Martin zur Nedden

Probing the Formation Process of Matter with Charm and Beauty Quarks

The experiment HERA-*B* at DESY Hamburg is investigating the production of charm and beauty quarks to shed light on the formation process of bound states of quarks within nuclear matter. On the one hand this is an important contribution to test different models describing how quarks form particles, we can observe in experiments. On the other hand, the results of HERA-*B* have a major impact on the interpretation of recent experiments producing a quark-gluon plasma, a new state of matter which exists only at extremely high temperatures and densities like those present in the Universe directly after the Big Bang.

Looking for a Needle in a Haystack – Finding Particles with Charm and Beauty Quarks

In the first half of the 20th century it was shown by Rutherford (1911) that all the mass of an atom is concentrated within the atomic nucleus with a spatial extension of 10^{-14} m. With the discovery of the proton *p* (1919) by Rutherford and the neutron *n* (1932) by Chadwick as the constituents of the nucleus, the periodic system of the chemical elements could be explained by different numbers of *p* and *n* within the nucleus. In the 1950s it became clear that protons and neutrons are not fundamental particles either. Numerous particles were discovered in cosmic ray experiments and at the new accelerators at that time, and the question was raised if there could be an underlying structure. Gell-Mann and Zweig proposed the quark model (1964), where two fundamental quarks, the *up* quark *u* and the *down* quark *d* form the particles as three- and two-quark states, the so-called *hadrons*, while quarks as such could not exist as free unbound particles. At today's reachable spatial resolutions of 10^{-18} m quarks appear still as pointlike structureless particles (see Fig. 1 in [1]). The forces between the quarks are mediated by gluons, whose existence was confirmed experimentally at DESY (Deutsches Elektronen Synchrotron) Hamburg in 1979.

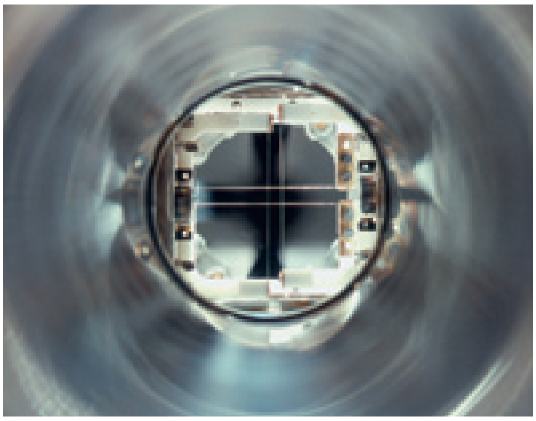

Fig. 2
*View into the beam pipe of the HERA proton accelerator right before the HERA-*B* experiment. Four very thin wires targets (made of Carbon, Titanium, Tungsten and Aluminum) are arranged around the beam line. Each of the wire targets can be moved individually to adjust the total interaction rate with the proton beam. (Source: DESY-PR Hamburg)*

Besides the *d* and *u* quark, there are also two other pairs of quarks with similar properties as the *u* and *d* quark, but with larger masses: the strange (*s*) and charm quark (*c*) and finally the beauty (*b*) and top quark (*t*). These are not stable and decay finally into *d* and *u*. Whereas the mass of the *s* quark is rather small, the masses of *c*, *b* and *t* are bigger than the proton mass. These so-called heavy quarks can only be produced in high-energy processes at accelerators or in cosmic air showers. While the decay processes of quarks are understood at a quite satisfying level, the process, how the bound states of quarks are formed, the *hadronisation*, is not well described yet by theoretical models [1].

An effective method to investigate the formation process of hadronic matter is to look at the generation of hadrons within the matter of nuclei. The nucleus acts then as a so-to-speak detector at the scale of 10^{-14} m. To analyse these processes, the HERA-*B* spectrometer (Fig. 1), making use of the 920 GeV proton beam of HERA (Hadron Electron Ring Accelerator) at DESY Hamburg, was built. Wires with a diameter of ~100 µm of different materials are brought close to the proton beam, which is surrounded by a halo of accompanying protons, to produce deep inelastic scattering of the halo protons with the nuclei of the wire target (Fig. 2). Since the phenomena of hadronisation can be studied best at the mass scales of heavy quarks, HERA-*B* is specialized to search for particles containing *c* quarks like the J/Ψ meson and particles containing a b quark, the so-called B-mesons. These particles are produced very rarely: only one J/Ψ in ~10^6 respectively only one *B*-meson in 10^{10} proton nucleus interactions. Therefore

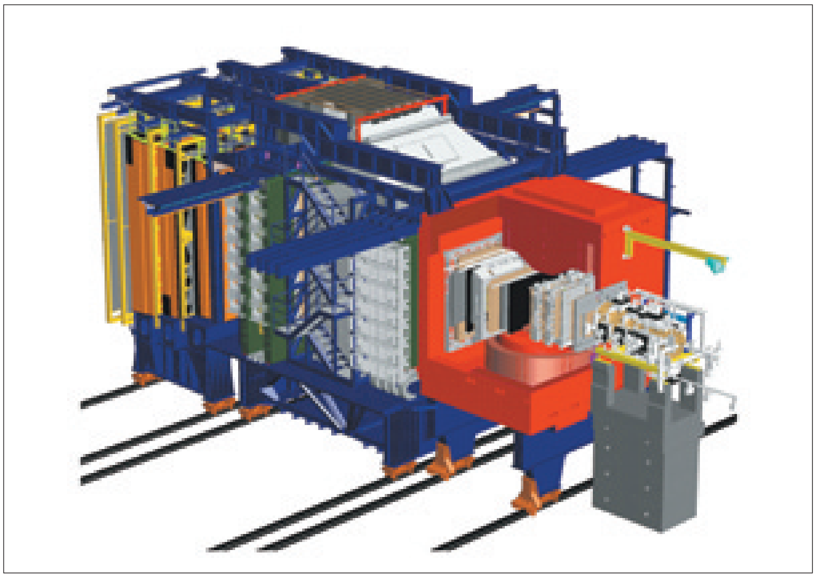

Fig. 1
*The HERA-*B* Detector at the HERA storage ring at DESY Hamburg: in the 6.3 km long storage ring accelerator HERA protons and electrons are brought to very high energies. The experiment HERA-*B* is making use only of the proton beam to investigate the physics of heavy quarks (charm and bottom). The proton beam is entering the experiment from the right side of, where the wire target is placed within a big vessel. The HERA-*B* spectrometer has an overall length of 21 m and an height of about 10 m. The picture visualizes the inner stucture of the bending magnet, where a part of the tracking system is visible.*

the measurements have to be done in the domain of such high particle fluxes, that had not been faced by previous experiments. HERA-*B* was forced to develop new detector and data taking techniques, to enable an experiment at this extreme condition [2].

The Unanswered Question - how Matter is formed out of Quarks

In the HERA-*B* target wires the charmonium particles, consisting of a charm quark *c* and its anti-particle $\bar{c}$, are formed within a nucleus of the target and have therefore to travel a short distance through nuclear matter before being detected in the spectrometer. Different states of charmonia particles could be produced. The charm and anti-charm quark are most closely bound together in the $J/\Psi = |c\bar{c}\rangle$, the lightest member of the family of charmonium particles. More loosely bound are the higher states as the χ_c and Ψ' which have consequently a smaller binding energy. The more loosely these charmonium particles are bound, the more easily they can break apart when they interact with a nucleon on their way through the nucleus. On their way through the nucleus they are obstructed by its constituents, the protons and neutrons consisting out of quarks and gluons. The larger the nucleus, the longer the path of the charmonium particle within the nuclear matter and thus the lower the probability that the charmonium will emerge unscathed. With increasing size of the nucleus, a decreasing fraction of charmonium particles, proportional to the total number *A* of protons and neutrons within the specific nucleus, is expected to emerge. If the proportionality of this fraction does not depend linearly on *A*, this phenomenon is called *nuclear suppression*.

Erforschung des Formierungsprozesses von Materie mittels Charm- und Beautyquarks

Das Experiment HERA-*B* bei DESY in Hamburg untersucht die Produktion von Charm- und Beautyquarks in nuklearer Materie, um fundamentale Einsichten in den Formierungsprozess gebundener Zustände von Quarks zu gewinnen. Damit lassen sich einerseits die zahlreichen theoretischen Modelle testen, die beschreiben, wie Quarks jene Teilchen bilden, die in den teilchenphysikalischen Experimenten beobachtet werden können. Andererseits leistet HERA-*B* einen essentiellen Beitrag zur Interpretation neuester Experimente, die ein Quark-Gluon-Plasma erzeugen. Dabei handelt es sich um einen Zustand der Materie bei extrem hohen Temeraturen und Drücken, wie er etwa im Universum unmittelbar nach dem Urknall herrschte.

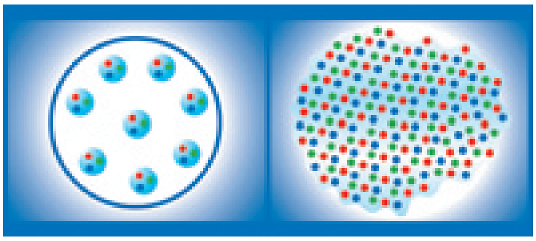

Fig. 3
In ordinary matter, quarks in atomic nuclei are confined within nucleons (left). In a quark-gluon plasma, quarks and gluons are no longer bound but exist as free particles (right). This state of matter has been existing in the early state of the Universe. (Source: DESY-PR Hamburg)

Following the arguments given above, the phenomenon of charmonium suppression should preferentially occur for those particles, which move slowest through the nucleus and therefore remain within the nucleus for a longer time. These particles typically have a low forward momentum leading to large scattering angles with respect to the proton beam direction. Since earlier charmonium experiments as NA48 at CERN (Centre Européenne pour la Recherche Nucléaire) in Geneva (CH) or E771/E789 at FNAL (Fermi National Accelerator Laboratory) in Chicago (USA) were restricted to small angles, HERA-*B* has access to an up to now uncovered range of scattering angles.

The Unexplored state of Matter – Quark Gluon Plasma

The interaction of a charmonium particle with nuclear matter explores numerous unresolved questions in nuclear and particle physics. But also for cosmology, the results of HERA-*B* are interesting. Since quite some time, several experiments have been searching for the quark gluon plasma, a state of matter comparable to the early state of the Universe, 10^{-6}s after the Big Bang (Fig. 3). According to our present understanding, quarks and gluons existed then as free particles before condensing into bound states forming nucleons, nuclei and consequently atoms as the Universe cooled down. At CERN (experiment ALICE) and at the Brookhaven National Laboratory BNL (USA) at the heavy ion collider RHIC, experiments are currently performed to create a quark gluon plasma in high energy heavy ion collisions. The creation of a plasma can only be inferred indirectly. One possibility to look for the appearance of a quark-gluon plasma is based on the observation of nuclear suppression of charmonium states, which HERA-*B* is able to study in detail. The rate at which J/Ψ's are created in a particle collision would be noticeably reduced by the presence of a quark-gluon plasma. Before the $\bar{c}$ and c quarks form a charmonium state, they interact with the plasma and are thus no longer available for particle formation. This phenomenon can be explained by the fact that the binding forces between $\bar{c}$ and c quarks in a quark gluon plasma are too weak to form charmonium states. Therefore, it is inevitable to understand first exactly the principle of charmonium suppression in conventional nuclear matter

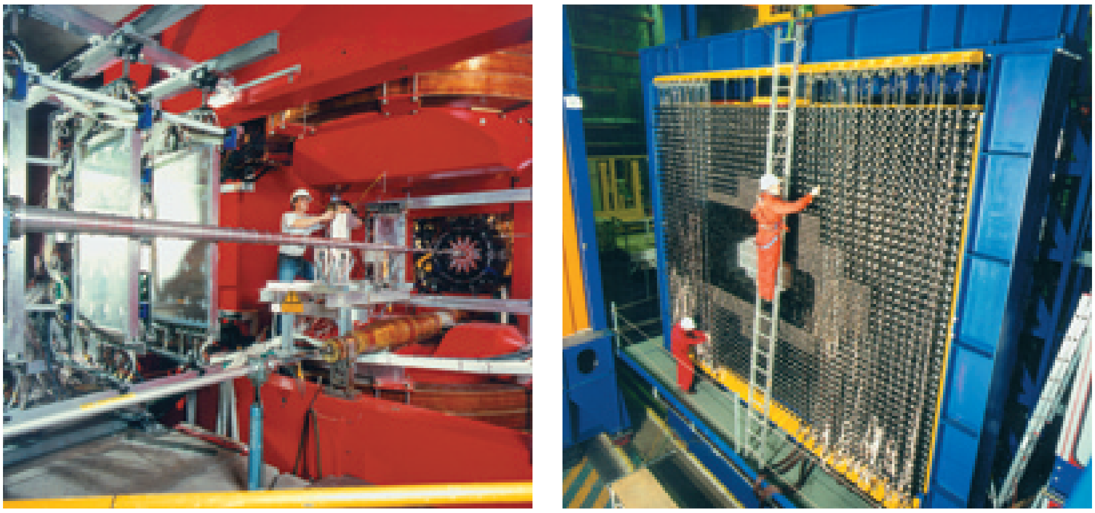

Fig. 4
The left picture (taken during the construction of the detector) shows the proton beam pipe (in the center of the picture) and the first detector components for the particle track measurement. In the electromagnetic calorimeter (ECAL, right picture) with a height of 5 m and a width of 6 m, the energy of electrons and photons is measured and these particles are identified. The proton beam direction is from the right to the left in both pictures. (Source: DESY-PR Hamburg)

before a physical interpretation of quark-gluon plasma experiments can be developed. The measurements of HERA-*B* are important to ensure that the charmonium suppression is due to the quark-gluon plasma and not the absorption of charmonium in nuclear matter.

New Technology to See New Things – the HERA-*B* Experiment

HERA-*B* was specially constructed to measure J/Ψ particles, originating either from a direct production at the targets or from the decay $B^0 \rightarrow J/\Psi$ + anything. The latter decay is the most important decay channel to study beauty quarks with the HERA-*B* spectrometer. Since the production of J/Ψ or *B*-mesons is extremely rare the detector must process a tremendous

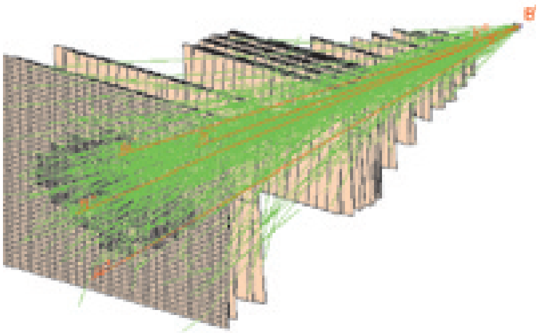

Fig. 5
The simulation of the production of a B*-meson in an inelastic proton nucleus scattering process demonstrates the extremely high occupancy in the HERA-*B *particle tracking detectors, posing extremely high requirements as for the radiation resistance of the detectors and the data taking system.*

amount of particle tracks before one of these interesting decays occurs (Fig. 5). The data flow that HERA-*B* was designed to deal with every second during data taking is similar to the entire flow of information in the network of the *Deutsche Telekom*. This huge particle flux poses a challenge for the electronic data processing system and the radiation resistance of the detector components.

All techniques and methods necessary to do an experiment under such extreme conditions did not exist when HERA-*B* was approved in the mid-1990s, therefore the collaboration had to develop entirely new technologies. Accordingly, a particle detector was developed and built that offered an unprecedented degree of radiation resistance, while also new high-speed electronic data processing methods where designed and realized. In both areas, HERA-*B* did pioneering work that has important impact on future experiments at other facilities like the Large Hadron Collider (LHC) at CERN, where experiments with similarly extreme conditions are currently under construction.

Recent Results from HERA-*B*

Since the charmonium states have a very short life time, only their decay products can be measured in the detector. One of the most prominent decay channels of charmonia is into two charged leptons, either into two electrons (e^+e^-) or two muons ($\mu^+\mu^-$). With the HERA-*B* detector it was possible for the first time to register both decays in the same detector. This is important to increase the statistics and to cross-check the results. Furthermore, the special topology of this J/Ψ decay was used to separate these events during data taking from the background. The electrons are identified and measured in the electromagnetic calorimeter ECAL presented in Fig. 4 (right part) and the muons in the μ-chambers at the downstream end of the HERA-*B* detector (see Fig. 1). Since there are various target materials available, this allows simultaneous measurements of different target materials.

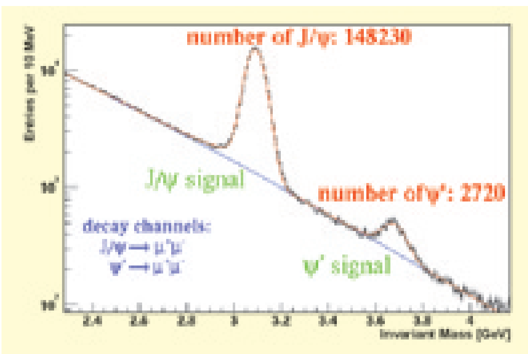

Fig. 6
The invariant mass spectra of events containing two muons originating at the same space point. The two peaks correspond to the J/Ψ and Ψ' events.

In Fig. 6 the reconstructed J/Ψ and Ψ' signals collected in the $\mu^+\mu^-$ decay channel from the data taking period of 2002/03 are presented. Due to the geometrical acceptance of HERA-*B* the unexplored kinematical regions at large angles can be studied now in detail. Recently the nuclear suppression of the J/Ψ production and the dependence of the production probability of several charmonia states on various kinematical variables could be measured for the first time. These measurements constrain theoretical models and others may even be ruled out completely.

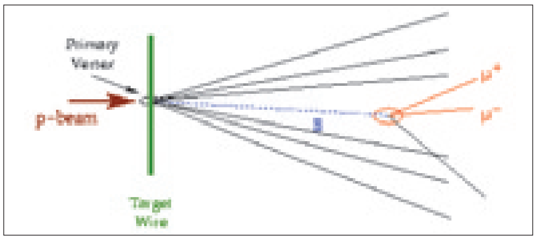

Fig. 7
A beam proton hits the wire target producing a B*-meson, which decays after an average decay length of DL ≈ 8 mm. This measurement is only possible, if the spatial resolution $\sigma\Delta_z$ is much smaller than the decay length. Since the resolution for Δz in the HERA*-B *experiment is ≈ 500 µm, which is much smaller than DL, a reliable measurement of DL is guaranteed.*

In the inelastic proton nucleus scattering, not only charm quark pairs are occasionally produced, but also the about 3 times heavier beauty quarks. They hadronise immediately to a *B*-meson, but their lifetime ($\tau \approx 1.5 \cdot 10^{-12}$ s) is large enough to measure the flight path before its decay (Fig. 7). Since *B*-mesons are decaying also into *J/Ψ*'s, this decay channel can be measured quite effectively with the HERA-*B* detector. To identify *B*-mesons on top of the *J/Ψ* selection, a minimal decay length Δz, defined as the distance along the beam axis between the production site of the *J/Ψ* and the target wire, is required. Using this very effective selection method, the production ratio of *B*-mesons to *J/Ψ* mesons is measured and found to be about $2 \cdot 10^{-4}$ as mentioned in the first section. Despite the good theoretical description of charmonium production in various experimental environments, the description of the production of *B*-mesons is still not satisfactory. While the dependence of the production probability on kinematical variables is usually reproduced quite well, the absolute values are still in disagreement by factors of 2 to 7 [3]. Although new theoretical calculations reduced the discrepancy, they still contain large uncertainties and consequently the measurement and the expectations from theory are not yet in good agreement [4]. This emphasizes the need of a precise measurement of the production probability to clarify the situation. The existing measurements from experiments at FNAL (E789 [5] and E771 [6]) suffer from large statistical errors and poor compatibility with each other. The newest and accurate measurement of HERA-*B* is therefore an important contribution to reduce the uncertainties within the models.

Members of the HERA-B group
Prof. Dr. Hermann Kolanoski; Prof. Dr. Thomas Lohse; Sergeij Shuvalov, PhD.

Although the standard model does not exclude particles with more than three quarks, such states have not been found until recently. In 2003, several experiments [7, 8, 9, 10] claimed to observe new types of particles with five quarks, the so-called pentaquarks. Recent experimental evidence suggests not only that pentaquarks exist, but also that the fact of their production is common to all types of high-energy collision. Since HERA-*B* has, in addition to the charmonium data sample, a unique huge sample of not preselected inelastic proton nucleon collisions with various targets (Carbon, Titanium and Tungsten), a search for pentaquarks was performed. In $2 \cdot 10^8$ inelastic events no evidence for pentaquark production in proton nucleus scattering was found and an upper limit for the production probability could be derived. This is an interesting result in particular in combination with the results from other high energetic particle reactions. Why are pentaquarks states produced in some types of high-energy particle collisions, but not in others? Are pentaquarks susceptible to interactions inside the nucleus suppressing their production in proton nucleus collisions? What are the implications for the production mechanism? The answers are currently unknown, but a new window to exciting particle physics might have opened up.

HERA-*B* has stopped data taking last year and the collaboration is in the phase of data analysis. The measurement of nuclear suppression, production ratios of chamonium states, and the measurement of production probability of *b* quarks and pentaquarks, presented in this article, are only some selected highlights of the rich physics outcome of HERA-B.

References

[1] *Pavel, N.*: Deeply Probing Quarks and Gluons, this Humboldt-Spektrum ((3–4/2004).
[2] *Kolanoski, H.:* The Eye of an Experimental Particle Physicist, this Humboldt-Spektrum (3–4/2004).
[3] *Salam, G.P.:* hep-ph/0207147 (2002).
[4] *Frixione, S.*: proceedings of Int. Eur. Conf. on High Energy Physics, in hep-ph/0111368, 2001.
[5] *Jansen, D. M. et al.*: (E789 Coll.), Phys.Rev.Lett. 74(1995)3118.
[6] *Alexopoulos, T. et al.*: (E771 Coll.), Phys.Rev.Lett. 82(1999)41.
[7] *Nakano, T. et al.*: (LEPS Coll.), Phys.Rev.Lett. 91(2003)012002.
[8] *Kubarovsky, V. et al.*: (CLAS Coll.), Phys.Rev.Lett. 92(2004)032001.
[9] *Airapetian, A. et al.*: (HERMES Coll.), Phys.Lett. B585(2004)213.
[10] *Chekanov, S. et al.*: (ZEUS Coll.), Phys.Lett. B591(2004)7.

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