The actual experiment with negative ions was to measure the lifetime of metastable (autoionizing) beams of negative helium, beryllium and calcium ions, with lifetimes of a fraction of a millisecond. The storage ring replaces the multi-kilometre beamline which would otherwise be necessary for the lifetime measurement.

Also positive beams of the recently discovered giant 'buckyball' C-60 molecule have been stored in ASTRID to investigate the lifetime of excited C-60 ions. This is by far the heaviest ion ever held in a storage ring.

DARMSTADT
Beta decay into bound states

In nuclear beta decay, a neutron decays, emitting an electron and an antineutrino. Nuclear beta decay should also be possible where the resultant electron, instead of being given off, remains bound in the daughter atom. This is the 'time-mirror' process of electron capture by the nucleus.

In the past, analyses of tritium lifetimes have hinted that such atoms can be formed, and now direct evidence comes from using fully stripped dysprosium-163 ions in the ESR storage ring at Darmstadt's GSI heavy ion Laboratory.

Neutral atoms of dysprosium-163 are stable, but fully stripped (66+) ions can beta decay into hydrogen-like atomic levels of holmium-163 66+ (there are only a few cases where this happens). To detect this, up to 10^8 Dy 66+ ions at 294 MeV per nucleon were stored and electron cooled in ESR.

During the storage, the daughter holmium ions, having very similar charge-to-mass ratio as their parents, were stored and cooled on the same orbit. The holmium daughter atoms were monitored using a gas jet to strip their electrons and produce detectable holmium 67+. Independent confirmation came from analysing the Schottky noise of the stored ions before and after their interaction with the gas jet, which showed a significant signal due to holmium 67+.

Although such decays are only of minor importance for neutral atoms, they might play a major role in the astrophysics of highly ionized atoms of stellar plasmas during nucleosynthesis. In some cases, the lifetimes change drastically, from say a few years to 10^{10} years.

WORKSHOP
QCD at 20

The modern theory of strong interactions - Quantum Chromodynamics (QCD), where quarks and gluons carrying the 'colour' quantum number play the essential role, is twenty years old. This birthday was duly celebrated at RWTH Aachen from 9-13 June, where recurring themes were - what has been achieved in the past twenty years?, where do we stand?, and what are the perspectives for the future?

The opening talk by Richard Taylor from Stanford (SLAC) described the high energy physics scene into which QCD was born. He showed how the violent (deep inelastic) lepton-nucleon scattering experiments at SLAC, and subsequently at other Laboratories, revolutionized ideas of hadrons, and he went on to explain how these experiments were inseparably linked to the birth and subsequent development of QCD.

However in the following talk F. Wilczek reminded the audience that many questions which QCD was supposed to answer 20 years ago remain unanswered. As he put it - 'QCD is only half solved'. While we think we understand the short distance regime (asymptotic freedom) where the quark forces are weak, we still lack a good understanding of longer distance effects, in particular when quarks and gluons are 'confined' inside hadrons.

The impressive story of QCD in the short distance regime was unfolded at the workshop by theorists and experimentalists. The structure functions (quark and gluon content) of the nucleon, as measured in various deep inelastic electron, muon and neutrino scattering experiments, are now in very good shape. Previous discrepancies between different measurements seem to be resolved and the kinematic behaviour (violations of Bjorken scaling) are in excellent agreement with QCD (M. Virchaux).

The wide spectrum of hadronic decays of the Z particle obtained at CERN's LEP electron-positron collider are a real bonanza for QCD studies (S. Bethke, J. Drees, B. Webber). In particular, Z decays into four jets open up the gluon self-coupling and its colour structure. Very satisfyingly, the self-coupling of the gluon and its eight colours are now explicitly verified by experiments.

Another important milestone is the experimental demonstration that the strong coupling 'constant' decreases with increasing momentum ('runs') precisely as predicted in 1973 with the discovery of asymptotic freedom, one of the pillars of QCD. Hadron-hadron collisions at high energies provide another QCD testing ground and there too theory generally compares well with experiment (S. Kuhlmann).

The theoretical tool to investigate QCD short distance phenomena is perturbation theory. A. Mueller reviewed its status where various Borel plane singularities like ultraviolet and infrared renormalons lurk to trap the unwary theorist.

Progress was reviewed by G. Altarelli and J. Stirling. For almost all reactions of interest, the next-to-leading-order corrections are known, thanks to heroic efforts by theorists. This allows meaningful extractions of the coupling constant from many hard scattering processes, as summarized by Altarelli. If the various values are scaled to the Z mass for comparison, they are consistent with a mean value at the Z mass of 0.117± 0.007, where the latter figure is a mixture of the experimental error and an educated guess at theoretical uncertainties.

Guido Altarelli - meaningful extractions of the QCD coupling constant from many hard scattering processes.

The transition to the long distance QCD regime, where theoretical understanding is less solid, was taken by E. Reya and E. Levin, who examined the spin structure of the nucleon and quark/gluon densities where a constituent quark carries only a small fraction of the total proton momentum (small Bjorken x). Why does the traditional constituent quark picture of the nucleon come unstuck when trying to explain the spin-dependent quark structure of the nucleon at high energies? Will small x multi-quark/gluon effects be seen in electron-nucleon scattering? Answers will come from the experiments just beginning at DESY's HERA electron-proton collider.

P. Landshoff moved further out in long distance physics, looking at the soft reactions which have only recently started to come under close QCD scrutiny. Here the challenge is to understand simple phenomenological rules, known since the 1960s, in QCD terms.

Deriving the spectrum of hadrons from QCD principles is another perennial theoretical goal. Results from calculations using hypothetical lattices (E. Laermann, R. Kenway, C. Michael) improve slowly but steadily. An example of progress in this sector are the nice results on quark-antiquark binding, which now check with phenomenology. However a milestone still to be reached in these calculations is to have a rho meson heavier than two pions.

QCD also needs glueballs (particles composed of gluons rather than quarks). The experimental search continues and appears to have some new candidates in hadronic reactions (E. Klempt), while the classic iota and theta glueball candidates have a hard time under detailed scrutiny (C. Heusch).

The foundations, successes and limitations of the QCD sum rule approach were reviewed by M. Shifman. Not far from first principle calculations, they have nevertheless become an indispensible tool for correlating various hadronic phenomena in terms of a few 'vacuum condensates'. Indeed the naive picture of the vacuum as being empty was definitely ruled out, at least theoretically, by K. Johnson. In contrast to familiar constituent quarks, he could see no meaning for a 'constituent' gluon.

For massless quarks, the natural chiral (left-right) symmetry of QCD is spontaneously broken by massless pions (as the corresponding Goldstone bosons). At higher temperatures, the chiral symmetry should be restored and the quarks deconfined. The blossoming of chiral perturbation theory, which dates back


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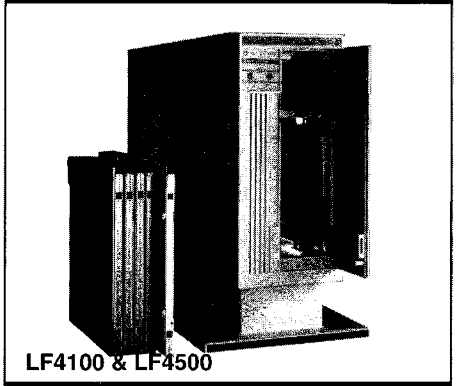
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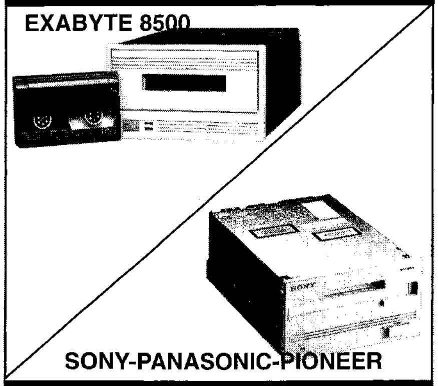
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to the 60s, was described by H. Leutwyler. Among many solid results in this sector, the combination of chiral perturbation and lattice techniques looks a promising way to get low energy hadron physics parameters.

The transition from QCD confinement to deconfinement is still more accessible on the lattice than in laboratory heavy ions collisions. F. Karsch showed exciting hints from lattice simulations for a complicated non-perturbative structure of the quark-gluon plasma near the critical temperature.

Progress in heavy ion collisions was reviewed by H. Satz. Good probes for monitoring the QCD phase transition have now been devised by theorists, and the 'smoking gun' may be provided by the production of the J/psi and related particles.

The future will bring new challenges for QCD. G. Wolf summarized the status of HERA, where a new chapter in deep inelastic scattering is about to begin, with the nucleon structure being explored down to 2x10^{-16} cm.

The long awaited sixth (top) quark, where indirect evidence points to a mass around 130 GeV, should soon show up at the Fermilab Tevatron. Startling new QCD effects are predicted for top physics (J. Kühn) due to the interplay between electromagnetic and strong interactions at these energies. Weak decays of hadrons containing heavy quarks (C. Sachrajda and A. Buras) is another frontier.

John Ellis looked at how QCD could fit eventually into a larger Theory of Everything, and Harald Fritzsch summarized. While QCD has some remarkable achievements to its credit after 20 years, there are still challenging problems to be solved in the next 20 years.

By O. Nachtmann

Looking at the antiworld

A popular pastime among amateur scientific historians is tracing key concepts in twentieth century physics back to their origins. Participants at the Antihydrogen Workshop in Munich on July 30-31 were astonished to hear 1989 Nobel prizewinner Wolfgang Paul mention in his introductory remarks that W. Nernst referred to antimatter as far back as 1897.

Nernst thus 'beat' Dirac by some 30 years, (breaking by a matter of months the previous record, held by A. Schuster's 1898 letter to *Nature*). These historical footnotes enhance Dirac's achievement in demonstrating the existence of antimatter as the price paid for combining quantum mechanics and special relativity.

As every physicist knows, Dirac turned the embarrassing 'redundant' solutions of his relativistic wave equation for electrons to good effect, hypothesising that they corresponded to '...a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to the electron...'. The positron obligingly appeared in 1932, but the discovery of the antiproton had to wait a further quarter of a century, and it was only at that time that the relationship of matter and antimatter was finally seen in terms of the CPT (charge conjugation/parity/time reversal) theorem.

In 1981, CERN began to mass-produce antiprotons, stacking millions of millions of them at a time for physics experiments. A few years later Fermilab too built an antiproton factory.

In spite of all this work with antiparticles, not one atom of antihydrogen has yet been synthesized for study in the laboratory. The enormous strides now being made in cooling, trapping, storing and manipulating charged and neutral particles, as well as in ultra high precision laser spectroscopy should soon change this.

The aims of the workshop were to review progress in these areas, assess the potential of antihydrogen as a test bench for answering fundamental questions of physics, and guide current deliberations on the future of the antiproton programme at CERN.

The workshop attracted some 100 participants from all over the world. The unifying nature of anihydrogen studies was evident in the diversity of their research backgrounds, which ranged from atomic to nuclear and particle physics, from laser spectroscopy to permanent magnet design, and from accelerator physics to cosmology. There were some eleven hours of oral presentations and discussions, as well as 23 posters.

Wolfgang Paul's introduction was followed by R.J. Hughes (Los Alamos) who reviewed the physics potential of high precision atomic spectroscopy of antihydrogen. Seen simply as a probe of CPT, such measurements are capable of reaching with atomic matter the four parts in10^{18} precision given by the neutral kaon system.