PROCEEDINGS

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THE ATHENA ANTIHYDROGEN DETECTOR

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Abstract: The goal of the ATHENA experiment is a direct comparison of the properties of antihydrogen and hydrogen atoms leading to a test of CPT invariance for leptons and baryons with unprecedented accuracy. The antihydrogen detector to measure the annihilations products is described.

CPT is a fundamental symmetry expected to be true for the strong, weak and electromagnetic interactions. It is derived from relativistic local quantum field theories which assume pointlike constituents. However, the ultimate constituents, superstrings, have a finite size of the order of the Planck length (presumably 10^{-33} cm). Thus the foundation of the CPT theorem is unsound at the Planck length and may be at a much larger distance [1]. The arguably best test of CPT, at the level of 10^{-18}, was performed in the $K^0 - \bar{K}^0$ system. However, matter-antimatter systems like $q\bar{q}$ mesons may not be sensitive to CPT violating effects. Also, assuming that antimatter and matter do not fall with the same acceleration in a gravitational field, a discrepancy between transition frequencies in hydrogen and antihydrogen could be ascribed to gravitational redshift in the field of the earth and sun, as clocks tick more slowly in the vicinity of large masses.

The long lifetime of the metastable 2s state (τ=122 msec) leads to a ratio of natural line width to energy of 5×10^{-16} for the 1s-2s transition, offering the possibility to compare antiatoms with their matter counterparts at the same level, or better, than 5×10^{-16}. Confined antiatoms in a suitable field and in the 1s level can be pumped to the metastable 2s level by Dopplerfree 2γ absorption (each with wavelength λ=242 nm). A short electric pulse mixes the 1s with the 2p level, whereby a fraction of the positrons flip their spins. The atoms then quickly return to the 1s level by Lyman α emission. Those with the wrong electron spin orientation move towards the electrodes and annihilate. In the experiment one would then measure the annihilation rate as a function of laser frequency to establish the energy difference between the 1s and 2s levels [2].

The ATHENA[1] apparatus (fig. 1) consists of a superconducting solenoid (3 T) with a cold bore to house the antiproton trap, the positron storage trap, and the $\overline{\mathrm{H}}$ recombination

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[1] CERN, MIT, Aarhus, Brescia, Genoa, Pavia, Tokyo, Swansea, Rio de Janeiro and Zurich collaboration

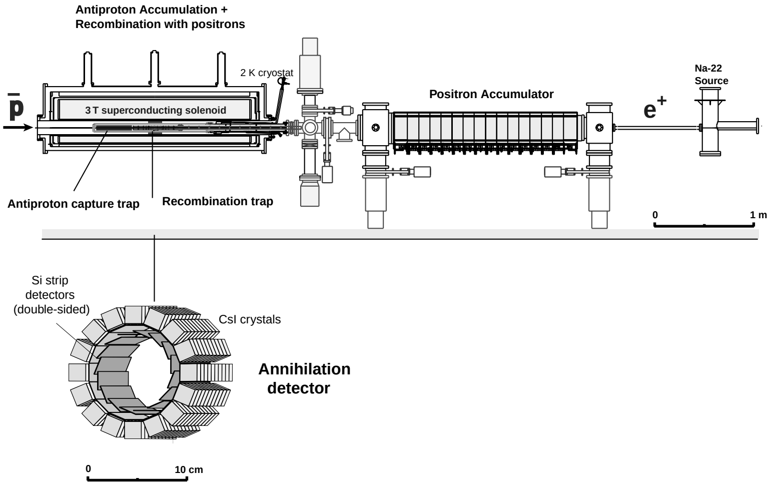

Figure 1: Overview of the ATHENA apparatus for the production of antihydrogen. A sketch of the annihilation detector is shown below.

trap. Antiprotons of 100 MeV/c from CERN's antiproton decelerator are injected along the axis of the magnet and are moderated through a silicon beam defining counter, an absorption foil and various windows. They are injected in the capture Penning trap (made of several cylindrical electrodes) and reflected by an electrostatic potential. The $\bar{p}$ shot lasts for 200 ns (repetition rate of 2 minutes) after which the voltage of the entrance electrode is raised to capture the antiprotons. They are then cooled to sub eV energies by interaction with a pre-loaded electron gas (which is cooled by synchrotron radiation) inside the capture trap.

Positrons from a strong ^{22}Na source are moderated in solid neon and transferred into a longitudinal magnetic field where they are moderated by nitrogen gas and electrostatic fields. They are then injected into a Penning trap similar to the one used to store the antiprotons. The particles stacked in the two traps are finally transported to the central recombination trap.

In the current first phase of the experiment the formation of antihydrogen is to be demonstrated by detecting the annihilation of the positrons (into two 511 keV γ's) and the antiprotons (into charged pions) which occurs when the unconfined (neutral) $\overline{\mathrm{H}}$ atoms hit the electrodes of the recombination trap. Since background positrons are generated in the apparatus by γ-showers from antinucleon annihilations, it is essential to search for two 511 keV photons from antihydrogen annihilation, emitted back-to-back from the annihilation point of the antiproton. This requires the annihilation vertex to be determined by measuring the charged annihilation products (e.g. pions) and the conversion points of the two 511 keV γ's in a high granularity γ detector.

The pions are detected in two layers of 16 double-sided silicon microstrip detectors (see fig. 1 for a sketch of the detector). For best detection efficiency the detector is installed as close as possible to the recombination trap, inside the superconducting solenoid and hence at a temperature close to 77 K. The two cylindrical layers of the double-sided silicon microstrip modules (8192 channels) detect the charged pions stemming from antiproton annihilation on the wall of the recombination trap, or with rest gas atoms. Figure 2 (left) shows the outer layer of 16 silicon microstrip modules.

The photons are detected by 16 rows of 12 scintillating pure CsI crystals read out by photodiodes. The crystal dimensions are $13 \times 17.6 \times 17.1$ mm^3. Figure 2 (right) shows one of the 12 rows of crystals wrapped in teflon tape before insertion into the support structure.

The support structure was manufactured from a single rod of aluminium. The inner wall separating the crystals and the outer layer of microstrip detectors had to be as thin as possible to minimize multiple scattering and γ-conversions and was electroeroded to a thickness of 500 μm.

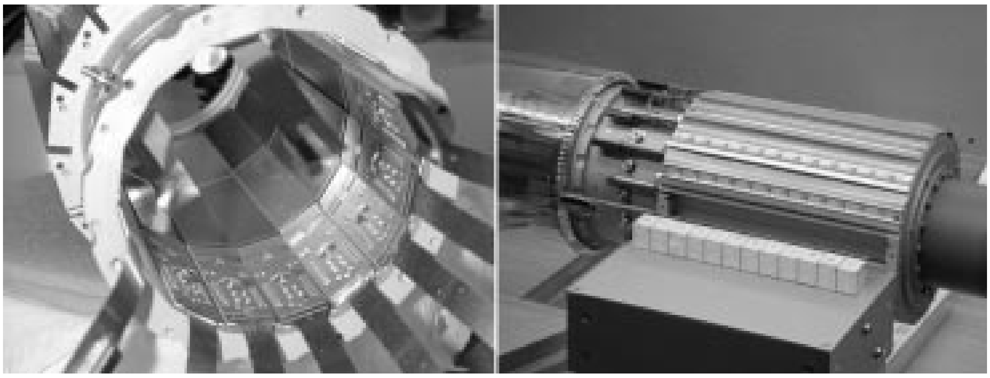

Figure 2: Left: outer layer of 16 silicon microstrip modules. Right: one of the 16 crystal rows before insertion into the support structure.

Two silicon microstrip detectors (manufactured from 6" wafers) are glued and connected (total length 160 mm) to increase the solid angle. The backplanes (pad side) of the detectors are glued to a silicon structure which holds at the same time the transmission lines for the 128 pads. This fragile structure can be cooled down to 77 K without any noticeable deformation. The module is connected to VIKING VA2_TA readout chips [3], modified to allow selftriggering, mounted with passive SMD electronics on a small ceramic hybrid. A similar readout system is used for the photodiodes. The 48 readout lines of a crystal row (12 × 4 pads) are connected to one VA2_TA chip on a PCB hybrid.

The self-triggering VA2_TA chip is multiplexing its 128 channels into one analogue output line. The two VA2_TA chips on the hybrid of each microstrip module are connected to the outside electronics through only 33 lines which provide e.g. the symmetric analogue output of the 256 channels, a symmetric trigger output, bias, digital and analogue control signals and supply voltages . Custom designed capton cables connect the 48 hybrids (2×16 for the 2 silicon layers and 16 for the crystals) with the patch panel (fig. 3). This circular PCB board works as a passive fan-in for common signals and collects analogue signals to the corresponding cable bundles. The patch panel is connected to the outside electronics through 250 coaxial cables and five vacuum feedthrough connectors.

Beyond the vacuum flange the signals are processed by custom made analogue and digital repeater cards. The analog signals from the repeater cards are digitized by 36 VME CAEN FADC modules. The readout system is controlled through a fast VME-PCI link by

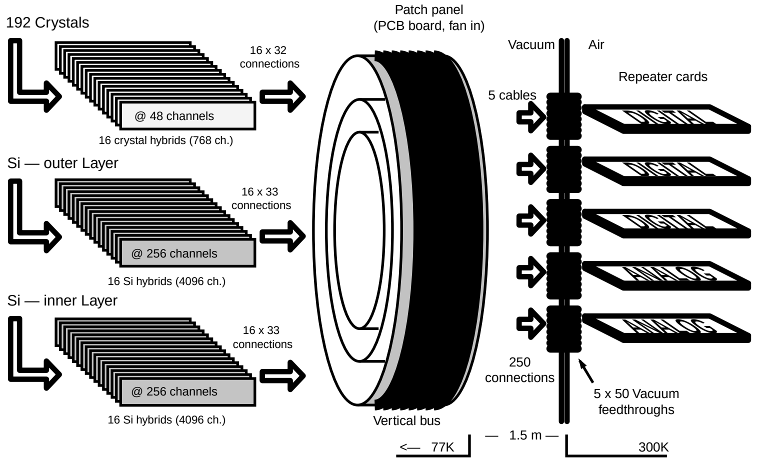

Figure 3: Block diagram of the readout electronics.

a PC running a LabView DAQ program.

A number of technical problems, related to the tiny space available for the detectors and the low operating temperature of 77 K, had to be solved. Let us mention for example the different temperature expansion coefficients for the various detector parts (capton striplines, silicon pads, ceramic substrates, etc) the temperature dependance of active electronics components (like capacitors and amplifiers) and the then unknown performance of crystals and photodiodes (light yield and efficiency) at low temperature.

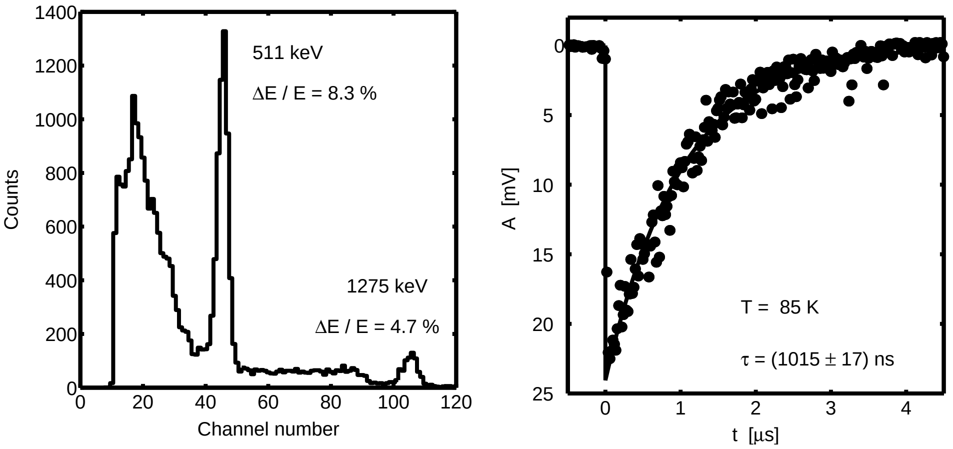

Figure 4: Left: ^{22}Na spectrum taken with a pure CsI crystal sprayed with red dye and read out by a photodiode at the temperature of liquid nitrogen. Right: Light emission curve at 85 K measured with a photomultiplier.

We have investigated the properties of pure CsI coupled to photodiodes as a function of temperature and final results are being published [4]. The scintillation yield of pure CsI increases with decreasing temperature. In the wavelength region of maximum light emission from CsI (340 nm at 77 K), the quantum efficiency of the photodiode oscillates between 10 and 20 % (presumably due to interference effects in the covering SiO_2 layer), but rises rapidly above 360 nm to reach ~ 75% at 600 nm.

To alleviate this problem we used a fluorescent red dye to shift the wavelength into the red range. With this method we obtained 50'000 ± 5000 photons / MeV at 80 K, deduced from the number of electron-hole pairs in the photodiode: 39'600± 1200 / MeV. This is 16 times more than at room temperature and comparable to NaI(Tl). The pulse height spectrum from the β^+ emitter ^{22}Na is shown in fig. 4 (left). One observes clearly the Compton plateau from the 1275 keV line and the 511 keV line, well separated from background. However, the decay time of CsI increases rapidly with temperature: 6 resp. 28 ns for the "slow" component at room temperature, to about 1 μs at 85 K (fig. 4, right). Such a slow decay time is acceptable for our experiment.

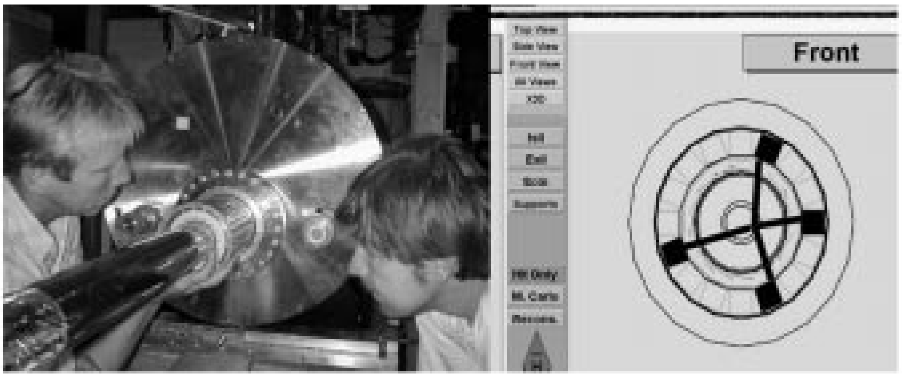

Figure 5: Left: Insertion of thedetector in the ATHENA supraconductive solenoid. Right: typical event observed on the online display, showing a 4-prong annihilation of a trapped antiproton hitting the electrode of the recombination trap.

At the time of writing this report the antihydrogen detector had been installed in the ATHENA apparatus (fig. 5). The first annihilations were observed with antiprotons trapped in the recombination trap. Figure 5 shows a typical 4-prong annihilation event from a trapped antiproton hitting the cylindrical electrode.

References

[1] T.D. Lee in *The Discovery of Nuclear Antimatter*, Conf. Proc. 53, Italian Physical Society (1995) p. 19

[2] Details on the experiment can be found in C. Amsler et al. (ATHENA Collaboration), Proc. Hydrogen II Conf., Castiglione de Pescaia, Hyperfine Interactions (2001, in print)

[3] O. Toker et al., Nucl. Instr. Meth. **A 340** (1994) 572 (the new VA2-TA chip is produced by IDEAS Oslo, see http://www.ideas.no/)

[4] C. Amsler, D. Grögler, W. Joffrain, D. Lindelöf, M. Marchesotti, P. Niederberger, H. Pruys, C. Regenfus, P. Riedler, A. RotondiRecombination Trap, Nucl. Instrum. Methods in Phys. Res. A (in print)