bar{N}$ N potential. In the simplest case, i.e. $\bar{p}$ -H the energy shift ϵ due to the strong $\bar{p}$ p interaction and the level width Γ of the 1s state are directly related to the $\bar{p}$ p s-wave scattering length $a_{\bar{p}p}$

$$\epsilon_{1s} + i \frac{\Gamma_{1s}}{2} = \frac{4}{a_B} a_{\bar{p}p} . \quad (13)$$

In a more adequate way the strong interaction is described by a complex $\bar{p}$ -nucleus optical potential V_{SI} inserted together with the full electromagnetic potential into the Schrödinger or Dirac equation. The solution of this equation yields the energies and widths of the atomic levels. In the zeroth approximation V_{SI} is obtained from the spin-averaged $\bar{p}$ p and $\bar{p}$ n scattering length ($A_{\bar{p}p}$, $A_{\bar{p}n}$) multiplied with the nucleon densities $\rho(r)$

$$V_{SI}(r) = - \frac{2\pi}{m} \left(1 + \frac{m_{\bar{p}}}{M_A} \right) \left\{ A_{\bar{p}p} \rho_p(r) + A_{\bar{p}n} \rho_n(r) \right\} . \quad (14)$$

A better approximation is to fold a $\bar{p}$ -nucleon potential v with the nucleon densities and thus allow for a finite range¹⁰:

$$V_{SI}(r) = \int \rho_p(r) v_{\bar{p}p}(\vec{r}-\vec{r}') d\vec{r}' + \int \rho_n(r) v_{\bar{p}n}(\vec{r}-\vec{r}') d\vec{r}' . \quad (15)$$

The $\bar{p}N$ potential v is usually taken from boson exchange models¹¹. It may be replaced by an $\bar{N}N$ t-matrix at threshold or even extrapolated to negative energies to account for the binding energy of the antiproton and the Fermi momentum of the nucleons^{12,13}).

The validity of this ansatz can be tested through the measurement of the widths and energies of the last observable levels in antiprotonic atoms of well-known nuclei. Since the $\bar{p}$ bound in an atom is in a well-defined state, particularly the magnitude and the range of the annihilation potential can be determined. By measuring strong-interaction effects in separated fine-structure levels the non-local part of the potential can be checked¹⁴ and the potential dependence on quantum numbers can be investigated. A comparison of the strong-interaction effects in isotopes of the same element enables $\bar{p}p$ to be disentangled from $\bar{p}n$ interaction.

A specific technique has been developed¹⁵ for pionic and kaonic atoms to use the energy degeneracy of a strongly suppressed atomic E2 transition with a nuclear transition from the ground state to excite the nucleus. This resonance leads to the attenuation of the allowed X-ray transition. By comparison with adjacent isotopes, where this resonance is weaker or does not show up, the $\bar{p}N$ interaction can be studied in a non-circular level. Applying coincidence techniques it should also be possible, to study $\bar{p}$ annihilation, where the nucleus is in the excited state.

Nuclear Physics: the $\bar{p}$ as a Probe

As has been seen from Eqs. (3) and (4), nuclear moments might be determinable if the X-ray transitions can be measured with very high energy resolution and accuracy. This is also true for the determination of the nuclear polarizability.

A satisfactory knowledge of the effective $\bar{p}N$ potential allows the determination of the proton and neutron distributions in nuclear matter. Owing to strong interaction, the $\bar{p}$ wave function rapidly decreases towards the centre of the nucleus and significant contributions come only from the surface of the nucleus and the tail of the nuclear-matter distribution. Hence the $\bar{p}$ is a very sensitive probe to explore the nuclear surface.

Antiproton absorption is expected to take place predominantly on a single nucleon at the nuclear surface. It thus may occasion-

ally restore a nucleus which has been reduced by one nucleon. The recoil spectrum of such a residual nucleus analyses the Fermi momentum of the nucleon involved in the absorption, which can be a proton or a neutron. The recoil spectrum can be evaluated by direct observation of the residual nucleus or from the Doppler broadening of nuclear gamma lines in the residual nucleus. The annihilation puts a source of many energetic pions on the nuclear surface. Their interaction with the residual nucleus could excite it to very high states or lead to fragmentation or disintegration, which provides a tool to study nuclear-cascade processes, nucleon configurations, and nuclear and possibly quark matter in extreme states.

There are no strong reasons for the existence of $\bar{p}$ hypernuclei, but also the existence of Σ hypernuclei was rather unexpected and their lifetime was surprisingly high. *A priori* an exotic $\bar{p}$ nucleus cannot be excluded. Owing to the speculations about the existence of $\bar{p}N$ bound states this aspect deserves great attention. Indications of such states could be seen in the recoil spectrum of the residual nucleus.

EXISTING DATA

Owing to the low intensity and bad quality of existing secondary $\bar{p}$ beams, the available data are scarce. They are shown in Table 1 (taken from Refs. 2, 16 and 17). Although the data are meagre a good amount of information could be extracted. From the energies of X-ray transitions between Rydberg states the mass of the $\bar{p}$ was determined¹⁸⁻²⁰ to be

$$m_{\bar{p}} = 938.215 \pm 0.036 \text{ MeV} \quad (\text{weighted mean})$$

and from the splitting of fine-structure levels the magnetic moment of the $\bar{p}$ was measured to be^{18,19}

$$\mu_{\bar{p}} = (-2.795 \pm 0.019)\mu_n \quad (\text{weighted mean}) .$$

The strong interaction widths of atomic levels are in addition plotted in Fig. 1. The shifts and widths were analysed in the framework of an optical potential model with ansatz (14). Under the assumption of equal neutron and proton distributions this ansatz was used to fit data of the spherical nuclei ${}^6\text{Li}$, ${}^{14}\text{N}$, ${}^{16}\text{O}$, ${}^{32}\text{S}$, and the average effective scattering length $A = \frac{1}{2} (A_{\bar{p}p} + A_{\bar{p}n})$ was determined to be¹⁶

$$A = \left\{ (1.1 \pm 0.3) + i(1.8 \pm 0.3) \right\} \text{ fm} . \quad (16)$$

Other authors^{16,20-22} have analysed the strong interaction effects with different sets of data. They are shown in Table 2. The real

Table 1. Measured X-ray energies, intensities, and level widths of antiprotonic atoms (averaged values)

Target	n_i	n_f	Energy [keV]	ϵ_{nf} [keV]	Γ_{nf} [keV]	I_{rel}	γ [%]	Γ_{ni} [eV]
^1H	4	2	2.343			29.0	0.017 ^{a)}	
	5	2	2.7			36.0	0.021 ^{a)}	
	3	2	1.736			35.0	0.02 ^{a)}	
	2	1					< 0.006 ^{a)}	
^2D	2	1					< 0.009 ^{a)}	
^4He	4	3	3.945 $\pm$ 0.055			100.0 $\pm$ 11.0		
	5	3	5.676 $\pm$ 0.028			44.0 $\pm$ 5.0		
	6	3	6.663 $\pm$ 0.035			17.2 $\pm$ 3.5		
	7	3	7.295 $\pm$ 0.045			9.7 $\pm$ 3.1		
	8	3	7.769 $\pm$ 0.075			7.3 $\pm$ 3.0		
	3	2	11.071 $\pm$ 0.008	-0.050 $\pm$ 0.018	0.105 $\pm$ 0.065	135.0 $\pm$ 24.0	77.0 $\pm$ 22.0	0.0028 $\pm$ 0.0010
	4	2	14.956 $\pm$ 0.026			26.0 $\pm$ 6.1		
	5	2	16.723 $\pm$ 0.037			17.7 $\pm$ 4.9		
	6	2	17.772 $\pm$ 0.033			22.6 $\pm$ 5.7		
^6Li	5	4	4.37 $\pm$ 0.04			40.5 $\pm$ 6.5		
	6	4	6.72 $\pm$ 0.03			11.0 $\pm$ 1.0		
	7	4	8.14 $\pm$ 0.03			5.5 $\pm$ 0.7		
	8	4	9.14 $\pm$ 0.09					
	4	3	9.401 $\pm$ 0.011			100.0		
	5	3	13.694 $\pm$ 0.012			23.4 $\pm$ 1.4		
	6	3	16.117 $\pm$ 0.056			7.8 $\pm$ 0.7		
	7	3	17.550 $\pm$ 0.080			2.6 $\pm$ 0.5		
	3	2	26.802 $\pm$ 0.066	-0.205 $\pm$ 0.066	0.41 $\pm$ 0.17	7.1 $\pm$ 2.5	3.9 $\pm$ 1.3	0.21 $\pm$ 0.45
^7Li	5	4	4.44 $\pm$ 0.02			41.6 $\pm$ 6.6		
	6	4	6.84 $\pm$ 0.03			10.5 $\pm$ 0.9		
	7	4	8.36 $\pm$ 0.09			6.9 $\pm$ 0.8		
	4	3	9.576 $\pm$ 0.008			100.0		
	5	3	13.988 $\pm$ 0.024			24.4 $\pm$ 1.4		
	6	3	16.436 $\pm$ 0.024			8.3 $\pm$ 0.7		
	7	3	17.890 $\pm$ 0.070			3.4 $\pm$ 0.4		
	3	2	27.134 $\pm$ 0.048	-0.312 $\pm$ 0.048	0.277 $\pm$ 0.113	4.5 $\pm$ 1.3	3.0 $\pm$ 0.7	0.24 $\pm$ 0.06
C	5	4	18.745 $\pm$ 0.012					
	6	4	28.893 $\pm$ 0.018					
	7	4	35.072 $\pm$ 0.034					
	4	3	40.539 $\pm$ 0.010	-0.004 $\pm$ 0.010	0.042 $\pm$ 0.018		51.6 $\pm$ 8.8	0.036 $\pm$ 0.015 - 0.011
N	4	3	55.806 $\pm$ 0.036	-0.018 $\pm$ 0.036	0.179 $\pm$ 0.031		54.0 $\pm$ 6.0	0.13 $\pm$ 0.03
^{16}O	7	5	29.53 $\pm$ 0.04			15.0 $\pm$ 2.4		
	8	5	36.76 $\pm$ 0.04			9.0 $\pm$ 1.4		
	9	5	41.62 $\pm$ 0.06			4.5 $\pm$ 1.0		
	10	5	45.222			3.0 $\pm$ 0.8		
	11	5	47.834			3.0 $\pm$ 1.0		
	12	5	49.823			4.3 $\pm$ 1.3		
	5	4	33.975 $\pm$ 0.020			100.0 $\pm$ 3.4		
	6	4	52.41 $\pm$ 0.025			20.1 $\pm$ 2.5		
	7	4	63.54 $\pm$ 0.03			11.2 $\pm$ 1.0		
	8	4	70.73 $\pm$ 0.035			5.9 $\pm$ 0.7		
	9	4	75.67 $\pm$ 0.04			3.3 $\pm$ 0.6		
	10	4	79.215			1.4 $\pm$ 0.6		
	11	4	81.828			0.4 $\pm$ 0.4		
	12	4	83.82			0.7 $\pm$ 0.6		
	4	3	73.438 $\pm$ 0.036	-0.124 $\pm$ 0.036	0.48 $\pm$ 0.11	19.2 $\pm$ 2.1	15.1 $\pm$ 2.3	0.64 $\pm$ 0.11
^{18}O	7	5	29.76 $\pm$ 0.04			18.1 $\pm$ 2.5		
	8	5	37.00 $\pm$ 0.04			10.6 $\pm$ 1.7		
	9	5	41.93 $\pm$ 0.04			2.9 $\pm$ 0.8		
	10	5	45.522			5.7 $\pm$ 2.0		
	11	5	48.152			3.5 $\pm$ 1.0		
	12	5	50.153			4.2 $\pm$ 1.3		
	5	4	34.200 $\pm$ 0.020			100.0 $\pm$ 3.2		
	6	4	52.745 $\pm$ 0.025			20.2 $\pm$ 1.8		
	7	4	63.946 $\pm$ 0.030			9.4 $\pm$ 0.9		
	8	4	71.205 $\pm$ 0.035			5.4 $\pm$ 0.6		
	9	4	76.180 $\pm$ 0.045			3.4 $\pm$ 0.6		
	10	4	79.741			1.3 $\pm$ 0.6		
	11	4	82.372			0.7 $\pm$ 0.6		
	12	4	84.377			0.8 $\pm$ 0.6		
	4	3	73.861 $\pm$ 0.042	-0.189 $\pm$ 0.042	0.550 $\pm$ 0.240	14.2 $\pm$ 2.6	11.7 $\pm$ 1.8	0.80 $\pm$ 0.12
Si	5	4	107.005 $\pm$ 0.039	-0.038 $\pm$ 0.039	0.11 $\pm$ 0.19			
	6	5	58.08 $\pm$ 0.11					

a) $I/\bar{p}_{stop}$

Table 1 (contd.)

Target	n_i	n_f	Energy [keV]	ϵ_{nf} [keV]	Γ_{nf} [keV]	I_{rel}	γ [%]	Γ_{ni} [eV]
P	6	5	66.953 $\pm$ 0.060	-0.065 $\pm$ 0.023	0.446 $\pm$ 0.069		25.8 $\pm$ 2.1	1.48 $\pm$ 0.18 - 0.16
	7	5	107.091 $\pm$ 0.049					
	8	5	133.20 $\pm$ 0.10					
	5	4	123.253 $\pm$ 0.022					
	6	4	189.85 $\pm$ 0.32					
S	5	4	140.440 $\pm$ 0.040	-0.06 $\pm$ 0.04	0.650 $\pm$ 0.100		19.0 $\pm$ 3.0	3.04 $\pm$ 0.70
Cl	5	4	158.95 $\pm$ 0.27				10.0 $\pm$ 2.0	8.0 $\pm$ 2.2
K	5	4	198.78 $\pm$ 0.65				5.0 $\pm$ 1.0	26.8 $\pm$ 7.0
Ti	8	7	56.890 $\pm$ 0.025			86.0 $\pm$ 15.0		
	9	7	95.78 $\pm$ 0.05			17.3 $\pm$ 2.1		
	9	8	38.99 $\pm$ 0.03			108.0 $\pm$ 5.0		
	10	8	66.77 $\pm$ 0.045			13.0 $\pm$ 1.5		
	7	6	87.66 $\pm$ 0.025			100.0 $\pm$ 4.0		
	6	5	145.28 $\pm$ 0.09			65.0 $\pm$ 4.0		
Fe	10	8	93.74 $\pm$ 0.10	-0.010 $\pm$ 0.310	0.54 $\pm$ 0.32		32.0 $\pm$ 13.0	4.0 $\pm$ 3.9 - 1.7
	8	7	79.827 $\pm$ 0.064					
	9	7	134.19 $\pm$ 0.17					
	7	6	123.21 $\pm$ 0.18					
	8	6	202.78 $\pm$ 0.17					
	6	5	204.28 $\pm$ 0.31					
Y	12	10	115.21 $\pm$ 0.14	-0.15 $\pm$ 0.16	0.80 $\pm$ 0.32		37.5 $\pm$ 5.7	6.8 $\pm$ 1.9 - 1.4
	10	9	88.584 $\pm$ 0.024					
	11	9	154.022 $\pm$ 0.046					
	9	8	123.927 $\pm$ 0.016					
	10	8	212.36 $\pm$ 0.15					
	8	7	180.942 $\pm$ 0.019					
	7	6	279.03 $\pm$ 0.16					
Zr	12	10	121.43 $\pm$ 0.15	-0.45 $\pm$ 0.10	0.70 $\pm$ 0.21		41.8 $\pm$ 5.7	6.4 $\pm$ 1.7 - 1.3
	10	9	93.181 $\pm$ 0.054					
	11	9	162.075 $\pm$ 0.064					
	9	8	130.412 $\pm$ 0.018					
	10	8	223.461 $\pm$ 0.073					
	8	7	190.422 $\pm$ 0.019					
	7	6	293.360 $\pm$ 0.010					
Sn	8	7	298.59 $\pm$ 0.27				65.0 $\pm$ 11.0	3.1 $\pm$ 1.8
I	8	7	336.13 $\pm$ 0.62				42.0 $\pm$ 13.0	9.9 $\pm$ 7.7
Cs	10	9	177.12 $\pm$ 0.19				< 25.0	< 0.25
	9	8	247.86 $\pm$ 0.19					
	8	7						
Pr	8	7	415.61 $\pm$ 1.50				31.0 $\pm$ 19.0	24.7 $\pm$ 56.9
¹⁷⁴ Yb	11	10	212.607 $\pm$ 0.074	0.26 $\pm$ 0.46	1.48 $\pm$ 0.66		29.5 $\pm$ 8.3	27.0 $\pm$ 18.0 - 9.0
	10	9	287.953 $\pm$ 0.088					
	9	8	403.76 $\pm$ 0.45					
Tl	15	14	107.73 $\pm$ 0.20					
	15	13	241.71 $\pm$ 0.33					
	14	13	133.56 $\pm$ 0.12					
	14	12	301.03 $\pm$ 0.56					
	13	12	168.56 $\pm$ 0.10					
	13	11	385.36 $\pm$ 0.17					
	12	11	216.94 $\pm$ 0.09					
	11	10	285.42 $\pm$ 0.10					
	10	9	386.05 $\pm$ 0.17					
Pb	11	10	291.875 $\pm$ 0.020					
	12	11	221.878 $\pm$ 0.016					
	13	12	172.605 $\pm$ 0.015					
	14	13	136.871 $\pm$ 0.020					
	15	14	110.358 $\pm$ 0.021					
	16	15	90.913 $\pm$ 0.041					
²³⁸ U	15	14	139.070 $\pm$ 0.016					
	14	13	172.495 $\pm$ 0.013					
	13	12	217.511 $\pm$ 0.013					
	12	11	279.735 $\pm$ 0.018					
	11	10	368.446 $\pm$ 0.027

Fig. 1 Measured strong-interaction level widths in antiprotonic atoms (the dashed lines are to guide the eyes).

Table 2. Fitted optical potential parameter A in fm

Re A	Im A	Ref.
1.1 ± 0.3	1.8 ± 0.3	16
0.85 ± 0.38	2.66 ± 0.28	20
2.0 ± 0.5	2.0 ± 0.5	21
1.53 ± 0.27	2.50 ± 0.25	22

part of this quantity is in all cases inconsistent with one-boson-exchange potential-model predictions for the elementary s-wave scattering length (negative sign) and the variation of the results are large (Table 2). This is not surprising since assumption (14) is very crude and is only justified in order to reduce the number of free parameters.

From the comparison of strong interaction effects in the isotopes of oxygen ($^{16}\text{O}/^{18}\text{O}$) the effective $\bar{p}n$ scattering length was determined²¹ using ansatz (14):

$$A_{\bar{p}n} = \left\{ (-0.3 \pm 1.4) + i \left(1.0 \pm 1.7 \right) \right\} \text{ fm} \quad (17)$$

and the ratio of its real to imaginary part was deduced independently as

$$\frac{\text{Re } A_{\bar{p}n}}{\text{Im } A_{\bar{p}n}} = -0.63 \pm 0.47 . \quad (18)$$

The strong interaction effects in antiprotonic atoms were furthermore analysed in the black-sphere model. This method, in which the nucleus is represented by a black sphere and strong interaction shift and width are calculated in WKB approximation, appears to be a very successful phenomenological description²³.

The $\bar{p}$ atomic cascade could in most cases be well reproduced under the assumption of a statistical population of the initial level ($n = 29$ for computational reasons). The He cascade was analysed with a more detailed model and well reproduced^{17,24}). However, also chemical effects were observed by comparing the X-ray spectra of ^{16}O for a water target with a CO_2 target²¹. In the latter case the cascade is shifted to higher ℓ -values and circular transitions are enhanced.

In Fig. 2 a typical X-ray spectrum is shown. These spectra of $\bar{p}$ - $^6\text{Li}/^7\text{Li}$ were obtained with 3×10^8 stopped $\bar{p}$ and targets of 0.5 g/cm^2 thickness¹⁶. The pure measuring time was 18 days: the in-beam time was however two months, required for special background studies and calibration checks. Figure 2c shows the difference spectrum between the two spectra. Owing to the slightly higher reduced mass, all $\bar{p}$ X-ray energies are shifted in ^7Li to higher values. Therefore in the difference spectrum the $\bar{p}$ -Li lines show up as dispersion curve patterns, whereas background lines from impurities cancel out. These spectra demonstrate the high sensitivity achievable for difference measurements in isotopes.

Owing to the relatively thick targets the low-energy X-ray transitions (below 10 keV) were considerably attenuated by absorption in the target itself. Large corrections had to be applied to determine their correct intensities. At LEAR these measurements could be repeated in less than one hour. Even for the same number of stopped $\bar{p}$ the achievable accuracy would be higher since the targets could be very small and at least a hundred times thinner, which would render corrections practically unnecessary and would suppress the background considerably.

In order to use very small target samples, as is necessary for the study of rare isotopes, the $\bar{p}$ extraction energy has to be as low as possible, since the range curve width is for momentum spreads lower than 10^{-3} essentially determined by the energy straggling of the $\bar{p}$ during moderation. The range straggling is about 2% of the $\bar{p}$ range.

Fig. 2 Antiproton X-ray spectra from lithium¹⁶. a) $\bar{p}$ -⁷Li. b) $\bar{p}$ -⁶Li. c) Difference spectra $\bar{p}$ -⁶Li - $\bar{p}$ -⁷Li.

GOALS OF THE EXPERIMENTS PS176 ²⁵ AND PS186 ²⁶

The information which is most urgently needed in order to establish an over-all description of the $\bar{p}N$ interaction in nuclear matter on the basis of a more microscopic model is a survey measurement of strong-interaction effects in various antiprotonic atoms and hence various atomic levels. To allow for a reliable analysis of the data such nuclei have been chosen where the strong-interaction effects are expected to be large and the nuclear-matter distributions are sufficiently well known.

Whenever possible high-purity monoisotopic targets have been selected. From these measurements the strong absorption level widths will be determined over a range of 4 orders of magnitude. An energy determination of the most intensive X-ray transitions to an accuracy of a few eV is aimed at. X-ray intensities will be determined to about 1%. This allows measurement of the strong interaction width down to values of a hundredth of the radiative transition width.

Simultaneously the $\bar{p}$ mass will be determined from the energies of the unperturbed transitions. We hope to achieve the same absolute accuracy as for the negative pion mass which is 10 ppm ²⁷. The magnetic moment of the $\bar{p}$ will be deduced from the fine-structure splitting in heavy atoms with an accuracy below 10^{-3} . The measurement of relative and absolute X-ray intensities in the survey study will allow us to establish a comprehensive model for the atomic cascade. Also, simultaneously, prompt and delayed nuclear γ -ray spectra of residual nuclei and nuclear fragments will be measured. From these spectra we want first to extract information about the amount of $\bar{p}$ absorption on single nucleons and the frequency of $\bar{p}p$ compared to $\bar{p}n$ annihilation. The shape of the nuclear γ -rays will be analysed to determine the recoil momentum distribution of the residual nucleus. In addition, experiment PS186 focuses on the observation of E2 resonances in selected isotopes and the determination of pion multiplicities.

A further aim of the experiment is the measurement of the strong-interaction effects in separated fine-structure levels and a study of particular terms of the strong force.

In the next step of the experiment selected nuclei will be studied and, in particular, strong-interaction effects in isotopes of the same element will be investigated. The previously developed technique will be applied to the measurement of relative effects with high accuracy. It is aimed at a separation of $\bar{p}p$ from $\bar{p}n$ interactions and the determination of neutron density distribution.

If intensities are high enough, coincidence spectra between atomic X-rays and between X-rays and nuclear γ -rays will be measured. In this way more detailed information about the strong-

interaction effects in specific levels and about the absorption process will be obtained. For instance, a coincidence of the last observable atomic X-ray transition with nuclear γ -spectra would allow the preparation of the $\bar{p}$ in a specific atomic level prior to absorption. The composition of nuclear fragments might completely differ from that where $\bar{p}$ annihilation out of a highly excited s-state is allowed.

EXPERIMENTAL TECHNIQUE

The experimental set-up is shown in Fig. 3. An incident $\bar{p}$ of 300 MeV/c or less will be identified in a beam telescope consisting of a few scintillation counters. In between the scintillators a variable moderator serves for the adjustment of the $\bar{p}$ range. Thin targets are mounted on a frame which is guided by a lead fixed in two tubes above and below the beam. With a remote controllable motor drive the various targets can be alternately exposed to the $\bar{p}$ beam. In the horizontal plane around the target in-beam position five semiconductor detectors are arranged. According to the X-ray energies they have to measure, these are Si(Li), planar Ge, and large-volume coaxial Ge(Li) detectors. The set-up will be complemented by a charged pion multiplicity counter for the experiment PS186. A trigger is given by the coincidence between a telescope signal and an event in one of the semiconductors. The energy and time signal of all fired X-ray detectors will be analysed with CAMAC ADCs and TDCs, which are read out by a fast microprocessor with the help of a newly developed interface²⁸. The event will be stored in a two-dimensional array for each detector in the large memory of the microprocessor, which serves essentially as a fast multichannel analyser with a big memory capacity. Additional information will be recorded simultaneously. Coincidence spectra will be treated and stored separately. After a given time (typically a stretcher cycle) the contents of the microprocessor memory will be read out by a PDP 11, written on tape, and preanalysed. This data acquisition technique will allow us the digestion of very high $\bar{p}$ rates ($\leq 10^5$) without dead-time losses. As instantaneous count rates for all detectors we expect a maximum of 10 kHz.

The arrangement of many targets on the same target holder, and alternative beam exposure, allows for a precise energy calibration using $\bar{p}$ X-rays between unperturbed levels. A standard X-ray source will also be mounted on the target holder for absolute energy calibration in beam.

OUTLOOK

What follows represents my personal point of view and does not necessarily coincide with the future programme of the Collaboration. Second-generation experiments at LEAR using the method of

Fig. 3 Experimental set-up of PS176 and PS186.
 S_1 , S_2 , S_3 scintillation counters.
 μ_1 , μ_2 variable moderators.

antiprotonic atoms will certainly be devoted to the study of effects where high-energy resolution is required and different experimental techniques are to be applied. There is a variety of experiments which can be anticipated.

One direction is the investigation of the $\bar{p}$ capture into atomic orbits, the cascade process, and the $\bar{p}$ interaction with the electron cloud. Very low energy (a few keV) antiprotons are required to determine the energy range in which the $\bar{p}$ is captured. Spectroscopy of Auger electrons, optical transitions, and electronic X-rays would provide valuable information about the Rydberg states. The feasibility of these measurements requires ultrathin targets and hence again very low energy antiprotons. It can be expected that, given all these possibilities, the antiprotonic cascade will become the best understood case amongst all exotic atoms.

High-precision experiments will be performed to deduce the mass and the magnetic moment of the $\bar{p}$ with ultimate accuracy and to determine the $\bar{p}$ polarizability and high-order QED effects. For this goal the use of a crystal spectrometer seems to be the most adequate technique.

Depending on the outcome of the first experiments, the study of the $\bar{p}N$ interaction in nuclei will focus on particular aspects such as the form of the real part of the potential, the magnitude and range of annihilation, and its quantum-number dependence. For this, more information about strong interaction effects in a specific nucleus is needed, e.g. energies and level widths of non-circular levels. A detailed study of the nuclear fragments will be necessary for the better understanding of the $\bar{p}$ absorption. The application of X- and γ -ray coincidence techniques and the detection of charged nuclear fragments and neutrons will be the key experiments. In this context the helium isotopes will play a particular role. Apart from the atomic cascade which is very interesting in itself^{8,9}, these atoms will allow the entire history of an antiprotonic atom to be followed, from formation to disintegration. The X-ray energies fall into a convenient energy range, the $\bar{p}$ reaches a low atomic level, and the nuclei are rather well understood. After absorption (mainly from the 2p-level) only a few nuclear fragments are left:

$\bar{p}-^3\text{He} \rightarrow$	d + mesons	from $\bar{p}p$ annihilation
	p + n + mesons	from $\bar{p}p$ annihilation
	n + p + mesons	from $\bar{p}n$ annihilation
$\bar{p}-^4\text{He} \rightarrow$	t + mesons	from $\bar{p}p$ annihilation
	d + n + mesons	from $\bar{p}p$ annihilation
	p + n + n + mesons	from $\bar{p}p$ annihilation
	p + p + n + mesons	from $\bar{p}n$ annihilation
	d + p + mesons	from $\bar{p}n$ annihilation
	^3He + mesons	from $\bar{p}n$ annihilation

of which a complete spectroscopy could be performed. Merely the determination of these branching ratios would provide important information. Measured in coincidence with atomic X-rays it would allow the study of $\bar{p}$ absorption from s-, p-, and d-levels separately.

A further topic of second-generation experiments with antiprotonic atoms will be the use of the $\bar{p}$ for nuclear-structure studies. Here the focus is on the determination of nuclear-matter density distributions, particularly neutron distributions, and of nuclear moments. Moreover it can be used to excite the nucleus to extreme states. To allow the investigation of rare isotopes, very low energy antiprotons and small beam sizes are needed to irradiate small samples. It should then be possible even to study radioactive isotopes and isomers.

MORE QUIXOTIC ATOMS

With the advances in accelerator techniques and particular schemes²⁹, it will be possible in a few years to produce and store antideuterons ($\bar{d}$) (possibly even heavier antinuclei) with reasonable intensity. Apart from other interests in $\bar{d}$, *antideuteronic atoms* could be formed. Owing to the unity spin of the $\bar{d}$, the level scheme is complex and neither the Klein-Gordon nor the Dirac equation gives an appropriate description of that system. The electric polarizability of the $\bar{d}$ could lead in the high field of the nucleus to a Coulomb dissociation³⁰. It is not yet clear how far the $\bar{d}$ remains intact in atomic states and to what extent it reaches low levels before it is broken up. The determination of the mass, magnetic moment, and electric quadrupole moment of the $\bar{d}$, and the study of $\bar{d}$ break-up would certainly be the first experiments to be done. Partial $\bar{d}$ annihilation of the antineutron with a proton or a neutron of the nucleus (the $\bar{p}$ remaining bound in an atomic state of a nucleus reduced by one nucleon) appears to be a possible $\bar{d}$ -absorption process. It is then likely that the residual antiprotonic atom is in a state where the nucleus is highly excited. This is a unique feature and here the excited nuclear states could be investigated with the $\bar{p}$.

The $\bar{p}$ annihilation and particular $\bar{p}$ reactions are the source of even more quixotic atoms. Most frequent annihilations are the two- and four-prong channels. In particular phase-space configurations it is possible that unlike charged meson pairs emerge as bound atomic systems. The formation of *pionium* ($\pi^+\pi^-$ atoms) is most likely. Its electromagnetic binding energy in the ground state is 1.86 keV. Hence the total mass of the object is 279.132 MeV. In low atomic states the $\pi\pi$ strong interaction is significant and leads to a decay of the atomic ground state in about 4×10^{-15} s³¹.

The dominant decay channel is

$$\text{pionium} \rightarrow \pi^0 \pi^0.$$

Other exotic atoms which are formed less abundantly are *pikanium* (πK atoms) and *kaonium* ($K^+ K^-$ atoms), which show up in the less frequent $\bar{p}$ annihilation into strange mesons. The ground-state binding energy of the strange πK atom (total mass 633.233 MeV) is 2.90 keV and its lifetime is estimated to be 1.2×10^{-15} s³². The only decay mode is

$$\text{pikanium} \rightarrow \pi^0 K^0 (\pi^0 \bar{K}^0) .$$

Kaonium is an even more sophisticated atom. It is the only purely mesonic atom which contains hidden strangeness. Its 1s binding energy is 6.58 keV and its total mass of 980.762 MeV coincides with the mass of the occasionally observed S^* meson ($I^G J^{PC} = 0^+ 0^{++}$), which has the same quantum numbers as the *kaonium* 1s-atomic state. Its lifetime has been estimated to be in the order of 10^{-17} s³². Since the $K^0 \bar{K}^0$ channel is closed, *kaonium* decays through strange quark annihilation:

$$\text{kaonium} \rightarrow \pi \pi .$$

Although the lifetime of the ground state of these atoms is very short, the cascade can prolong the total lifetime of the atom considerably, depending on the initial state of formation.

The measurement of the energy and width of the s and p-levels of these atoms would be of great importance since they can be directly related to the scattering length of the involved particles. Such measurements provide a unique way to determine this quantity.

GLOSSARY

m	: reduced mass of antiprotonic atom = $(m_p \cdot M_A)/(m_p + M_A)$
m_p	: mass of antiproton
M_A	: mass of nucleus
c	: speed of light
Z	: nuclear charge
n	: main quantum number
ℓ	: angular momentum quantum number
j	: total angular momentum quantum number
α	: fine-structure constant
g_0	: Dirac g-factor = -1 (for the antiproton)
g_1	: anomalous g-factor of the antiproton
μ_N	: nuclear magnetic moment
μ_p	: $(g_0 + g_1) \mu_N$ = magnetic moment of the antiproton
i_p	: nuclear spin quantum number
f	: quantum number of coupled atomic and nuclear angular moment
$\psi_{i,f}$	: initial- and final-state wave function of antiproton, respectively
$\phi_{i,f}$	: initial- and final-state wave function of electron, respectively
ΔE	: transition energy
ϵ	: $E_{em} - E_{exp}$
E_{em}	: pure electromagnetic binding energy of an atomic level
E_{exp}	: measured binding energy of an atomic level
a_B	: Bohr radius
a_{vp}	: vacuum polarization coefficient
$a_{\ell j}$	: relativistic spin-dependent coefficient

See Ref. 4b.

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