Recent Results on Antiprotonic Atoms using a Cyclotron Trap at LEAR

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Abstract
A new technique to stop negatively charged particles inside a cyclotron field is motivated and presented. Its ability to produce a sufficient number of antiprotonic atoms is demonstrated with experimental results at target gas pressures previously not attainable. Thus the knowledge of the cascade processes in antiprotonic hydrogen could be extended considerably and the strong interaction parameters in this system could be measured with good precision. It could also be shown that antiprotonic noble gas atoms up to Krypton are ionized completely. Moreover, the possibility to extract slow antiprotons out of the center of the cyclotron trap is discussed shortly.

1. Introduction
Exotic atoms are systems in which a negatively charged particle with a mass heavier than an electron is implanted in the Coulomb field of a nucleus. In the past these atoms served to determine particle parameters such as the mass or magnetic moment of the implanted particles. Also a rich amount of data on nuclear charge distributions could be accumulated, especially with muonic atoms. Moreover, the strong interaction of hadronic particles (π−, K−, p, Σ−) with the nucleus could be determined with high precision via the shift and broadening of the atomic states [1].

Future experiments with exotic atoms are hindered by the following problems:
Sometimes the amount of target material which is available to stop the particles is limited. This is the case for instance in measurements with separated isotopes. Another example is the observation of low energy X-rays, which requires thin targets.
Density effects can influence the observability of X-ray transitions. One well-known example is the pressure dependence of the lifetime of the 2s-state in muonic hydrogen or helium, which is shortened by orders of magnitude going from vacuum to STP conditions [2, 3]. The experimental method described later was motivated by the difficulty of observing the K−-transition in antiprotonic hydrogen. Such a measurement offers the only possibility to determine the strong interaction of the antiproton with a proton at threshold.
The electromagnetic binding energy of the ground state in the pp-system is 12.533 keV. The complex energy values for the hyperfine levels of the ground state with shifts and widths of the order of a keV could be conveniently measured provided the K− transition could be observed with good intensity. Other K transitions are not of much use because the np level energies for n ≥ 3 differ from each other by energies smaller than the expected strong interaction width of the ground state.

A further quantity to be measured would be the strong interaction width of the 2p-state which can be obtained from an intensity balance of the L-transition feeding this level and the K−-transition leaving it. Earlier approaches to detect the K−-transitions in liquid hydrogen were not successful [4, 5, 6]. The reason for this is the Duy-Snow-Sucher effect [7]. The neutral pp-system travels through the liquid hydrogen with an assumed velocity of about 106 cm/s and will experience the strong Coulomb field inside the hydrogen molecules. This causes Stark mixing at a rate much faster than the competing deexcitation mechanisms (external Auger effect, Coulomb deexcitation, chemical deexcitation, radiative transitions) [8, 9].
The Stark effect mixing adds s-wave character even to levels with high l and destroys the antiprotonic hydrogen atom before it reaches levels where radiative transitions can be observed. With the advent of the LEAR-ring at CERN a source of low energy antiprotons with high intensity became available. This made it possible to form antiprotonic hydrogen atoms in hydrogen gas at pressures of about 1000 mbar within reasonable stop volumes. From more refined calculations it follows, however, that a saturation of the Balmer- and Lyman-transition intensities is to be expected at pressures below 10 mbar. Even at the low momentum of 105 MeV/c for the p beam now routinely available at LEAR the stop volume would be several m3. This prohibits the use of high resolution detectors necessary to measure the strong interaction parameters with high precision.

2. The cyclotron trap
A way to decrease the stop volume is to wind up the range path of the stopping particles in a gas inside a weak focusing field typical for cyclotrons [10]. The particles of the beam are injected at a radius r near the maximum radius allowed for stable particle orbits. Here their momentum is decreased from the beam momentum down to the momentum of the equilibrium orbit with a moderator. The energy loss due to the deceleration in the target gas together with the focusing properties of the cyclotron field then yields a concentrated stop distribution. A first insight into the physical principles governing the motion of decelerating particles in a cyclotron field is provided by the quasipotential picture. For a rotationally symmetric magnetic field (no electric field, no energy loss) the motion of particles is determined by a quasipotential U(r, z). r, z are cylindrical coordinates. U(r, z) is given by

\[ U = \frac{1}{2m} \left( \frac{p}{c} \right)^2 - \frac{1}{c} \int_{0}^{r} \frac{B_i(r', z) \, dr'}{r'} \right)^2 \tag{1} \]

P is a constant of motion, the generalized momentum, which depends on initial conditions. The equations of motion are
Fig. 1. Quasipotential in radial direction in the median plane for different positive generalized angular momenta.

given by

\[ m^2 = -\frac{dU(r, z)}{dr} \]

\[ m^2 = -\frac{dU(r, z)}{dx}. \]  

(2)

With the help of extremum principles and expanding \( B_z \) to first order in the Taylor series, the conditions for focusing in both axial and radial direction require

\[ 0 < n < 1 \]  

(3)

where \( n = -\frac{dB}{dr} \cdot r/B \) is the field index.

For the field of the real cyclotron trap [11] the quasipotential curves in the radial direction in the median plane are shown in Fig. 1 for decreasing generalized momenta. They correspond to decreasing energy of the particles in the field. Below a certain generalized momentum a potential minimum develops for which particles can be trapped. This corresponds to particle momenta of \( p < 123 \text{ MeV/c} [p_z = 0, r < 0.143 \text{ m}] \).

Particles loosing energy at a rate slow compared to the cyclotron frequency will follow the development of the quasipotential. The wall becomes deeper and narrower with decreasing energy and the particles will be guided to the center. When the particles lose energy too rapidly a concentrated stop distribution will not result. In the worst case, eccentric orbits are excited which do not include the geometrical center of the magnetic field. These orbits are characterized by negative angular momenta (Fig. 2). In Fig. 3 quasipotentials are shown in the axial direction for different equilibrium orbits. Potential minima exist which, contrary to the radial case, become shallower with decreasing equilibrium radius. Nevertheless, a loss of particles is avoided because the axial momenta will also decrease correspondingly due to the overall momentum loss. As long as the initial amplitudes of oscillation in the \( z \)-direction are kept below a particular limit, particles cannot leave the potential.

Compared to the quasipotential method, the extended Liouville theorem [12] provides a more quantitative description of the development of radial and axial amplitudes of betatron oscillation. It is used to trace the momentum spread \( \Delta p \) of decelerating particles, which in turn determines the development of the radial spread \( \Delta r \),

\[ \Delta r = r \cdot \frac{1}{1 - n} \cdot \frac{\Delta p}{p} \]  

(4)

The increase in \( \Delta r \) for decelerating particles is counteracted for sufficiently slow deceleration by the shrinkage of the amplitudes for betatron oscillations. In this case the conservation of the action integral leads to changes in amplitudes \( A_r, A_z \) for radial and axial betatron oscillations:

\[ A_r \propto \frac{1}{\sqrt{B_z \sqrt{1 - n}}} \]  

(5)

\[ A_z \propto \frac{1}{\sqrt{B_z \sqrt{n}}} \]  

(6)

The principal result of this application of the Liouville theorem is that the radial spread of the beam at the beginning of the deceleration process gives the radial extension of the stop distribution. The axial extension of the stop distribution, however, is almost a factor of two greater than the initial axial width of the beam.

The technical realisation of this deceleration scheme was done with a superconducting split coil magnet which provides the cyclotron field but also allows good access to the stop region through axial warm bore holes. This magnet accepts particles with a momentum up to 123 MeV/c inside a field.
diameter of 290 mm. The radius of injection is about 120 mm. A target chamber is mounted in the free gap and the bore holes of the cryostat (Fig. 4). The 202 MeV/c antiprotons from the beam pipe enter the target chamber through a 50-μm thick Mylar window and are moderated down to about 105 MeV/c in a scintillation-moderator arrangement. An additional deceleration in a 10-μm thick polyethylene foil placed almost opposite to the main moderator prevents the anti-protons from hitting the moderator again. The X-ray detectors are axially mounted in the bore holes, and are directly flanged to the gas volume. In addition there are 24 scintillation counters placed radially between the target chamber and the cryostat walls. They cover 30% of 4π solid angle and serve to detect annihilation products. This proved to be useful in optimizing the moderator thickness and to determine the stop efficiency (Fig. 5). At a pressure of 36 mbar He, 30% of the incoming antiprotons could be stopped in the He gas.

3. Results

3.1. Antiprotonic hydrogen X-rays

The X-rays have been measured with Si(Li) and Ge solid state detectors. The efficiency and resolution of the detectors for energies above 5 keV could be determined with radioactive sources. In the region below 5 keV a novel method was

Fig. 6. Antiprotonic nitrogen spectrum measured at 21 mbar.

Fig. 5. Stop efficiency for 202 MeV/c antiprotons versus $p_{H_2}$ (mean $H_2$ equivalent pressure).

Fig. 7. Spectrum of L X-rays in antiprotonic hydrogen at three different pressures.
applied to obtain the response function of the detectors. In antiprotonic \( N_2 \), for example the X-ray intensities for transitions \( n \to n - 1 \) between high principal quantum numbers are constant on the percent level, because the cascade process is radiative and goes mainly through circular levels with \( n, l = n - 1 \to n - 1, l = n - 2 \). The response function of the detectors can therefore be taken directly from the measured \( p\bar{p}N \) spectra. An example of such a spectrum is shown in Fig. 6. The slope of the efficiency curve is taken from the measured X-ray intensities calibrated to the absolute efficiency measured at 6.4 and 14.4 keV with a \( ^{57}Co \) source. Thus absolute yields for the measured \( L \) X-rays (Fig. 7) could be determined both for \( p\bar{p}H \) and \( p\bar{p}D \) (Fig. 8).

For antiprotonic hydrogen the measured yields are well reproduced by the cascade code of Leon and Borie assuming a kinetic energy of the \( pp \)-system \( T = 1 \) eV, and the Stark mixing parameter, \( k = 2 \). A consistent picture of the cascade process could be obtained over a pressure range of 2 orders of magnitude.

The intensities of the \( p\bar{p}D L \) X-rays compared to \( p\bar{p}H L \) X-rays are lower by 30\%. This can only be explained assuming that the strong interaction broadening of the 3d-level is bigger by a factor of 5 than anticipated theoretically [13].

The measured yields of the \( L \) X-rays indicate that a measurement of the \( 2p-1s \) transition should be performed at pressures below 10 mbar: here the \( 2p \)-population is almost maximum. The measurement of the \( K \) X-rays was performed at a pressure of 30 mbar because the minimum beam momentum which could be obtained was 202 MeV/c. The X-ray spectrum was measured with a 300 mm\(^2\) Si(Li)-detector covering 10\(^{-3}\) of a 4\( \pi \) solid angle. In the spectrum obtained (Fig. 9) from 2.8 \( \times \) 10\(^7\) incoming antiprotons, the two narrow peaks stem from the \( pO (8-7) \) and \( pO (7-6) \) transitions due to water evaporating from the walls of the target chamber. The intensities observed correspond to a partial pressure of 10\(^{-7}\) mbar \( O_2 \). This \( O_2/H_2 \) ratio could be confirmed by a mass-spectroscopy measurement. Inside the detector the only electronic fluorescence X-ray produced stems from copper, as confirmed by an irradiation measurement. The intensity ratio of the \( pO \)-lines is known from the cascade of a bare antiprotonic oxygen atom. The intensity ratio of \( pO \) to \( e^- \) Cu is known from a spectrum in which no correlation between stopped antiprotons and X-rays is required. From that spectrum the slope of the background was determined to be flat. This smooth background originates from the low energy photon component of the electromagnetic shower produced by annihilation products everywhere in the neighbourhood of the detector crystal.

At pressures below one atmosphere, the total intensity of the \( K \) transition is shared by the \( 2p-1s \) and the \( np-1s \) transitions with \( n \geq 10 \). The sharing ratio is determined completely by non-hadronic parameters of the cascade which are known from the measurement of the \( L \) X-ray intensities. For the computer fit the intensity ratio \( 2p-1s \) to \( np-1s \) \( (n \geq 10) \) was fixed to 1.73. The distance between the two \( K \)-lines was fixed by the theoretical electromagnetic energy difference. The Lorentz widths were assumed to be equal. The background was fitted with a 4th order polynomial. The fit yielded \( (5200 \pm 870) \) events, \( \epsilon (K \)-structure). The measured hadronic shifts and widths are:

\[
\Delta E = (8.75 \pm 0.13) \text{ keV} - 9.41 \text{ keV}
\]
\[
\Gamma = (1.13 \pm 0.23) \text{ keV}
\]

The yields are:

\[
Y_{L-1} = (4.9 \pm 1.6) \times 10^{-3}
\]
\[
Y_{ac} = (7.8 \pm 1.9) \times 10^{-3}
\]

Using the total \( L \)-yield of \( (48 \pm 8) \% \) at 30 mbar then yields a hadronic \( 2p \)-width of \( (37 \pm 13) \) meV.

To summarize: the atomic cascade process of \( p\bar{p}H \) is well reproduced by recent calculations. The smaller yields of the \( L \)-series in \( p\bar{p}D \) can be explained by a hadronic 3d-width of 30 meV. The other measured shifts and widths agree with theoretical predictions from potential models [14, 15, 16, 17, 18, 19]. However, a real comparison to the theory requires data which are an order of magnitude more precise. In \( p\bar{p}H \) an increase of statistics by more than an order of magnitude is necessary to resolve the hyperfine structure of the ground state. A crystal-spectrometer combined with a small stop distribution at low pressure could measure the shifts and the widths of the \( 2p \)-levels of the hydrogen and helium isotopes.
A measurement of these quantities would permit an analysis of the spin and isospin dependence of $\bar{p}$-nucleon forces.

### 3.2. Ionization of antiprotonic noble gas atoms

The cascade [20] of antiprotons proceeds mainly via radiative and non-radiative (Auger) dipole transitions. The antiprotons are enriched in the circular orbits ($l = n - 1$; $n$ denotes the principal quantum number, $l$ the orbital quantum number), because the antiprotons having reached these levels will remain there through the whole cascade (circular cascade). If electrons are present and if permitted by energy conservation, the Auger process is the dominant mode for cascade steps with $n \geq 7, 9, 13$ in Neon, Argon and Krypton, respectively. This is also true for the low-energy Auger transitions in Xenon involving the outer electrons ($M^-, N^-, O$-shell). But in Krypton the probabilities of the higher-energy Auger transitions ejecting the $L$- or $K$-electrons are of the same order or smaller than the corresponding radiative transitions [21]. Therefore, the observation of radiative transitions from circular orbits ($|\Delta n| = 1$) in the Auger-dominated part of the cascade is a clear signal for ionization for Ne, Ar and Kr.

Fig. 10 shows a part of the radiative cascade in Neon proceeding almost completely via circular levels. Corrected for the detector efficiency, all lines have the same yield, on an average of $0.55 \pm 0.03$. The observation of these lines and the identical yields are direct proof that the Neon atom is totally ionized.

The ejection of the last two electrons in Argon can be seen in Fig. 11. The X-ray transitions $17 \rightarrow 16$ and $16 \rightarrow 15$ are suppressed. These transitions are induced by the Auger effect. Their energies correspond to the binding energies of the two $K$-electrons in an Argon atom stripped of all other electrons. The reason for the small, but non-vanishing X-ray yield is that the $K$-shell is already partially depleted via inner $|\Delta n| > 1$ transitions.

Fig. 12 demonstrates the ionization of the $L$-shell in Krypton. The transitions $28 \rightarrow 27$ to $25 \rightarrow 24$ proceed via the Auger effect. Then a radiative cascade emerges, because all $L^-, M^-$ and $N$-electrons are ejected, and the energies of the lines are not sufficient to deplete the remaining $K$-shell. Depletion of the $K$-shell is possible via the Auger transitions $16 \rightarrow 15$ and $15 \rightarrow 14$. The corresponding X-ray intensities are suppressed. Similar to the $K$-electrons in Argon the $K$, and $L$-shell in Krypton are also partially ionized by higher transitions before steps with $|\Delta n| = 1$ are energetically allowed.

For Xenon (Fig. 13) the situation is more involved. The suppression of the lines between $6 \text{ keV}$ and $10 \text{ keV}$ indicates a high degree of ionization in the $L$-shell. However, the appearance of the radiative transitions is not a strict argument for complete ionization, because the radiative transition rates begin to dominate the Auger rates, independently of the number of electrons present.

To summarize, the spectra show the complete ionization of
ionization of Neon, Argon, Krypton and possibly of Xenon. The ionization is due to the cascade of the antiproton. The depletion proceeds smoothly by peeling off the electron shell from the outer to the inner electrons.

4. Extraction of low energy antiprotons out of the cyclotron trap

In order to pursue an earlier suggestion [22] to extract antiprotons from the center of the cyclotron trap we can use the results of a recent SIN experiment which studied the stopping process of negatively charged particles in hydrogen. The experiment provided a measurement of the time $T$ for decelerating muons in hydrogen from velocities of $1/173c$ (where $c$ is the velocity of light) to their velocity at atomic capture. The result can be approximated by the formula

$$T[n s] = 2000 / (P [mbar])$$

(9)

For the deceleration in H$_2$, the time is a factor of 3 larger [23]. The measured deceleration times support recent theories describing the moderation and capture process of negatively charged elementary particles in hydrogen [24]. These theories predict that the time $T$ of antiprotons in 0.1 mbar H$_2$ is 2 μs. The mean energy loss during that time would be 9 eV/μm. The radial and axial distribution for these antiprotons in the trap would be $Δr < 10$ mm, $Δz < 15$ mm. For axial extraction, a pulsed electrical field with a duration of 50 ns can be used. The field could be produced by a grid structure. For illustration an electrical field of 500 V/cm and a time between the pulses of 100 ns is assumed. The magnetic field of the cyclotron trap forms a magnetic mirror with $B = 43$ kG in the median plane ($z = 0$) at $r = 0$ and maximum field 57.5 kG at $r = 0$, $z = 160$ mm. Therefore only particles with axial momentum $p_z$ and total momentum $p$ satisfying

$$p_z / \sqrt{p^2 - p_r^2} > 0.5$$

(10)

can leave the trap. In the absence of an electrical field, $p_z$ is much smaller than $p$. The field strength can therefore be chosen in a way that only antiprotons below a certain momentum can be extracted. For 500 V/cm only momenta below 1 MeV/c ($\lesssim 0.6$ keV) are affected. They will be accelerated to 4.3 MeV/c (10 keV) and can then be transported through a thin carbon foil to a high vacuum region. Then a guide field of 1 kG is sufficient to guide them further. A momentum spread of 30% for 4.3 MeV/c is expected. This corresponds to an energy spread of 1.4 keV at 10 keV. The radial spread $Δr$ would be about 10 mm and $Δz$ about 23 mrad.

Hence an efficient conversion of a 5 MeV d.c. beam into a 10 keV pulsed beam could be made. Such a beam would be a natural source for the phase space compressing device as proposed by D. Taquzi [25]. It would also permit construction of cheap beam transport systems in order e.g. to fulfill the needs of several experiments requiring low energy antiprotons.

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References