PHYSICS WITH ANTIPROTONS: FROM ANTIHYDROGEN TO THE TOP-QUARK

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Abstract

The talk gives a survey on experiments performed with antiprotons of different energies. The emphasis will be on results obtained at LEAR/CERN, but the exciting investigations with higher energy antiprotons, leading to the discovery of the intermediate bosons W^+, W^-, Z^0 and the top quark t, will also be discussed.

1 Introduction

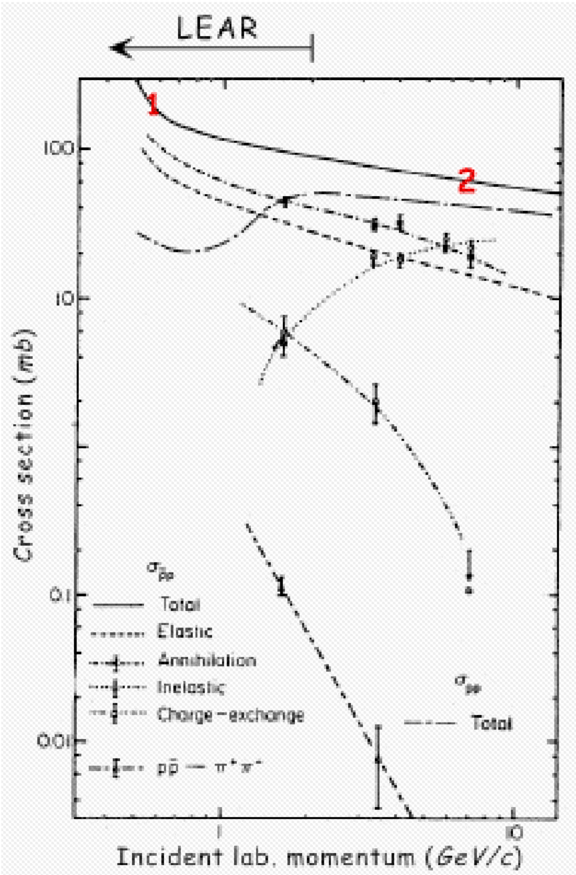
This talk is intended to give a survey on physics results obtained so far using antiproton beams. They span the energy range from TeV (discovery of the top quark) down to meV (experiments with trapped antiprotons). In the high energy domain the top quark and the intermediate vector bosons $W^{\pm}$, Z^0 have been discovered and high precision experiments in the $(c\overline{c})$-system (c = charm quark) have been performed. In the medium and low-energy region most data have been measured at LEAR/CERN bearing relevance to various topics:

- Low and medium energy $\overline{p}N$ interactions
- Antiprotonic X-ray measurements
- $\overline{p}$-nucleus interactions
- T/CP/CPT-tests
- Meson/Exotics-Spectroscopy
- Physics with trapped antiprotons
- Antihydrogen

In the following, selected examples of the measurements mentioned above will be discussed. The $(c\overline{c})$-spectroscopy and the largest part of antihydrogen studies are omitted. They are covered by special talks at this workshop (R. Calabrese, G. Gabrielse).

2 Survey on $\overline{p}p$- reactions

In Figures 1 and 2 $\overline{p}p$-cross sections are shown at lab-energies from about 100 MeV up to 10^3 TeV, the latter ones being measured in colliders. At high energies diffractive processes dominate (most particles go forward), at medium and lower energies



the importance of annihilation channels, e.g. $\bar{p}p \rightarrow \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K\bar{K}\pi, \cdots$, is evident.

In the figures is marked, where the LEAR experiments ① and the $(c\bar{c})$-spectroscopy experiments at FNAL ② were performed. At energies marked with ③ and ④ the intermediate vector bosons and the top quark were discovered at CERN and FNAL, respectively.

Fig. 1:
$\bar{p}p$-cross sections in the low and medium energy regime. From [1]

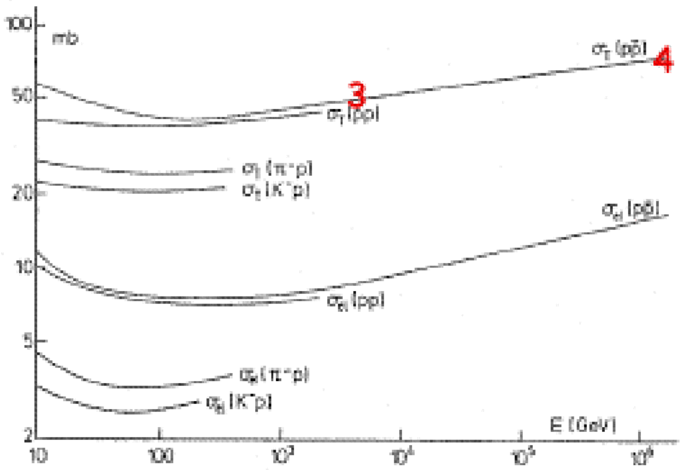


Fig. 2:
$\bar{p}p$-cross sections in the high energy regime. From [2]

3 Top-Quark

Fig. 3 shows the signals for the top quark as measured in 1995 with the CDF- and the D0-detector at FNAL at a cm-energy of 1.8 TeV. The production proceeds via the fusion of two gluons from the proton and the antiproton, respectively, resulting in a cross section as low as $4pb$. It is ten orders of magnitude smaller than the total (hadronic) cross section, but could be extracted by sophisticated triggering on high $p_{\perp}$-events and on secondary (B-meson) vertices.

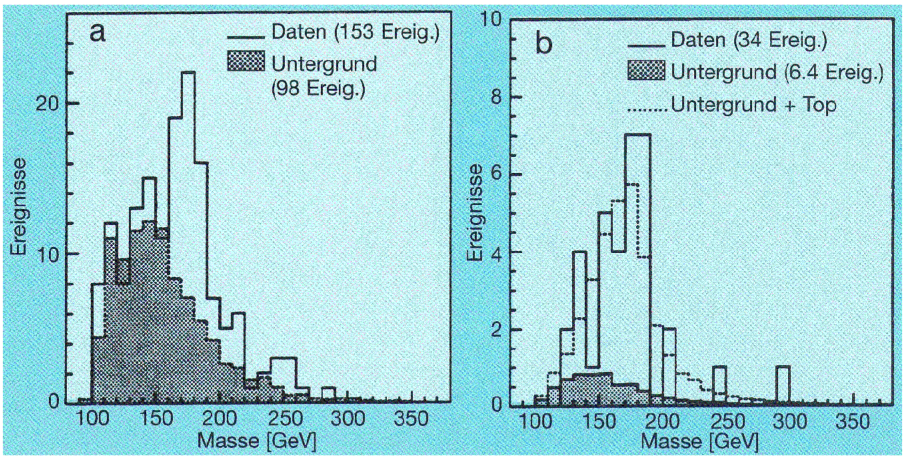


Fig. 3: Signals for the Top-Quark. From [3]

4 Intermediate Vector Bosons $W^{\pm}$, Z^0

Fig. 4 shows $Z^0 \rightarrow e^+e^-$events as seen at CERN in 1983. The $W^{\pm} \rightarrow e^{\pm}\nu$-spectra look similar. The underlying process is the annihilation of a quark and an antiquark to $W^{\pm}$ or Z^0-particles. Again, the process has a very small cross section (nb), but could again be selected by high $p_{\perp}$-triggering.

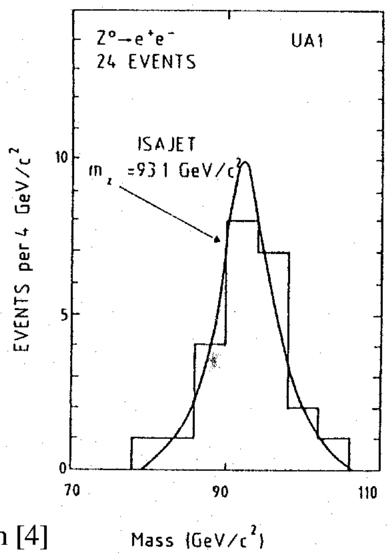


Fig. 4: $Z^0 \rightarrow e^+e^-$ events. From [4]

5 Physics at LEAR

5.1 Low and medium energy $\bar{p}p\,(n)$-reactions

Elastic and charge exchange ($\bar{p}p \to n\bar{n}$) cross sections, angular distributions and sometimes also spin observables have been measured with high precision [5-9]. Originally, these measurements were driven by the search for eventual resonant and bound states near the $\bar{p}p$-threshold, but no convincing signal was seen yet. The interpretation of the data was performed in terms of meson-exchange- and of quark-models. Both methods fit the data well, but do not yet allow a distinction between these alternative descriptions. A lot of effort went into measurements of various annihilation channels. They are accessible from ($\bar{p}p$)-atoms as initial states or from the usual scattering states. Many branching ratios, exhibiting dynamical selection rules and strong *OZI*-violations, were measured with high precision. The interpretation of the data is quite involved because of the non-perturbative nature of the annihilation process and gives hints for further theoretical work.

Particularly well investigated are the channels $\bar{p}p \to \Lambda\bar{\Lambda}$, $\bar{\Sigma}^0\Lambda$, $\bar{\Sigma}^-\Sigma^-$ and $\bar{\Sigma}^+\Sigma^+$. The Hyperon decays are self analyzing, so that polarizations, spin correlations and even spin-transfers could be measured [10]. Very detailed measurements were performed near threshold (Fig. 5). It was observed that - in contrast to pp-reactions - a strong p-wave contribution is present at very low energies and that the Λ- and $\bar{\Lambda}$-spins are aligned to $S = 1$, maybe reflecting a polarized $s\bar{s}$- sea in the nucleon [11].

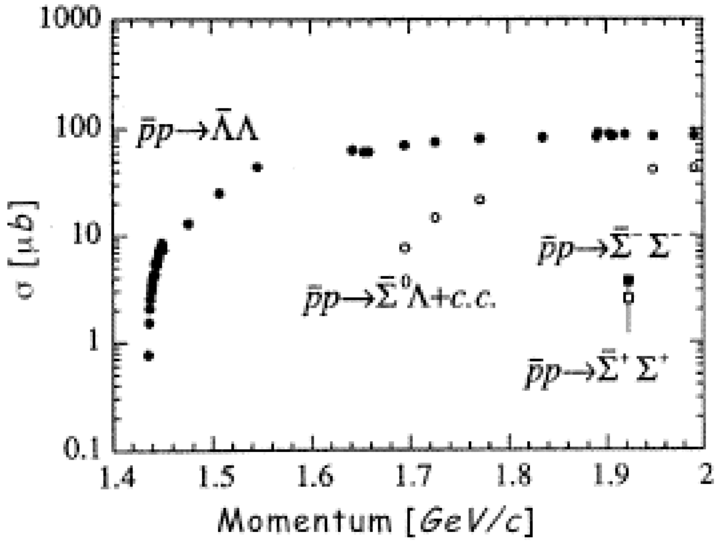


Fig. 5: Cross sections of the reactions $\bar{p}p \to \Lambda\bar{\Lambda}, \cdots$ near their respective thresholds. From [10]

5.2 Antiprotonic X-rays

Light nuclei: The precision in the determination of shifts and widths of atomic $\bar{p}p$-levels originating from the strong and absorptive $\bar{p}p$-force is remarkable. Using the cyclotron trap technique, high resolution crystal spectrometers and CCD's, the spin averaged shifts and widths of the $1s$- and the $2p$- levels could be determined with relative errors of 5 - 10%, resulting in a value of $a_s(\bar{p}p) = (-0.88 \pm 0.03) + i\ (0.67 \pm 0.04) fm$ for the $p\bar{p}$-scattering length [12]. The most spectacular results have been obtained in investigations of the $\bar{p}$-He-system [13]. Here, at higher $\bar{p}$-He energies metastable states with lifetimes in the order of μs exist (Fig. 6). They can be depopulated with laser light of the appropriate energy, thus allowing an unprecedented precision of 0.5 *ppm* for the energy differences. Very stringent tests of calculations in the three-body Coulomb system were possible and eventual mass and charge asymmetries between proton and antiproton were tested with an accuray of 5×10^{-7}.

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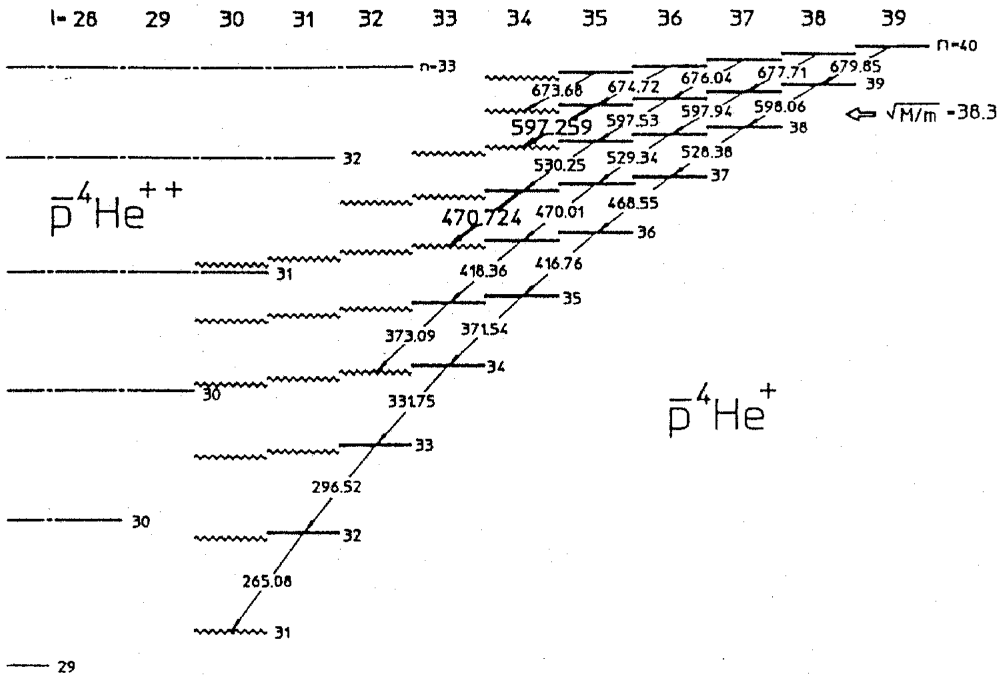

Fig. 6: Level schemes of the $\bar{p}\ {}^4He^+/\bar{p}\ {}^4He^{++}$-systems. From [13]

Heavier nuclei: From X-ray measurements in this regime [14] the most accurate value for the magnetic moment of the antiproton $\mu_{\bar{p}} = (2.8005 \pm 0.0090)\mu_{nm}$ could be extracted. The study of strong interaction effects in the last observable X-ray transitions established clearly the existence of neutron halos in heavier nuclei, e.g. in ${}^{172}Yb$ [15].

5.3 $\bar{p}$-induced nuclear reactions

Low energy antiprotons interact mainly with the nuclear periphery. From the annihilation of antiprotons following the formation of an antiprotonic atom quantitative evidence for neutron halos in various nuclei could be obtained. As expected, the neutron halos extend, as the binding energies of the last bound neutrons decrease [15].

Higher energies antiprotons annihilate in the bulk of a nucleus giving rise to a soft heating of the nuclear matter with possible formation of Δ-matter [16, 17]. The observed particle spectrum can be well described by the INC (Intra Nuclear Cascade) model.

5.4 CP/T/CPT-Tests

The CP-LEAR experiment succeeded for the first time in determining time dependent decay asymmetries for some $K^0/\bar{K}^0$-decay modes, as shown in Fig. 7 for the $K^0/\bar{K}^0 \to \pi^+\pi^-$ decays [18]. The strangeness of the $K^0/\bar{K}^0$ at production time was tagged using the reactions $\bar{p}p \to K^-\pi^+\bar{K}^0$ and $K^+\pi^-\bar{K}^0$. Detecting semileptonic $K^0/\bar{K}^0$-decays ($K^0 \to \pi^- e^+ \nu_e$, $\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$) even allowed the determination of the nature of $K^0/\bar{K}^0$ at the time of its decay, enabling unique experiments [19]. From measurements of decay asymmetries in the reactions $K^0 \to f$, $\bar{K}^0 \to f$ (f = ππ, πππ, ···), the η and ϕ- parameters relevant for CP-violating decays could be measured. The results confirmed other measurements, for the phase ϕ_{+-} the so far most accurate value was obtained.The most spectular results, however, appeared in the semileptonic sector. Measuring decay asymmetries of the kind $\bar{K}^0 \to K^0/\bar{K}^0 \to K^0$ and $\bar{K}^0 \to \bar{K}^0/K^0 \to K^0$ allowed sensitive tests of T- and CPT-violation. CTP-invariance was proven to hold within the experimental errors, but T-invariance is definitely violated. The results show, that CP-violation in K-decays is due to T-violation.

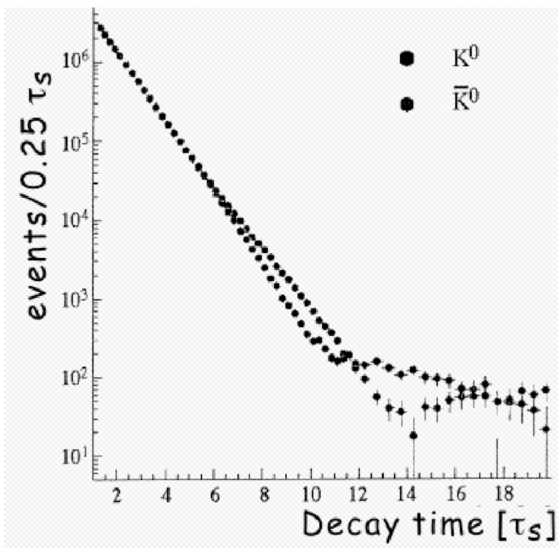

Fig. 7:
$\pi^+\pi^-$-decay rate for K^0-and $\bar{K}^0$-decays. From [18]

5.5 Meson/Exotic Spectroscopy

The field of meson spectroscopy in the mass region up to 2 GeV/c^2 has been revived by the high precision data measured at LEAR. The $\bar{p}p(n)$-annihilation is a copious source for normal $(q\bar{q})$-mesons, but also for glue rich systems, like glueballs (gg-systems, g = glue) and hybrids ($(q\bar{q}g)$-systems) [20]. Nearly all known mesons were seen and confirmed in the three experiments on the floor (Crystal Barrel, Jet Set, Obelix) [21]. In addition a candidate for the glueball ground state ($f_0(1500)$, $J^{PC} = 0^{++}$) [8] was firstly found, and two spin-exotic states ($\pi_1(1400)$, $\pi_1(1600)$, $J^{PC} = 1^{-+}$) have been confirmed with high statistics [22, 23]. The latter can't be $(q\bar{q})$-states, so that definitely a new state of hadronic matter is established. The high accuracy of the data is obvious from Fig. 8, showing a high statistics (700000 events) Dalitz Plot of the reaction $\bar{p}p \rightarrow \pi^0\pi^0\pi^0$ [24]. Indicated is the narrow band showing the candidate for the glueball ground state. Non $(q\bar{q})$-states are produced with rates similar to the usual $(q\bar{q})$-states making $p\bar{p}$-annihilation reactions an ideal tool for further searches for exotic hadrons (see talk of K. Peters at this workshop about the HESR project at GSI).

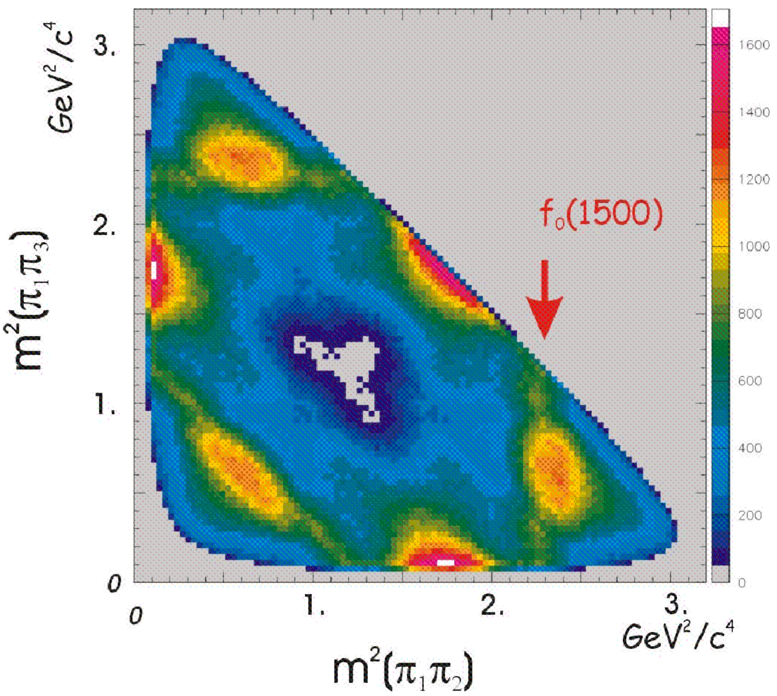

Fig. 8: High statistics Dalitz-Plot of the reaction $\bar{p}p \rightarrow \pi^0\pi^0\pi^0$. From [23]

5.6 Trapped Antiprotons

Low energy (5.4 *MeV*) antiprotons were cooled down at LEAR to energies in the *meV* region and trapped in combined electric and magnetic fields. With highly sophisticated methods the cyclotron frequency of the antiproton could be measured and compared to the one of H^--ions. The precision of the measurement (10^{-10}) is spectacular and allows a comparison between the (*e/m*)-ratio for antiprotons and H^-. Both agree within the extremely small experimental error [25]. At present, these techniques are further developed at AD/CERN with the aim to perform high precision measurements on Antihydrogen (see talk of G. Gabrielse at this workshop).

5.7 Antihydrogen

The first signals for Antihydrogen formation in flight were firstly seen at LEAR [26] and shortly later at FNAL [27]. The positrons are produced by an antiproton reacting with the electric field of a heavy atom (Fig. 9) and form antihydrogen in rare cases. A few antihydrogen atoms were detected via the measurements of their components ($\bar{p}$, e^+) after stripping the $\overline{H}$-atom on a foil, which also acted as detector. A total of 11 events was seen at LEAR, while the Fermilab experiment encountered 67 events.

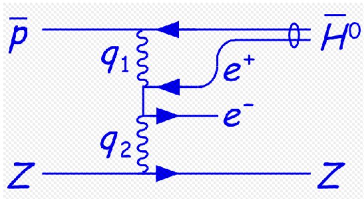

Fig. 9:
Formation of Antihydrogen in Flight. From [28]

6 Conclusion

It is evident that experiments with antiprotons as yet produced a large variety of results of top interest in different fields of nuclear and particle physics. Particularly, in the study of $\bar{p}$-induced reactions in nuclei, in further investigations of gluonic hadronic matter and in experiments on antihydrogen very interesting data are expected also in the future.

7 Acknowledgement

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8 References

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