Production of Antihydrogen

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The idea of the existence of antimatter goes back to the work of Dirac [1]. For each particle a corresponding antiparticle exists as predicted by the CPT theorem. Furthermore, it follows that particle and antiparticle have the same mass, spin and total life time and the same value but opposite sign of charge and magnetic moment. Since there is no reasonable doubt about the existence of the symmetry between particle and antiparticle, it should be possible to combine antiparticles into antimatter under the same forces as particles bind to form normal matter, in particular, to produce the simplest antiatom out of an antiproton and a positron: $\overline{\mathbf{H}}^0$.

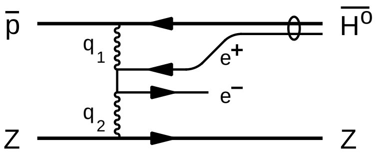

Fig. 1: A schematic view of the two–photon mechanism for e^+e^- and $\overline{\mathrm{H}}^0$ production

Though there is hardly any doubt that $\overline{\mathrm{H}}^0$ exists, it has never been observed. Once it is produced $\overline{\mathrm{H}}^0$ is certainly an ideal laboratory for studying CPT invariance by comparing interactions in matter and antimatter environments.

Two principal solutions for $\overline{\mathrm{H}}^0$ production, at rest and in flight, have been suggested and are discussed in References [2]–[7]. The variant of the flight method used here has first been suggested by Munger et al. [5]. An antiproton passing through the Coulomb field of a nucleus with charge Z will create an e^+e^-–pair. Occasionally the antiproton will capture the positron from the produced pair and both will form a fast moving antihydrogen. In lowest order two kinds of mechanisms have been estimated [4],[6]:

1. the space like $\gamma\gamma$–production of e^+e^-–pairs, see Fig.1:

$$\overline{\mathrm{p}}\mathrm{Z} \rightarrow \overline{\mathrm{p}}\gamma\gamma\mathrm{Z} \rightarrow \overline{\mathrm{p}}\mathrm{e}^+\mathrm{e}^-\mathrm{Z} \rightarrow \overline{\mathrm{H}}^0\mathrm{e}^-\mathrm{Z}$$

2. the e^+e^-–pair production converted from virtual time like Bremsstrahlung photons:

$$\overline{\mathrm{p}}\mathrm{Z} \rightarrow \overline{\mathrm{p}}\gamma^*\mathrm{Z} \rightarrow \overline{\mathrm{p}}\mathrm{e}^+\mathrm{e}^-\mathrm{Z} \rightarrow \overline{\mathrm{H}}^0\mathrm{e}^-\mathrm{Z}$$

The second mechanism is calculated [7] to be two to three orders of magnitude lower than the $\gamma\gamma$ induced one, which has been evaluated by several authors [5],[7] resulting in a Z^2 and a $ln\,(E_{\overline{p}}/m_{\overline{p}})$ dependence, where $(E_{\overline{p}}/m_{\overline{p}})$ denotes the Lorentz factor. The cross section is expected to be in the order of 2 pb for a $\overline{\mathrm{p}}$–momentum around 2 GeV/c, the maximum momentum at LEAR.

The production of $\overline{\mathrm{H}}^0$ requires a rather thin target since otherwise the antiatom would break up into its constituents. However, due to the small production cross section a large luminosity is demanded and therefore only the technique of using a cluster target at an internal antiproton beam seems possible. The present results were taken in a dedicated beam time period with effectively 15 hours beam on target, distributed over several days of running in parallel to the Crystal Barrel (PS197) experiment. A Xe–cluster target was used [8]. The beam target interaction intensity was optimized such that a fairly constant luminosity was maintained, i.e. the target density was low (about $1 * 10^{12}$ atoms/cm^2) at the beginning and was increased to about $3 * 10^{13}$ atoms/cm^2 according to the decrease of the 1.94 GeV/c $\overline{\mathrm{p}}$–beam intensity. Starting typically with $1.7 * 10^{10}$ $\overline{\mathrm{p}}$'s in LEAR beam lifetimes of at least 3 minutes were possible with the optimum settings of the LEAR accelerator and cooling system. A typical run lasted for twelve minutes before a new filling of LEAR was done. The integrated luminosity was estimated from the number of antiprotons and target thickness to be $\mathcal{L} = 5 * 10^{33}$ cm^{-2} $\pm$ 50 % for the total running period in September/October 1995. Since the cross section of the $\overline{\mathrm{H}}^0$ production is expected to be $2\mathrm{pb} * Z^2 \simeq 6 * 10^{-33}$ cm^2 a total production rate of 30 $\overline{\mathrm{H}}^0$ would be expected. According to both test measurements and Monte Carlo calculations the acceptance of the detection system was determined to be $\epsilon = 0.3$ which would result in the observation of nine $\overline{\mathrm{H}}^0$ with a clear signature during the running period.

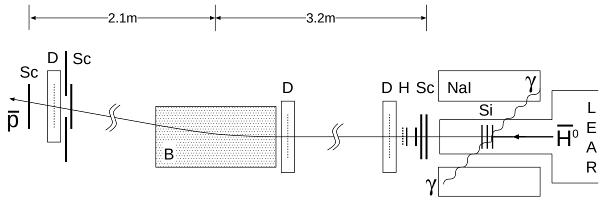

Fig. 2: Lay–out of the experiment PS210: Sc: trigger and time of flight scintillators, Si: three silicon detectors, D: Delay wire chambers, NaI: six–fold segmented NaI detector, H: scintillating fibre hodoscope, B: magnetic dipole field

A clear signature for a good event has to fulfill the following criteria (see Fig.2 for the detector set–up):

i) As a neutral object an $\overline{\mathrm{H}}^0$ — produced ten meters upstream in the center of the straight section of LEAR — will exit the accelerator ring tangentially and will be stripped in the first silicon counter still in the LEAR vacuum system. Here both constituents of $\overline{\mathrm{H}}^0$ have the same velocity and therefore at a $\overline{\mathrm{p}}$ beam momentum of 1.94 GeV/c the kinetic energy is 0.663 MeV for e^+ and 1217 MeV for $\overline{\mathrm{p}}$, respectively. These two particles hit simultaneously the first silicon counter (700 μm thick and 1200 mm^2 active area [9]) which, together with the second one (500 μm thickness and 1200 mm^2) measures the dE/dx of the $\overline{\mathrm{p}}$ plus the kinetic energy of the e^+ being stopped in these two detectors. The third silicon counter with dimensions the same as the first one should give a signal proportional to dE/dx of the $\overline{\mathrm{p}}$ only.

ii) The two 511 keV photons from the e^+–annihilation will be detected back to back in the cylindrical six–fold segmented NaI counter [10], which forms an inner and outer diameter of 8 cm and 40 cm, respectively, covers a solid angle of 91 %, has an energy resolution of 14 % FWHM, and provides a 511 keV γ–detection efficiency of 82 % which has to be multiplied by 0.71 for the peak–to–total ratio [10]. The silicon counter telescope is located in the center of the NaI crystal arrangement. The NaI detector was temperature controlled during the runs to $17 \pm 0.5\ ^0$C.

iii) The $\overline{\mathrm{p}}$'s resulting from the stripped $\overline{\mathrm{H}}^0$ will continue with a velocity of $\beta = 0.900$. They penetrate through a set of three start scintillators, each 4 mm thick, a scintillator hodoscope of 16 fibers $2 * 2 * 32$ mm^3 in vertical and horizontal orientation, and a group of four stop scintillators arranged as indicated in the figure. All scintillator ADC and TDC values have to be in specific intervals which were determined by cosmic ray calibrations before and after the installation of the detector system in the experimental set–up at LEAR.

iv) The deflection of the registered charged particles was measured with a spectrometer consisting of three horizontally sensitive delay–line readout drift chambers [11] with a used active area of $8 * 8$ cm^2 and a dipole field varied between 0.05 Tm and 0.15 Tm. The deflection should be within the predicted values for the $\overline{\mathrm{p}}$ from $\overline{\mathrm{H}}^0$, taking the straggling of $\pm$ 12 mm into account due to matter in the flight path.

Since in the present situation no additional well known reaction could be measured in parallel to the reaction to be studied, the entire detector system had to be calibrated before the start of the experiment. These calibrations were done with cosmic rays for the time–of–flight and energy losses, with a ^{22}Na source for the NaI crystals and with both ^{106}Ru and ^{207}Bi sources for the energy and timing determination for the silicon detectors and the scintillator hodoscope.

The chain of analysis used for the identification of the produced $\overline{\mathrm{H}}^0$ employed neither cuts on the time–of–flight nor on the deflection in the magnetic separator. In Fig.3 the time–of–flight via the signal amplitude from one of the time–of–flight start scintillators is shown. In the range from 17 ns to 19 ns the signal amplitude is due to single pion (amplitude $\simeq$ 130), double and multi pion production. The main source of these mesons is most likely the reaction chain: $\overline{\mathrm{p}}\,\mathrm{Xe} \rightarrow \overline{\mathrm{n}}$"anything", where the $\overline{\mathrm{n}}$ annihilates in the silicon detector telescope and produces multi–pion events. The band starting at amplitude values

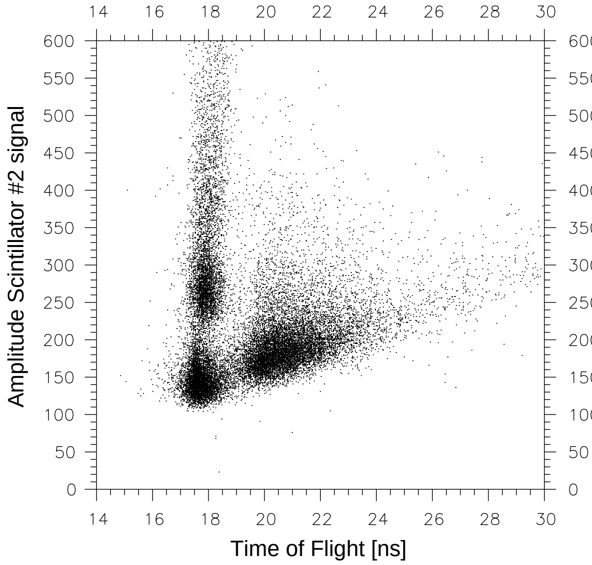

Fig. 3: Two dimensional display of time–of–flight vs. scintillator signal amplitude

of about 160 and ranging from 19.5 ns to 30 ns with decreasing intensity is due to fast and slow protons or antiprotons which probably again are due to secondary reactions from $\overline{\mathrm{n}}$'s leaving the LEAR accelerator tangentially. Here we can not distinguish in general whether the slower baryons are due to additional pion production and/or to any kind of excitation of the Xe target nucleus.

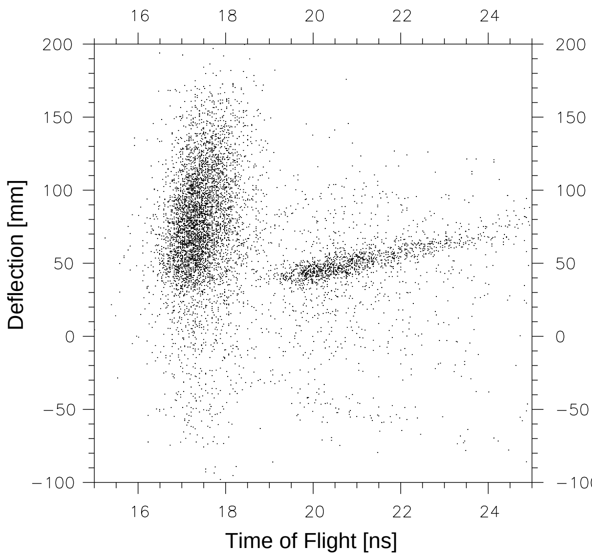

Fig. 4: Two dimensional display of time–of–flight vs. deflection due to the magnetic dipole

Whereas in Fig.3 the sum of all data taken in 1995 with about 300,000 triggers is shown, Fig.4 presents only a single run with a magnetic field setting of 0.136 Tm which results in an expected deflection of the $\overline{\mathrm{p}}$'s from $\overline{\mathrm{H}}^0$ of 39.5 mm $\pm$ 12 mm and a time–of–flight of 19.7 $\pm$ 0.6 ns where the allowed range corresponds to 2.5 σ around the expected value. In Fig.5 again the integral of all data taken at different magnetic field settings is shown now with the deflection normalized such that the expected position for the $\overline{\mathrm{p}}$'s from $\overline{\mathrm{H}}^0$ should be zero.

Naturally the upper display in Fig.5 includes and selects only those triggers ($\simeq$ 23,300) where a track through all three wire chambers could be defined, but has no additional cut on the data.

Additional cuts were introduced in order to produce the second part of the figure, with 94 events remaining, where now the essential conditions are that:

i) the sum of the signal from the first two silicon detectors is equivalent to the kinetic energy of the stopped e^+ plus the energy loss of the $\overline{p}$ whereas the third silicon detector gives an energy signal relevant for the $\overline{p}$ energy loss only.

ii) the determined particle trajectory points back into the area of the target region.

iii) the signal amplitude from the time of flight scintillators is in reasonable agreement with the energy loss of the $\overline{p}$'s from $\overline{\mathrm{H}}^0$.

With these requirements the pionic events disappear as can be seen from the middle part of Fig.5. Essentially only events due to antiprotons are left. Demanding in addition a back–to–back yy–coincidence from signals in two NaI crystals eleven events remain which follow the clear signature of $\overline{\mathrm{H}}^0$. They show an expected deflection and the correct time–of–flight range, as can be seen in Fig.5 bottom. Thus, it can be concluded that **11 $\overline{\mathrm{H}}^0$ atoms have been observed**. The $\overline{\mathrm{H}}^0$ production rate is in good agreement with the expected value following the theoretical $\gamma\gamma$–production mechanism [5],[7]. No production of $\overline{\mathrm{H}}^0$ has ever been reported or observed before.

Based on Poisson statistics the number of background events would be less than three with a confidence level of 95 %. This is in agreement with a background estimate from the present data of 2 ± 1 out of the 11 events.

In the future more $\overline{\mathrm{H}}^0$ atoms should be produced and especially under conditions such, that spectroscopy could be done to test the CPT symmetry of matter and anti–matter.

Acknowledgements

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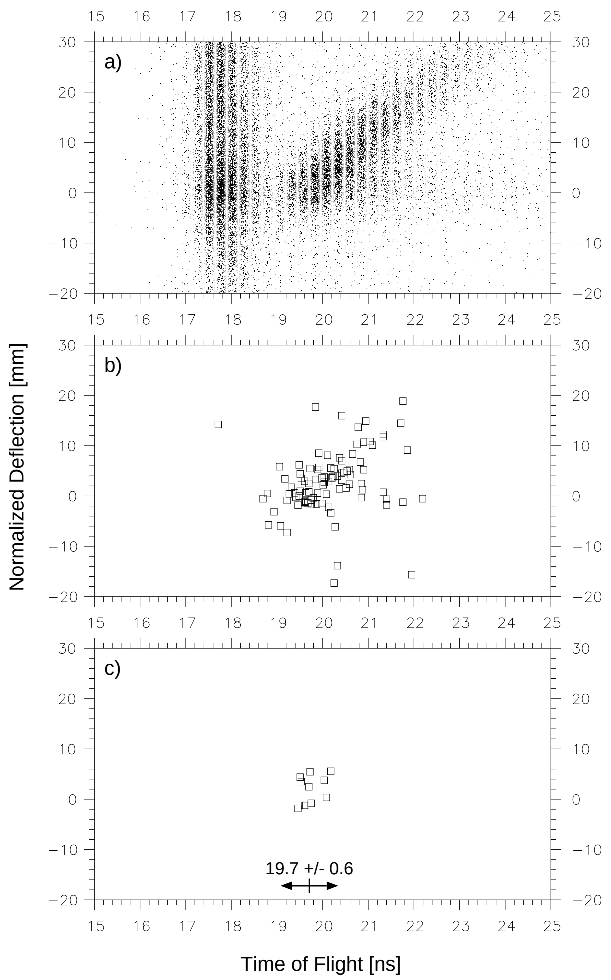

Fig. 5: Time–of–flight vs. deflection spectra, steps of different cuts were applied to the raw data, see text for details

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