Overview antiproton physics

Walter Oelert

Institute for Nuclear Physics, Research Centre Jülich,

D–52425 Jülich, Germany

It appears to be an unsolvable challenge to present an overview of antiproton physics during this talk in view of the many interesting activities carried out with this exciting tool of physics. Therefore, reference is given to the two review articles which recently appeared [1] and especially to the Low Energy Antiproton Physics conference LEAP-05 which will take place in Bonn/Germany in May 2005 [2] and will concern about: fundamental symmetries, hadron–antihadron systems, atomic physics, facilities, quark–gluon phenomena, and application of antimatter, radiation and particle detection.

Before talking of physics with antiprotons some warnings about actions of frivolous scientists for unnecessary and dangerous applications of antimatter will be exposed.

During the talk some general aspects of research with antimatter will be presented followed by a discussion of the useful energy scale and dreams of physics to be achieved.

In the second part some spin dynamics results from the former PS-185 $\Lambda\bar{\Lambda}$ production will be presented.

1 Introduction

As mentioned in the abstract the physics of antiprotons at low energies will be discussed at the upcoming LEAP-05 conference [2] with the following subsections:

1.1 Fundamental symmetries

Experimental tests have made physicists to discard earlier assumptions: first, that reality is invariant under parity (P) transformations and second, that it is invariant under charge plus parity (CP) transformation. The direct CP violation has been established in K-meson and recently in B-meson decays. On the contrary, the charge plus parity plus time (CPT) invariance is believed to hold to a very high degree of accuracy. Up to now only upper limits are determined experimentally for any possible CPT violation indicating that this

belief is based mainly on theory – though some dedicated experiments with extremely high precisions were performed. The symmetries under T, CP, and CPT transformations are interconnected. The first observation of a breakdown of T invariance required that the semileptonic K-meson decays obey CPT, however, the data could be reproduced without T violation when assuming a rather large CPT asymmetry in a specific K-meson decay.
The CPT theorem demands that for each particle the equivalent antiparticle has the same mass, lifetime, spin, and isospin but an opposite value for all of the additive quantum numbers. In the absence of a theory incorporating CPT violation effects, physics is still in a phase where it is important to accumulate high precision experimental data from different spectroscopic tools as leptonic and/or hadronic systems. The role of matter–antimatter – especially the baryonic proton (p)–antiproton ($\bar{p}$) physics – is significant and powerful. The research on fundamental symmetries is a very important part of the scientific program of the LEAP-05 conference.

1.2 Hadron–antihadron systems

When describing the nucleon (N) – antinucleon ($\bar{N}$) interaction it is implicitly assumed that the N–$\bar{N}$ six quark system can be regarded as a product of quark– antiquark nucleon wave functions times a complex potential being dominated by the distance between the nucleons. Such a potential predicts a rich spectrum of states when neglecting the annihilation part. Rich dynamics of resonances or bound states exist around thresholds, where the annihilation effects are less dominant, since the phase space for the decay into meson resonances is more restricted. The transition from a N–$\bar{N}$ system to a multiquark state where quarks and antiquarks interact directly by gluon exchange must be fully understood, before invoking exotic mechanisms based on details of the interaction. New dedicated experiments could determine the energy and the quantum numbers of N–$\bar{N}$ clarifying definitely the details of the long range interaction.
In antiproton–proton annihilations particles with gluonic degrees of freedom as well as particle–antiparticle pairs are copiously produced, allowing spectroscopic studies with unprecedented statistics and precision. Using antiproton beams is an excellent tool to address the regime of strong coupling where phenomena arise which represent open problems of the quantum–chromo–dynamics having their origin in the specific properties of the strong interaction and represent a major intellectual challenge for the community: quarks are confined within hadrons, the hadron mass does not balance with the summed mass of the composing quarks and the characteristic self–interaction among gluons should allow for the existence of glue-balls and hybrids, consisting predominantly of gluons and/or glue plus a quark – antiquark pair, respectively.

1.3 Atomic physics

Investigations on the interaction in $\bar{p}$–atom systems have produced very interesting and unique results on high precision spectroscopy of metastable antiprotonic atoms. Details of the ($\bar{p}$) interaction with matter at very low energies is still a topical field of electromagnetic and strong forces and their interplay. Here, the antiprotonic helium atoms can be studied to a precision sufficient to test the CPT theorem. An alternative approach for such tests is the production and comparison of hydrogen and antihydrogen. A reasonable requirement of a new and unique CPT test of such kind is that it is eventually more stringent than existing tests with leptons and baryons. The accuracy of the CPT test extracted must be distinguished from the accuracy with which the relevant physics quantities must be measured since these can be very different. To reach the required high precision spectroscopic measurements the hydrogen– and antihydrogen atoms have to be at such low temperatures that laser cooling of trapped atoms appears to be necessary. The Lyman-alpha fluorescence has been developed as a tool for relative accuracies of $\approx 10^{-14}$ and can be used for a very high resolution spectroscopy even with only a small amount of antihydrogen atoms trapped. Such measurements will be a very useful tool for first CPT tests on charge and mass separately. When all the basic technical needs to produce antihydrogen atoms will be explored and optimized also tests of the gravitational force on antimatter will be possible, free from the problems associated with charged particles.

1.4 Future facilities

At the Research Centre CERN/Geneve/Switzerland the **A**ntiproton–**D**ecelerator (AD) has been put into operation during the year 2000 and spectacular production rates of antihydrogen atoms have been reported as well as topical observations of antiprotonic Helium atoms. The AD is regarded as the successor of the **L**ow **E**nergy **A**ntiproton **R**ing (LEAR) after CERN's antiproton machines, AA, AC and LEAR were closed down in 1996. An extracted beam of 1.5×10^{13} protons at 26 GeV/c is produced in 4 bunches with a total duration of 500 nsec for producing antiprotons. The AC machine was modified to become the decelerator (AD), decelerating the antiproton beam from the momentum of 3.57 GeV/c to 100 MeV/c. During deceleration, the beam is cooled with stochastic and electron cooling. The extracted beam intensity is about $3 \times 10^{7} \bar{p}$ in a pulse of 100 nanoseconds, repeated once per 90 seconds. AD delivers antiprotons only at the lowest energy of LEAR. The antiproton beam can be further decelerated to about 60 keV with an RF Quadrupole (RFQD) as presently done in one of the experimental lines.

In addition, plans start to be realized for a new antiproton facility at GSI where both very low energy antiprotons and antiprotons with high enough energy for strange and especially charm meson physics can be studied. An accelerator complex for research with ion – and antiproton beams is planned providing a new outstanding experimental facility for studying matter at the level of atoms, atomic nuclei, protons and neutrons as the building blocks of hadrons - and the subnuclear constituents quarks and gluons. The facility offers the possibility to provide high quality beams of antiprotons and ions for the experimental program.

Both facilities – the existing one at CERN and the planned one at GSI – will be used by research groups of a few hundred physicists, a large user community.

The foreseen conference will bring together both groups: experienced and active LEAR and AD users and potential researchers for the GSI facility learning from each other physics and techniques.

1.5 Quark–gluon phenomena

Though in the previous section quark–gluon phenomena have already been introduced there will be dedicated sessions during the conference for the fundamental understanding of strong interactions in terms of the quantum–chromo–dynamics (QCD), which was greatly supported and stimulated by the discovery of a meson consisting out of charm–anticharm quarks. The charmonium system has ever since turned out to be a powerful tool in the understanding of the strong interaction. The spectroscopy of the charm–anticharm system helped tuning potential models of mesons where the gluon condensate is determined, which is closely related to the charmonium masses since it is the gluon– and the quark–antiquark condensate which represent the energy density of the QCD vacuum.

The QCD spectrum is much richer than that one of the simple quark model, as the gluons, which mediate the strong force between quarks, can also act as principle components of entirely new types of hadronic matter, where these gluonic hadrons fall into the two general categories: glueballs and hybrids. The additional degrees of freedom carried by gluons allow glueballs and hybrids to have exotic quantum numbers in the sense that they are forbidden for normal mesons and other fermion–antifermion systems. Such exotic systems can be identified by the observation of an overpopulation in the experimental meson spectrum and by comparing their properties with predictions from models or lattice–quantum–chromodynamics considerations. Very promising results for gluonic hadrons came from antiproton annihilation experiments.

1.6 Application of antimatter, radiation and particle detection

Positron emission tomography (PET) is a modern diagnostic imaging tool to localize and quantify physiological and metabolic functions in the human body in vivo. The advantages of PET are based on its specific physical and technical characteristics and its utilisation of biochemistry. Especially the usefulness of PET in the follow-up of cancer disease has lead a world-wide rapid increase of PET-installations over the last five years. The common property of all positron emitters is that they produce pairs of annihilation photons of an energy of 511 keV emitted in opposite directions, so that they can be detected by the coincidence measurement with a cylindrical system of gamma detectors. Brain research at Jülich aims at exploring neural mechanisms in the brain from the molecular level to the level of complex systems, understanding their organization and function, identifying dysfunctions and developing new diagnostic methods and treatment approaches. Positron emission tomography is applied for in vivo receptor distribution studies to evaluate the pathogenesis and to improve diagnosis and therapy of brain diseases. Another series of experiments aims at using PET with radio labelled amino acids to improve the diagnosis of brain tumors.

By a combined action of deuterons, α's, n's and γ's in coincidence it is possible to i) routinely retrieve quantitative chemical formulas of hidden substances through steel in terms of $C_aN_bO_cH_d...$, where a, b, c, d, are the atomic proportions, and ii) to get a 3-D image of the objects investigated. Blind tests have demonstrated 100 % accuracy in distinguishing explosives from innocuous substances, and 80 % in determining the exact stoichiometry of each target material.

2 Proton – antiproton

It is our general understanding that reality is invariant under CPT transformation (C for charge, p for Parity and T for Time) which is well founded insofar as it seems virtually impossible to construct a reasonable theory which violates this invariance. Axiomatic quantum filed theory e.g. commonly used to describe all interactions except for gravity is CPT invariant. Consequently if we think that we know the proton wave function as illustrated in figure 1 we can construct the antiproton wave function just by the CPT transformation of all single parts, symbolically depictured according to [3] at the right side of the figure.

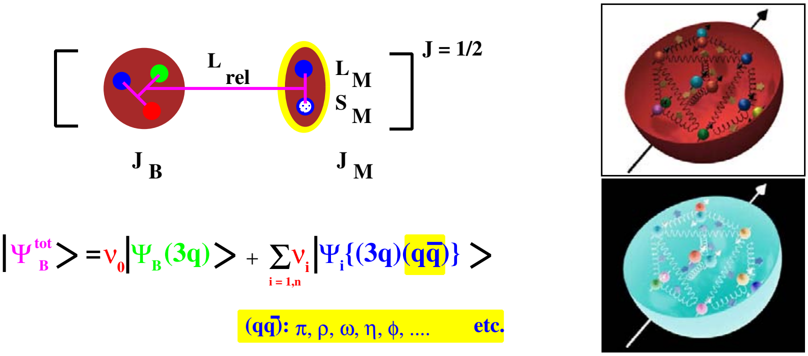

Figure 1: Wave function of the proton and the symbolic pictures for proton and antiproton

3 Energy density of particle - antiparticle systems

When talking in public about antihydrogen as a perspective for testing fundamental symmetries people like to zone out to antimatter application and the mystery of antimatter dreaming about space traffic, star-ships and Dr. Spock & Co. There is no question that a combined matter–antimatter system carries the highest energy density possible. There are very good reasons that we need numerous but still countable atoms of antimatter for scientific reasons but there is absolutely no need for any production of antimatter in macroscopic quantities as milligrams of even grams. Still frivolous suggestions are around asking agencies for funding in promising unrealistic fictions and unwanted possibilities. Out of the many floating articles and press notes I would like to quote a recent one here [4] based on an initial proposal to ESA/NASA for some funding for exploratory research where *"controlled antihydrogen propulsion for NASA's future in very deep space"* is feigned.

Let me quote from the abstract of the paper:

i) *"To world-wide notice, in 2002 the ATHENA collaboration at CERN announced the creation of order 100,000 low energy antihydrogen atoms"*

Certainly there was an enormous notice but after all much less than at the time where only 11± 2 antihydrogen atoms were announced. The interest was in the fact that antimatter was produced with no realistic correlation to the quantity.
ii)*"Thus, the concept of using condensed antihydrogen as a low-weight, powerful fuel for very deep space missions has reached the realm of conceivability."*
This statement is absolutely not true and lacks any justification on scientific, realistic, and justified grounds.
iii) *"We estimate that, starting with the present level of knowledge and multi-agency support, the goal of using antihydrogen for propulsion purposes may be accomplished in about 50 years."* Such kind of unrealistic promises should not be made for getting funding if our community does not want to loose any credibility.
The paper continues with a mixture of correct statements about the few light years distance of the nearest extra–solar systems, about the three orders of magnitude higher energy per gram for antimatter than for fission or fusion, about the Dirac equation, and about the CPT theorem, it describes the ATHENA experiment forgetting about the high velocity the produced antihydrogen atoms still have, and puts the antiproton cancer therapy towards an application which has entered the realm of being a realistic possibility, which is incorrect as it only can be.
Though no concept is given in the paper the suggestion is made that a much stronger antiproton facility as CERN is needed and a break-through is demanded, but still it is pretended that 50 B$ would do the job in 50 years.
Exaggerating this presentation in 2004 the San Francisco Chronicle newspaper reported: *"Air Force pursuing antimatter weapons ...... a positron bomb could be a step towards one of the military's dream from the early Cold War: a so-called 'clean' superbomb".*
Can anybody explain to me what a "clean superbomb" is? I think that any serious scientist should refrain from such kind of thoughts for two essential reasons:
a) the production of antimatter is by thousands of orders of magnitude too little and too inefficient to ever become a realistic choice for technical applications,
b) for ethical and moral reasons scientists should refrain from such kind of investigations just from the beginning and for good reasons most laboratories do absolutely forbid any kind of weapons research.
Let us remain being a reliable community of scientists to keep our credit and to remain our dignity.

4 Antihydrogen

In his public lecture during the conference Kienle was asking about the antihydrogen atoms, which should have been produced just as hydrogen in the course of the history of development, where did they go? We all would like to know, however, I would suggest to read the paper of A. Schuster [5] saying: *....If there is negative electricity, why not negative gold, ... as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. ..... if it ever existed on our earth, it would long have been repelled by it and expelled from it.*

Experiments at CERN are progressing to produce sufficient quantities of antihydrogen atoms in order to study any possible difference between atoms of matter and antimatter, to test the CPT invariance or find some CPT violation. Up to date the most stringent tests have been performed in the $K_0\bar{K}_0$, the e^+e^-, and the $p\bar{p}$ systems with accuracies better than 10^{-10}, where a certain caution is required on the relative normalizations of these numbers.

Still, an observation of CPT–violation would mean the existence of yet unknown properties of fields and interactions and that is why searches for effects of CPT–violation in different processes are desirable.

It is generally believed that physics is invariant under CPT transformation. The CPT-symmetry has been experimentally tested at various systems, as collected in figure 2. The extremely precise value for the relative mass difference of the neutral K-meson stem $|m_{\bar{K}^0} - m_{K^0}/m_{average}| \leq 10^{-18}$ is obvious, where it should be realized that the measurement accuracy is on the 2×10^{-3} level. Still, even a very precise CPT–test in one particular system does not make further tests in other systems unnecessary, especially since questions of normalization have to be considered very carefully [6]. Considering the sensitivity to CPT violation in the standard model, usually the Lagrangian is expressed for single terms of different sectors. As one example, Colladay and Kostelecky [7] invented within the non-locality of the string theory an extension of the standard model providing a consistent theoretical framework which includes the standard model features but additionally allows for small violations of Lorentz – and CPT symmetry. The QED sector, relevant for atomic physics, is described by a modified Dirac equation with effective coupling constants which violate CPT for each particle sector independent. As pointed out in ref [8] up-to-date experiments in atomic physics – which are sensitive to frequency shifts as low as $m\ Hz$ – correspond to a sensitivity of $\approx 4 \times 10^{-27} GeV$ on the energy scale, bounds which are well within the range associated with suppressions from the Planck scale. Thus, atomics physics has a rich history of searching and testing for low–energy signals, for effects which originate from high energy. That is why the ATRAP collaboration aims for studying the relative spectroscopy of H^0 and $\bar{H}^0$.

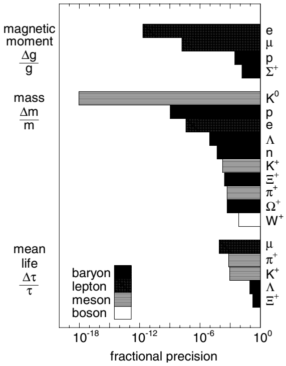

Figure 2: Assembly drawing of various CPT-Tests.

The largest challenge on the road to spectroscopy of antihydrogen is to produce useful antimatter atoms in the sense that they can be captured by their magnetic moment in a magnetic quadrupole trap (Ioffe trap) which can be built with present days technology up to a trap depth of about 0.6 K temperature which is equivalent to a gradient of the magnetic field of about $\Delta B \approx 1T$, see figure 3.

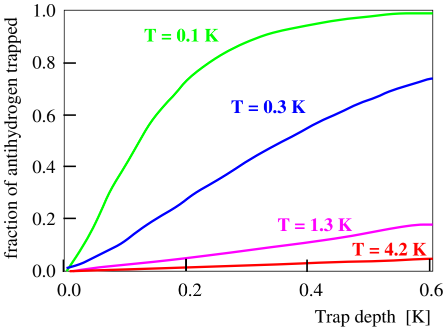

Figure 3: Correlation between antihydrogen trapping and trap depth in temperature.

Results from ATRAP on two different production mechanisms for antihydrogen atoms has been given during the EXA-05 conference by Gabrielse, indicating that the three body recombination yields a much hight rate but far too fast antihydrogen atoms, whereas the double charge exchange experiment suffers from low production rates but should provide antihydrogen atoms at the surrounding temperature which has been 4.2 T during the performed experiments.

In order to improve on the efficiency of low energy antiproton trapping, as the first step for the antihydrogen production, the AD users are working for a proposal for adding a further decelerator ring between the present AD and the experiments such that antiprotons can be slowed down to a few hundred kev kinetic energy. The envisaged layout of the ELENA ring is such that it would fit into the present AD hall.

The main features of ELENA are:

- A compact machine with a circumference of less than 20 meters.
- Energy range from 5.3 MeV (present AD extraction energy) down to 100 keV.
- The cycle length is much shorter than the AD cycle.
- An electron cooler to maintain small emittances for the $\bar{p}$'s.
- An ultra low vacuum of few 10^{-12} Torr.
- The beam lifetime at 100 keV is longer than 10 seconds.
- The ring would fit inside the existing AD hall.
- The commissioning can be done without disturbing the present AD operation. A dedicated 100 keV proton source can be used to optimize ring parameters.
- Fast extraction is foreseen.
- Slow extraction, necessary for a certain type of experiments, could be envisaged depending on the users requirement.

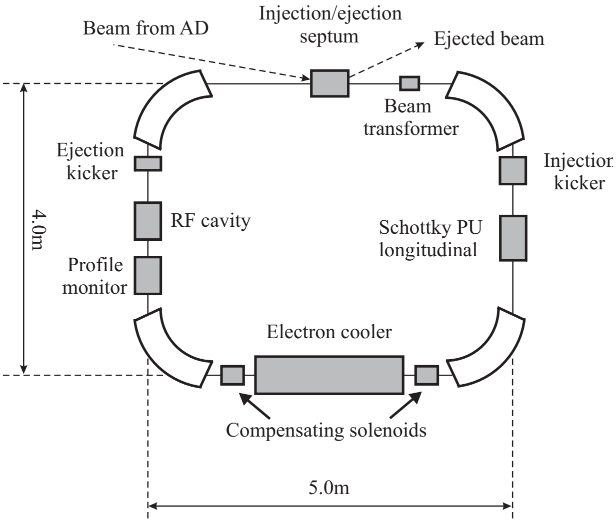

Figure 4: *Layout of the ELENA ring.*

Special challenges are to maintain high intensity in view of the space charge limitations, construction of the electron gun for the electron cooler with low transverse and longitudinal temperatures in the energy range from 500 eV to 55 eV, $\bar{p}$ beam diagnostics at low energies and intensity.

5 Hyperon – antihyperon production

During the days of LEAR operation the PS185 collaboration collected lots of data for the light hyperon – antihyperon production from the proton – antiproton annihilation. Most of the measured cross sections, excitation functions, angular distributions, spin correlations and singlet fractions have been published, see [9]. The polarization analysis yields results on the products αP for $\Lambda \to p\pi^-$ and $\bar{\alpha}\bar{P}$ for $\bar{\Lambda} \to \bar{p}\pi^+$ decays. Charge–conjugation invariance in $\bar{p}p \to \bar{\Lambda}\Lambda$ allows the ratio A to be determined: $A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = \frac{\alpha P+\bar{\alpha}\bar{P}}{\alpha P-\bar{\alpha}\bar{P}}$.
The sum over all experiments of PS185 yields an average value of $A = 0.006 \pm 0.014$, where the numbers quoted are the average obtained for the entire centre–of–mass angular range, and the errors are only the statistical ones resulting from the polarization analysis.

The data set accumulated by PS185 is well fit by at least two models, the quark model which contains only a modest tensor force and the meson exchange model being dominated by the tensor interaction, which provides a spin–flip by connecting states with $\Delta L = 2$. There was the hope that a comparison of the polarization states of the initial and the final state particles might help to distinguish between these models, since they do have very different predictions for the correlation between the normal components of the target polarization and the produced Λ polarization, see figure 5.

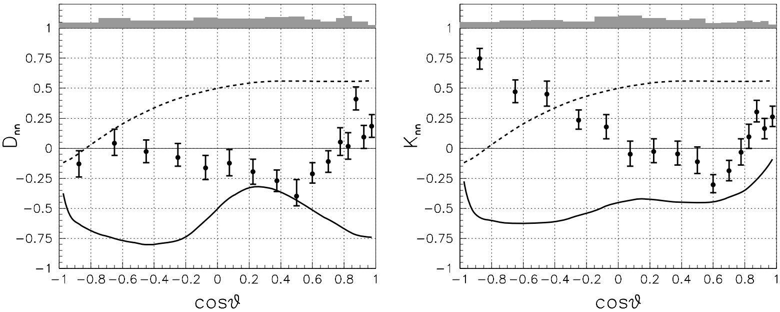

Figure 5: Depolarization and Polarization transfer of the reaction: $\bar{p}\vec{p} \rightarrow \bar{\Lambda}\vec{\Lambda}$ D_{nn} measures the transfer of the polarization from the target proton to the Λ, where as K_{nn} gives the polarization transfer again from the target proton to the $\bar{\Lambda}$.

It is seen from the figure [10] that the data do not favour one of the models under discussion and thus a kind of hybrid model had to be invented which will be discussed at the upcoming LEAP-05 conference [2].

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