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LETTER OF INTENTION

A STUDY OF THE X-RAYS OF PROTONIUM ($p\bar{p}$ ATOM) IN HYDROGEN GAS

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ABSTRACT

We intend, with other collaborators, to present a full proposal about one month from now. The attached proposal, which has already been presented and conditionally approved at Daresbury, will form the basis of the final CERN proposal.

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DARESBURY NUCLEAR PHYSICS LABORATORY

DARESBURY LABORATORY SELECTION COMMITTEE

PROPOSAL TO STUDY THE X-RAYS OF PROTONIUM ($p\bar{p}$ ATOM) IN HYDROGEN GAS

by

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ABSTRACT

We propose a collaboration with Mainz University, Pisa University, Queen Mary College, University of British Columbia, and the CERN-Karlsruhe group, to study the X-rays and annihilation products of the $p\bar{p}$ atom. Our contribution would be the construction of a gas target containing a multiwire proportional counter with several special features, in particular using the proportional signal for pulse-height analysis.

The experiment would take place at CERN.

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1. GENERAL PURPOSE

A slow antiproton in matter loses energy primarily by ionization and comes to "rest", with little loss by annihilation in flight. In H_2 one expects it to be captured by a proton into an orbit of about the size of the first Bohr orbit of H, 0.53×10^{-8} cm. The "protonium" so formed has $n \simeq 30$, large ℓ, and velocity somewhat above thermal.

The subsequent cascade results in the de-excitation of the protonium either by collisional de-excitations or by radiative transitions. Some purely Coulomb transition energies are:

K_α(2p-1s)	9.368 keV
K_β(3p-1s)	11.103 keV
L_α(3d-2p)	1.735 keV ,

The strong interaction gives both a level shift and a level width due to absorption from the particular state. The energy shift of an S-state is:

$$\Delta E = \frac{-1}{2m} |\psi_n(0)|^2 a_0 ,$$

where a_0 is the s-wave scattering length, related to the phase shift by $k \cot \delta = a_0^{-1}$. The energy shift is much smaller for levels with $\ell \neq 0$. If we take $a_0 = +1$ fm 1), then

$$\Delta E_{n=1} = +0.9 \text{ keV} , \quad \Delta E_{n=2} = +0.1 \text{ keV} ,$$

so that the energy of the protonium K_α line would be 8.6 keV. However, a_0 may be highly spin-dependent, giving a "hfs-splitting" $\simeq$ 0.2 keV.

The imaginary part of the scattering length, corresponding to annihilation, gives a level width similar in magnitude to the level shift, so that if a value of -0.8 fm is taken for Im a_0, the level width, and hence K_α line width, is about 1.4 keV from perturbation theory, or 0.8 keV from numerical integration 2).

Contributions to level shift from vacuum polarization are small ($\sim$ 0.04 keV for n = 1) 3). Likewise the fs-splitting is expected to be hidden in the absorption broadening.

When the protonium reaches low-n orbits, it can pass within the electric field of nearby protons, and Stark mixing of its states will occur. Theoretical computations 4) of the capture rates from nS and nP states of protonium suggest that capture occurs predominantly from S-states. This is also expected theoretically in the $\pi^- p$ atom 5) [where theory agrees fairly well with experiment 6)] and the $K^- p$ atom 7). It is in agreement with the experimental fact 8) that the decay mode $K_L^0 K_S^0$ is seen, but never $K_L^0 K_L^0$ (or $K_S^0 K_S^0$). However, it contradicts another recent experimental fact, namely that 9) the decay mode $\pi^0\pi^0$ is seen, from which one can conclude that about 40% of all annihilations into two pions take place from odd-ℓ atomic states. This anomaly may be due to annihilations in flight, but it deserves study.

Again, the calculation indicates that in liquid H_2 the Stark collisions considerably reduce the fraction of protonium atoms reaching the lower levels, annihilation occurring from higher S-states, but there is as yet no experimental evidence on this point.

Analysis of bubble chamber data 10) on stopping $\bar{p}$ in liquid hydrogen gives the following distribution:

$\bar{p}p \to$ 0 prongs			3.2%
$\bar{p}p \to$ 2 prongs	$\pi^+\pi^-$	0.32%	42.6%
	$\pi^+\pi^-\pi^0$	7.8%	
	$\pi^+\pi^- X^0$	34.5%	
$\bar{p}p \to$ 4 prongs	$\pi^+\pi^+\pi^-\pi^-$	5.8%	45.8%
	$\pi^+\pi^+\pi^-\pi^-\pi^0$	18.7%	
	$\pi^+\pi^+\pi^-\pi^- X^0$	21.3%	
$\bar{p}p \to$ 6 prongs	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	1.9%	3.8%
	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	1.6%	
	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^- X^0$	0.3%	
$\bar{p}p \to$ non-pionic	$K\bar{K}$ etc.		4.6%

In addition to phase space considerations, it is known that given states of protonium can result only in certain pion multiplicities 11) in the annihilation products, so that these products give information on the spin of the initial atomic state [12] and its isospin, and thus on the lower state of an X-ray transition. For example, if we see a $\pi^+\pi^-$ annihilation in coincidence with an X-ray, we are sure that the X-ray was to an even-S sub-level.

In complementary fashion, the X-ray gives information on the spin of the state from which annihilation occurs. Thus if we see a 2p-1s X-ray in coincidence with annihilation products, we are sure that annihilation took place from an S-state.

Clearly the $p\bar{p}$ atom deserves attention both because it is an ideally simple system for studying the nucleon-antinucleon interaction(1-3,13-15) and because of the experimental anomaly discussed above. We therefore propose the following:

i) To measure the K X-rays from the $p\bar{p}$ atom. The energy shift will give the sign and magnitude of the strong interaction correction to the Coulomb energy of the 1s state, and hence the sign and magnitude of the scattering length a_0. The line shape, if we have sufficient resolution, will give information on the spin (and isospin) dependence of a_0 and in particular on its imaginary part.

ii) To measure the L X-rays from the $p\bar{p}$ atom, and deduce a relative value for annihilation from the $n = 2$ states compared to the $n = 1$ states of protonium.

If this is successful, we shall then extend the experiment to study the combination of X-ray and charged particle emission, which gives information on the various pion and kaon channels (especially $\pi^+\pi^-$, $K_S^0\, K_L^0$, and $\pi^0\pi^0$) from a definite, known angular momentum state of protonium.

Even if few X-rays are observed, the $p\bar{p}$ atom should be studied in gas in order to shed light on the anomaly observed by Devons et al. [9]. Thus if the $2\pi^0$ decay mode occurs with a different branching ratio in low-density (gas) and high-density (liquid) hydrogen, the anomaly is probably a Stark-mixing effect.

The experiment might finally be extended to the $\bar{p}d$ atom.

2. EXPERIMENTAL TECHNIQUE

2.1 Antiproton beam

At the CERN PS results have been reported [14]) for the k_{17} beam line, a low-energy electrostatically separated beam built for experiments with stopping K^- and $\bar{p}$. This has given 630 $\bar{p}$ of 850 MeV/c (= 325 MeV) per burst of 21×10^{10} protons. The separator appears to reject all K^-, so that the contamination is $\leq 1/20$. There remains a $\pi^-/\bar{p}$ ratio of 100/1.

The beam moderated by Cu becomes relatively large at the target -- about 50 × 100 mm (compared to the width at the mass slit of ±1 mm). A Be degrader would reduce this beam spread (a piece of Be 230 × 60 × 60 mm costs £200). Two hundred $\bar{p}$ atoms per burst are estimated, formed in a 4 g/cm^2 Cu target.

The m_{11} and m_{13} beams are similar to k_{17}, and any of these three beams would give us a suitable stopping $\bar{p}$ beam. Perhaps the best long-term possibility is to suppress the m_{13} beam, allowing one to put a large-acceptance quadrupole close to the PS, thus getting one excellent $\bar{p}$ beam in place of the two average-quality beams now existing. All $\bar{p}$ work in Europe must be done at CERN, so that some effort in improving beams will be very fruitful.

2.2 Target

If Stark-mixing-induced annihilation from higher states is negligible, one could use a liquid H_2 target with mylar windows and a suitable solid-state detector of the 8.6 keV K-radiation, as is now being attempted by the CERN-Karlsruhe group (Backenstoss, Tauscher, H. Koch et al.) at CERN. However, one cannot detect the soft L-radiation through two 19 μ mylar windows (dictated by safety) which give only 3% transmission, and the alternative of putting the detector inside the liquid is difficult. Moreover, Stark and Auger effects may kill most of the X-rays in liquid.

The alternative we propose is to use a H_2 gas target with proportional counter technique for X-ray detection, similar to that used by Zavattini et al. [18]), but in a long cylinder configuration with nearly 4π coverage. For good resolution the pressure of the counter gas and hence of the H_2 is kept ≤ 4 atm. With 100 cm useful target length, the H_2 mass is 35 mg/cm^2, so the $\bar{p}$ atom rate should be about 2 per burst (= per 2 sec), or 10^4 in an 8-hour shift. Selection of X-rays accompanied by 2, 4, or 6 charged tracks is achieved by dividing the proportional counter into 16 (or more) separate counters, as shown in Fig. 1. Simple electronics distinguishes charged tracks ("high" pulses) from X-rays. The continuously flowing counter gas (probably argon plus quencher, but if we find it necessary to run at lower pressures we can use Kr) is separated from the H_2 by a 10 μ mylar sheet aluminized to provide a conducting surface, with a transmission of about 50% to the L-radiation. There is a mechanism for moving one or more thin foils in front of the counter, thus gaining information [19)] by using known X-ray absorption edges (Co to Zn). Fast coincidence timing of the annihilation pions is achieved by scintillators, and accurate event-tracking will be done with multiwire planes in the second stage of the experiment. Part of the beam-defining telescope will be an ultra-thin (30 μ) scintillator inside the target, and another "veto" scintillator inside the far end of the target will define stops.

The energy calibration of the 16 counters requires frequent checking. We will use K-capture radioactive sources: ^{41}Ca, ^{55}Fe, ^{65}Zn, ^{75}Sc, together with ^{37}A which can be introduced into the counter gas. These sources give their own lines and can also excite fluorescent lines of other elements. Also muonic and pionic X-rays would serve as a calibration.

With 4 atm and a counter depth of 50 mm (= 35 mg/cm^2) of argon, the absorption of photons is 100% for the 1.7 keV L-radiation and 95% for the 9 keV K-radiation. A minimum ionizing particle will deposit 60 keV or more in a counter. Hence 80% of produced X-rays should be detected, so perhaps 6000 X-rays should be seen in 6 hours. It is difficult to give a realistic background estimate until the beam is measured. Probably the chief source will be $\bar{p}$ annihilating in flight in the degrader, and π^- produced near the mass slit.

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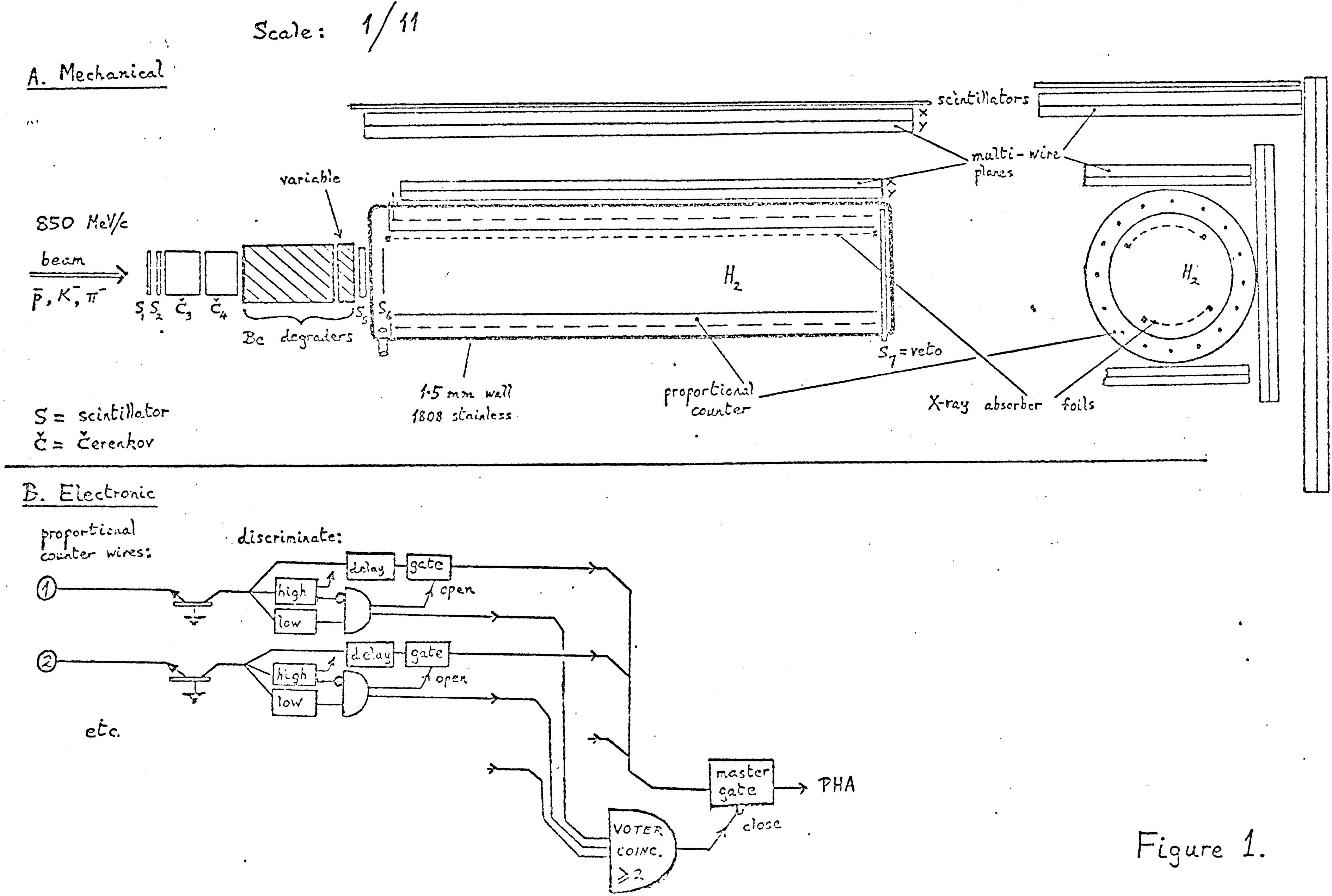
Scale: 1/11
A. Mechanical
850 MeV/c
beam
$\bar{p}, K^-, \pi^-$
S_1 S_2 $\check{C}_3$ $\check{C}_4$
variable
Be degraders
S_5 S_6
H_2
S_7 = veto
1.5 mm wall
1808 stainless
proportional counter
X-ray absorber foils
scintillators
multi-wire planes
X
Y
H_2
S = scintillator
Č = Čerenkov
B. Electronic
proportional counter wires:
discriminate:
①
②
high
low
delay
gate
open
etc.
master gate
PHA
close
VOTER COINC. ≥2

Figure 1.