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FIRST OBSERVATION OF X-RAYS FROM ANTIPROTONIC HYDROGEN

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ABSTRACT

We have observed the Balmer series of antiprotonic hydrogen atoms formed in gaseous hydrogen at 4 atm. The yield of L X-rays was determined to be $(6 \pm 3)\%$ per stopped antiproton. The 2P state is dominantly depopulated via $\bar{p}p$ annihilation and not by radiative transitions to the 1S state.

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Investigations of the zero relative momentum states and of annihilation at rest of the $\bar{p}p$ system have recently been of considerable theoretical [1-11] and experimental [12-20] interest. Particular attention is given to a) the possibility of determining the zero relative momentum scattering length for the $\bar{p}p$ interaction from measurements of the energies, widths, and decay branching ratios of X-ray transitions between low-lying states of the $\bar{p}p$ atom (protonium); and b) the connections between the structure of the protonium levels and possible quasi-nuclear $\bar{p}p$ bound states.

This letter reports the first observation of X-rays from protonium; we present evidence that in hydrogen gas at 4 atm there is in the $\bar{p}p$ L energy region a yield of $6 \pm 3\%$ X-rays per $\bar{p}$ stopping in the gas, that these X-rays are from protonium, and that they populate mostly the 2P level. This level decays by annihilation at least 10 times more frequently than by radiative decay to the 1S state.

The experiment was performed at the m_{14} low-momentum antiproton beam of the CERN Proton Synchrotron (PS) [21]. At a momentum of 900 MeV/c the total flux of antiprotons into a $\delta p/p$ of $\pm 1.5\%$ acceptance beam line was 2000 $\bar{p}$ /burst for 2×10^{11} protons on the production target. The π^- contamination of the electrostatically separated beam was $10 \pi^-/\bar{p}$. The length of the spill was 300 msec. Time-of-flight selection and a Čerenkov counter were used to identify the antiprotons. The beam entering the experimental target [22] (Figs. 1a, 1b) was defined by a counter telescope $(B_1 B_2)_{TOF} \bar{C} T_1 T_2 \bar{T}_3$ and was moderated in energy by a copper degrader before traversing the final beam-defining counter T_2 and entering the target gas. The energy threshold of the thin counter T_2 (50 μ m thick plastic scintillator) was adjusted to select $\bar{p}$'s near the end of their range and therefore having large dE/dx . The thickness of the external moderator was adjusted to place the counter gas at the peak of the $\bar{p}$ range curve (Fig. 1c). Particles entering the gas and satisfying the trigger $(B_1 B_2)_{TOF} \bar{C} T_1 T_2 \bar{T}_3$ were called CANDIDATES. A CANDIDATE which was not subsequently vetoed by a downstream counter T_4 or the surrounding array of E_i counters was called a STOP. The threshold and timing of T_4 and of the E_i

counters were chosen so that the dependence of the STOP rate upon the target gas pressure was optimized in both the slope and the zero pressure offset; the latter was due to inefficiencies of the veto counters and to stops of antiprotons in solid parts of the X-ray detector. The factor connecting the observed STOP count rate to the rate of true stops in H_2 gas was determined from the stop-pressure curve of Fig. 1d. The contribution to the slope of the pressure curve from pions stopping in H_2 gas is discussed later on and was less than 1%. With 1000 $\bar{p}$'s in the $(B_1B_2)_{TOF}$ telescope, we had, with optimal setting of the electronics, about four CANDIDATES yielding 0.7 STOPS at 4 atm and 0.35 STOPS at zero pressure.

Low-energy X-rays produced in the target gas were detected by an array of 36 independent gas proportional counter cells X_i surrounding the target gas volume [23] and separated from it by a 12 μm thick mylar foil. Each signal in a given proportional counter produced three separate outputs, which were recorded when triggered by a CANDIDATE pulse, and provided for every signal i) the total charge E_x , ii) the rise-time t_r , and iii) the delay t_d versus the STOP trigger time. The gain and resolution of each counter were continuously calibrated during the measurements, using the 5.5 keV line from a ^{54}Mn source and the 3.0 keV fluorescence line from the argon counter gas (histogram in Fig. 2a). The FWHM resolution at 5.5 keV in beam was about 25%. The solid angle subtended by the counter array at a typical point in the target gas was about 0.94 (4π), and the calculated average efficiency for detecting an X-ray produced at a typical point in the target is shown by the smooth line in Fig. 2a. The efficiency given in Fig. 2a must be multiplied by a factor, depending on the $\bar{p}p$ annihilation mode, that takes into account the average number of cells of the X-ray detector that were not usable for detecting X-rays because of charged annihilation prongs traversing them.

The array of 36 scintillation counters E_i surrounding the X-ray detector was used in the STOP trigger as a veto on large-amplitude pulses produced by antiprotons scattered out of the target gas through the proportional counters, and was also used independently (with a lower threshold) to register the pattern of minimum ionizing particles produced by annihilations associated with a STOP trigger.

Each CANDIDATE trigger generated an event record containing E_x , t_r , and t_d for each of the 36 proportional cells which had responded, the pattern of the coincidences defining the STOP trigger, and the pattern of E counters which fired on minimum ionizing particles. The data presented here were produced by events recorded by 300,000 STOP triggers (corresponding to 150,000 stops in H_2 gas) over a period of 480 hours of running time.

X-ray spectra were obtained from the event records by accepting only those proportional counter pulses with rise-times lying in the X-ray rise-time window determined in-beam from the X-ray calibration spectra. This allows rejection of most of the pulses produced by charged particles scattered through the proportional counter, since these pulses are due to the amplification of all the clusters of primary electrons produced along ionizing tracks and are then longer in rise-time than X-ray pulses which are originated by one isolated cluster. Spectra from all 36 proportional counters were added following a gain-normalizing correction for each individual counter determined from the calibration spectra. The gain correction also depended on t_d , which was a measure of the drift-time of electrons in the counter and hence a measure of loss of ionization with time. The gain correction algorithm distorted the spectra only in the few uppermost energy bins, which were therefore not used in the analysis.

The resulting spectra are shown in Fig. 2 without applying any kind of background subtraction; data for all triggers were taken under identical in-beam conditions and in the same time window, and the various triggers used were indicated, event by event, by a CAMAC flag; the same rise-time cut on t_r and drift-time cut on t_d were applied to events associated with different triggers. The spectrum in Fig. 2b was generated by requiring a STOP trigger and, in addition, that only one X counter, X_i , among the 36 should have recorded a signal and that no E_j counter with $i-2 \leq j \leq i+2$ should have fired. This condition meant that no charged particle had traversed the proportional counter gas so that no argon fluorescence background should be present in this spectrum. Spectrum 2c was generated requiring a STOP trigger and adding in the spectrum the signals of each of the 36 X_i counters,

which were surrounded by four contiguous X_j counters ($j \neq i$, $i-2 \leq j \leq i+2$) that did not fire (to eliminate the argon fluorescence propagating directly between adjacent counter cells), and for which the same restriction as that of Fig. 2b on the associated E counters was satisfied. The spectra in Fig. 2a are collected with the same restrictions on E_j and X_i as those used in Fig. 2c. The dotted spectrum in Fig. 2a is an in-beam ^{54}Mn calibration spectrum (5.5 keV X-rays) obtained by triggering the event record by the 835 keV gamma-ray produced in all the ^{54}Mn decays; the histogram in Fig. 2a is an argon fluorescence spectrum (3 keV X-rays) obtained by triggering on events in which a CANDIDATE had scattered out through the X counters. Spectrum 2b is essentially due to annihilations producing no charged particles since it contains about 5% of the total X-ray flux, while annihilation into two charged products has a probability of less than 0.5% of contributing to this spectrum; the corresponding probability with higher charge multiplicities is even less. The trigger for Fig. 2c accepts events in which an X-ray background generated by charged particles in materials other than the target gas is possible. An important background line is present at 3 keV. It distorts and shifts the L-line peak, as one can see by comparing Fig. 2b and Fig. 2c, and it is identified with a 3 keV argon fluorescence line. This line provides, indeed, an excellent in-beam calibration peak when using the trigger $(B_1 B_2)_{\text{TOF}} T_1 T_2 \bar{T}_3 \bar{T}_4 \Sigma E$ (see spectrum in Fig. 2a). The interpretation of this line as argon fluorescence was confirmed by using Ne and CO_2 counter gases, which yielded spectra that were free of any structure at 3 keV, using the same trigger as that for the spectrum of Fig. 2a.

The experimental results were analysed with the objective of establishing that the observed X-rays came from $\bar{p}$ stopping in hydrogen, and determining the energies and yields of the X-rays and thence the identity and properties of the protonium states involved in the X-ray transitions.

The most immediate possibility suggested by the results is that the peak in the spectrum 2b, in the region between 1 and 3 keV, is due to L X-ray transitions in protonium, because the energies are consistent with the QED L X-ray energies

and the yields are reasonable. Several checks were carried out to test this interpretation of the data. In a separate run, a 9 μm thick aluminium absorber foil was deposited on the mylar window and covered the nine bottom proportional cells. The peak in the $\bar{p}p$ L region was absent only for the nine cells covered by the Al foil, thus showing that the X-ray source of the peak is on the target side of the mylar foil. Different target gases (D_2 , He) were used at 4 atm with the same Ar + 5% C_3H_8 counter gas. The He spectra show a completely different topology, as the $\bar{p}\text{He}$ X-ray lines dominate the argon fluorescence signal and are distant in energy from the $\bar{p}p$ lines [24]. When D_2 was substituted for H_2 , the peaks in Figs. 2b and 2c shifted towards the higher energy region, as was expected from the increase by a factor of 4/3 of the reduced mass of the radiating system. The X-rays in the peak of Fig. 2b were therefore identified as being produced by antiprotons stopped in the H_2 target gas. In addition to $\bar{p}p$ X-rays, two physical effects caused by stopping particles could produce an X-ray structure that would be difficult to distinguish from $\bar{p}p$ L X-rays. First, a fraction of low-energy π^- due to $\bar{p}$ annihilating in the moderator could lead to π^- stops in the hydrogen, and the π^-p K series could simulate the $\bar{p}p$ L series. The yield of the K lines of π^-p was estimated to be negligible. In any case, it cannot exceed 2% of the events in the peak, if we take into consideration that i) all eventual π^-p X-rays are contained in the "0-prong" spectrum of Fig. 2b, since π^-p can lead only to γn and $\pi^0 n$; ii) the L X-rays in the "0-prong" spectrum represent 5% of the L X-ray content of the total spectrum (see Tables 1 and 2); and that iii) according to bubble chamber data [14] at least 3% of the total spectrum is due to $\bar{p}p$ annihilations in 0-prongs, as Stark mixing is weaker in gas than in liquid. Secondly, the spectral shape of the inner bremsstrahlung produced by annihilation of $\bar{p}p$, when folded with the counter efficiency, could have produced a bump in the 2 keV region. Such a bump was disallowed, as it would not have suffered the observed energy shift on changing from hydrogen to deuterium target gas. Therefore we conclude that the peak in the spectrum of Fig. 2b originates from antiprotonic hydrogen atoms, and that the existence of these new exotic atoms has been shown for the first time.

After subtraction of a smooth background, the relative intensities of the L transitions were estimated by fitting the peak in the spectrum of Fig. 2b with three lines (i.e. L_α , L_β , and one line representing the convolution of the lines $L_\gamma \dots L_\infty$) with energy fixed by the QED values for the $\bar{p}p$ L transitions and instrumental widths obtained by scaling the widths of the 3 keV and 5.5 keV calibration lines. The results are shown in Table 1. The absolute intensities of the L transitions were deduced using the data of Fig. 2c and the pressure curve of Fig. 1d. The peak in Fig. 2c was fitted, after subtraction of a smooth background, with the three $\bar{p}p$ L lines of fixed energy and relative intensity derived from Table 1, plus a line of free intensity at 3 keV to establish the contribution of the argon fluorescence line. The results are shown in Table 2.

The total absolute yield of $\bar{p}p$ L transitions is estimated to be $6 \pm 3\%$. The error estimate is conservative to account for systematic effects due to the rise-time and drift-time cuts applied to the data. Main sources of error are the steep energy dependence of the efficiency curve and the critical setting of the dE/dx conditions on T_2 . The steep variation in the efficiency curve makes the unfolding of the L_α lines from the other L lines critical. Instabilities of the T_2 counter show up as a vertical sliding of the pressure curve. On the other hand, the slope of the pressure curve is essentially due to $\bar{p}$ stopping in the target gas. The contribution from π^- which originated from annihilations in the moderator is below the 1% level, when one takes into account that the relative yield of the K lines of π^-p in the peaks of the spectrum is, at the maximum, 2% compared to 98% L transitions from $\bar{p}p$, and that the absolute yield of $\bar{p}p$ L lines is 6%, to be compared with the measured 15% absolute yield of π^-p K lines at the same pressure [25]. In agreement with the assumption that the $\bar{p}p$ X-ray peak in Fig. 2b is due to L transitions and not to a K_β - K_∞ series of transitions to a 1s level enormously shifted, we looked for K transitions in the energy region around the QED one (9.36-12.5 keV). No clearly defined structure appears directly in the spectra of Figs. 2b and 2c nor in spectra taken over a wider dynamical range (1-15 keV). Assume that all the X-rays of Fig. 2c in a 5 keV wide energy region

(to account for the K_{α} - K_{∞} spacing of 3.1 keV, the instrumental resolution, and a strong broadening of the 1S level) belong to $\bar{p}p$ K transitions; then, by selecting the region outside the L peak where the total count rate, weighted by the efficiency, is maximum, we get a conservative upper limit of 7% for the total K transition yield. From this number and considering that the ratio between the probabilities of nP-1S and nP-2S radiative transitions is 7.2 ± 0.4 for all $3 \leq n \leq 14$ in all hydrogen-like atoms [25], we get an upper limit of 1% for the total yield of L transitions that populate the 2S level. This shows experimentally that more than 80% of the detected L transitions populate the 2P level.

Figure 2d shows a coincidence spectrum containing the X-rays of Fig. 2c which are accompanied by another X-ray, X_1 , present in the same STOP trigger and detected in a separate cell with energy in the bin window X_1 indicated in the drawing.

The X_1 X-ray has an energy compatible with all L transitions. The topology of this coincidence spectrum is substantially different from the one of Figs. 2b and 2c. A peak is present with energy slightly below 3 keV, and is interpreted as being due to coincidences between L X-rays and argon fluorescence X-rays. The high-energy region is enhanced with respect to the one in spectra 2b and 2c. A 2 keV broad structure could be present, centred at 8 keV. The total number of L X-rays present in spectrum 2c and falling in the X_1 energy region is 1800, and only the K_{α} line of the K series can be present in the coincidence spectrum in coincidence with an L transition. Since the maximum number of counts weighted by the efficiency in a 2 keV wide energy region (to account for the instrumental resolution and a strong widening of the K_{α} line) is 175 when selecting the 2 keV window in any region of the spectrum outside the X_1 region, an L transition is then followed in less than 10% of the cases by a K_{α} transition in the energy range 4-11 keV. Unless the K_{α} line is much broader than 1 keV and is shifted to an energy higher than 11 keV, it can then be concluded that the total yield of K_{α} transitions is less than 0.6% and that the dominant decay mode of the 2P level is annihilation ($\Gamma_{\text{ann}} \geq 4 \times 10^{-3}$ eV, $\Gamma_{\text{rad}} = 0.4 \times 10^{-3}$ eV), since the probability of Stark mixing at the $n = 2$ level is negligible in H_2 gas. Moreover, since both

the radiative and the annihilation widths of P-levels scale as $1/n^3$, we deduce from the relation $\Gamma_{\text{ann}} \geq 10 \Gamma_{\text{rad}}$ an upper limit of 10% on the total absolute yield of K lines, independent of the atomic cascade development. This number is in agreement with the 7% upper limit derived from the singles spectra of Fig. 2c.

Our direct observation of P-wave annihilation from an atomic state and the previous observations of P-wave annihilation in liquid [15,19] requires probably a dynamical reason for the suppression of the $\bar{p}p K_S K_S$ decay in liquid hydrogen [13,14]*).

The experiment is being continued in order to improve the statistics of the coincidence spectra and of the $\bar{p}d$ data.

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Table 1

Relative intensities of L lines (normalization $\Sigma L = 100$)

Line	Energy (keV)	Counts in spectrum of Fig. 2b	Detection efficiency	Counts weighted by efficiency	Relative intensity
L_{α}	1.736	30	0.22	136	35
L_{β}	2.343	60	0.52	115	29
$L_{\gamma}-L_{\infty}$	~ 2.7	90	0.64	140	36

Table 2

Absolute intensities (X-rays per $\bar{p}$ stopping in H_2 gas)
of L lines and of argon fluorescence line

Line	Energy (keV)	Counts in spectrum of Fig. 2c	Total detection efficiency ^{a)}	Counts weighted by efficiency	Absolute intensity (%)
L_{α}	1.736	300	0.10	3000	2
L_{β}	2.343	600	0.23	2600	1.7
$L_{\gamma}-L_{\infty}$	~ 2.7	900	0.28	3200	2.1
Argon fluorescence	3	1800	0.30	6000	4

- a) Takes into account the detection efficiency, the number of cells discarded for poor resolution, and the percentage of cells inhibited by the charged prongs.

Figure captions

Fig. 1 : Side view (1a) and front view (1b) of the apparatus: Incident $\bar{p} = (B_1 B_2)_{TOF} \bar{C}$; $\bar{p}$ stop CANDIDATE trigger = $(B_1 B_2)_{TOF} \bar{C} T_1 T_2 \bar{T}_3$; $\bar{p}$ STOP trigger = $(B_1 B_2)_{TOF} \bar{C} T_1 T_2 \bar{T}_3 \bar{T}_4 \bar{\Sigma} E_H$; ΣE_H is the output of an OR unit fed by E_H discriminators with high threshold so as not to veto on annihilation prongs. Range curve (1c), with C the external degrader ($\rho = 1.84 \text{ g/cm}^2$). Pressure curve (1d) taken with 4.5 cm thick C degrader.

Fig. 2 : X-ray detection efficiency of the array of 36 proportional cells (2a, smooth line). ^{54}Mn in beam calibration spectrum; 835 keV γ trigger; peak at 5.5 keV (2a, dotted curve). X-ray spectrum with outward-scattered CANDIDATE trigger = $(B_1 B_2)_{TOF} \bar{C} T_1 T_2 \bar{T}_3 \bar{T}_4 \bar{\Sigma} E$; the peak at 3 keV is the Ar fluorescence line (2a, histogram). X-ray spectrum with STOP and "0-prong annihilation" trigger; the peak in the 2-3 keV region is from $\bar{p}p$ L transitions (2b). X-ray spectrum with STOP trigger; the asymmetric peak in the 2-3 keV region is from $\bar{p}p$ L lines and Ar fluorescence line (2c). X-ray spectrum with "STOP and one coincident X-ray in the X_1 energy region" trigger (2d).

Fig. 1

Fig. 2