Report on the session “SPS Hadrons and Ions” at the workshop *New Opportunities on the Physics Landscape at CERN*.

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1.) Hadron Physics

1.1) Introduction

Hadron physics aims at a fundamental understanding of all bound and resonant systems and their interactions that are subject to the strong force. The theory of the strong interactions, quantum chromo-dynamics (QCD), is conceptually quite simple: it is a relativistic quantum field theory of quarks and gluons interacting according to the laws of non-abelian forces between colour charges. It is an integral part of the Standard Model of particle physics.

The deceptively simple looking QCD Lagrangian is at the basis of the rich and complex phenomena of hadronic and nuclear physics. How this complexity arises in a theory with quarks and gluons as fundamental degrees of freedom is only qualitatively understood. It is one of the great challenges of contemporary physics to understand the key feature of QCD, the confinement of quarks and gluons. As a consequence of confinement, information about quarks and gluons can only be obtained through investigations of hadronic systems – mesons, baryons and possibly exotic states – their production, decays and interactions. The important questions deal with the very existence and the properties of hadrons. How does nature form the observed hadrons? Does QCD generate – so far undiscovered – exotic structures? New experiments have to address these issues, like the PANDA experiment at FAIR and GlueX at Jefferson Lab.

In the macroscopic world, QCD manifests itself through the underlying symmetries, chiral symmetry for the light (*up*, *down*, *strange*) and heavy quark symmetry for the heavy quarks (*charm*, *bottom*). Chiral symmetry is explicitly and spontaneously broken. The explicit breaking is a trace of the Higgs mechanism that leads to the small but finite quark masses. However, most of the hadron mass is given in terms of QCD field energy. A precise understanding of the generation of mass is one of the key problems in QCD. The spontaneous breaking of chiral symmetry severely constrains the interactions of the hadrons in the regime of large quark-gluon coupling (strong QCD). This can be analyzed in terms of suitably tailored effective field theories (EFT), which are controlled by the chiral and heavy-quark symmetry of QCD but also in part by additional symmetries of QCD that arise in the limit of a large number of colours (N_c).

One key problem of QCD is to understand its spectrum. Most observed states could be understood as conventional mesons (quark-antiquark) or baryons (3 quark composites). However, the theory also predicts glueballs, states entirely made of the QCD gauge bosons and also more exotic forms of matter, like tetra- or penta-quarks or hybrids composed of quarks and gluons. There are some indications for the existence of such states in the light-quark sector, but the overall picture remains puzzling. The important step is to identify exotic states in the heavy quark sector, where mixing of states is considerably smaller, predictions are more precise, and therefore interpretations are less ambiguous. This field has experienced a dramatic revival in the last few years due to the appearance of the so-called *X*, *Y*, *Z* states observed at BaBar, Belle, BES and CLEO. These observations further prove that our understanding of QCD is in many respects only marginal and shows the need for more refined and "surgical" experiments to eventually unravel the nature of these states and the true spectrum of QCD. Unfortunately no proposal was presented which focuses on these important issues.

1.2) Summary of the talks

Fixed target hadron spectroscopy (Jan FRIEDRICH), Abtracts [58+60]

a) Doubly Charmed Baryons

Spectroscopy of baryons with heavy quarks adds complementary information on understanding strong interactions. Heavy quark offers an important advantage as they constitute a static source of color to all other quarks. Experimental evidence for doubly charmed baryons is still very weak as they only have been observed at a hyperon beam experiment at FNAL (SELEX), produced relatively copiously. COMPASS offers a modern high rate spectrometer, a prerequisite for such studies.

Baryons with single charm or beauty quarks have been studied in recent times and in the case of charmed baryons many excited states have been identified, partially with surprising results (see heavy Lambda_c at a mass of about 2600 MeV/c^2). Baryons with two heavy quarks offer an interesting extension to this field of research, as the structure of the ground state looks meson like with a single light quark feeling a quasi static color charge in the center similar to a B-meson . Excited states may show vibrational and rotational structures of the heavy pair in addition to the excitation of the light system, thus being quasi molecular. Experimental evidence for such states is still very weak as they only have been observed at a hyperon beam experiment at FNAL (SELEX), produced relatively copiously. Mass splitting and lifetimes observed deviate from expectations and are not really understood. As such states have not been observed in photo- nor simple hadro-production it is intended to repeat the experiment with high energy hyperons using the COMPASS spectrometer. COMPASS offers a modern high rate spectrometer, a prerequisite for such studies. The drawback of it is the maximal energy at the SPS of only 400 (450) GeV/c offering at most 350-400 GeV/c hyperons impinging on a target as compared to 600 GeV/c at SELEX. If the cross sections of FNAL can be confirmed, COMPASS should produce doubly charmed baryons copiously, allowing also studying the excitation spectrum of theses states.

b) Crucial Tests of chiral perturbation theory

The SPS-M2 beam line offers a unique possibility for essential tests of chiral perturbation theory, particularly by measuring the pion (and kaon) polarisabilities and the chiral anomaly amplitude.

Scattering high-relativistic charged pions in the Coulomb field of nuclei denoted the Primakoff effect, accesses (quasi-real) photon-pion reactions with different final states. Apart from the scattered charged pion, a real photon, or one or more neutral pions are produced. The first process, effectively pion Compton scattering, is a clean way to determine the leading-order threshold deviation from the structure less QED cross section, parameterized in the pion polarisabilities. Those play a key role in understanding the standard model low-energy expansion of QCD (chiral perturbation theory, ChPT). This test of ChPT can be extended to kaons if an appropriate beam is available. A single neutral pion produced via the Primakoff effect violates natural parity in the process, parameterized in the chiral anomaly amplitude, for which ChPT also provides a firm prediction, to be tested experimentally. Equivalently, double neutral pion production, allowed in ChPT at tree level, constitutes a test of pion-

pion scattering at low energy. At the adjacent region of higher center-of-momentum energies, resonances formed in pion-photon scattering, including exotic candidates, can be studied. The measurements require pion and kaon beams and a spectrometer with high rate capability and excellent electromagnetic calorimetry, which are available with the unique SPS-M2 beam line and the COMPASS spectrometer. Here the possibility to switch rapidly from a pion/kaon beam to a muon beam offers a unique possibility to directly compare point-like and extended particles.

More intense and energetic muon and hadron beams for nucleon structure and spectroscopy (Fabienne KUNNE), Abtract [92]

Fundamental QCD questions could be answered only at COMPASS with a substantial increase of luminosity of the muon beam, and of the energy of both the muon and hadron beams. Higher energy polarized ep collider will not be built before 10 or 15 years, and CERN has a major role to play meanwhile. Since the topic of hadron structure is discussed elsewhere, the summary contains only the hadron part.

Some of the important physics channels using hadron beams within COMPASS require highest possible energies from the SPS. These comprise central production of hadron resonances, where central production and diffractive production can only be separated kinematically. The central production process is governed by double region exchange and Pomeron-Pomeron scattering, the fraction of which is strongly energy dependent, where the latter one raises with energy. The second topic is connected with the installation of a hyperon beam inside the north area to study doubly charmed baryons. High energy boosts the decay length and thus yield of hyperons extracted from a double bent channel. In addition, charm production cross sections are strongly energy dependent at low center of mass energies, thus the gain in yield of doubly charmed baryon seems substantial. At present, the COMPASS beam line can only transport 270 GeV/c beams, mostly connected with power supplies of the magnets installed. It is desirable to increase the energy up to 450 GeV/c, the highest one available from SPS.

Scientific plans of the DIRAC experiment beyond 2010 (Leonid NEMENOV), Abtract [76]

The main task of the DIRAC experiment is to check precise predictions of low-energy QCD using ππ and πK atoms. At present, theory predicts the ππ s-wave scattering lengths with a precision of 1.5% for |a0-a2| and about 2.5% for a0 and a2. The theoretical uncertainty is mainly determined by uncertainties on two constants of ChPT. At present, the precision of ππ scattering lengths measurements is a few percents worse than the theoretical precision. For this reason, improving the experimental accuracy is an important task. The experimental data collected by DIRAC in 2008 and 2009 will allow reaching the precision of about 2.5% for |a0-a2|. The low-energy QCD predicts πK scattering lengths with a precision of about 10% and direct measurements of the πK phases do not exist. The DIRAC experiment plans to observe πK atoms using data collected in 2007-2009 and to measure the lifetime of these atoms and, hence, to obtain the first evaluation the s-wave scattering length combination |a1/2-a3/2|. In 2009, a request is planned for a data-taking run in 2010 with the aim of observing the long-lived states of ππ atoms. This experiment can be performed with the existing setup without modifications, neither of detectors nor of electronics. Further data taking will allow us to obtain experimentally a value of the Lamb shift ΔE(2s-2p) in this atom. From the data to be collected in 2008 and 2009, it will be possible to observe the Coulomb enhancement in the production of K^+K^- pairs, and thus to determine, in a model independent way, the number of K^+K^- atoms produced at the same time. This analysis will allow us to estimate the feasibility to observe these atoms and to measure their lifetime. The 2008-2009 data will also allow us to search for the

Coulomb enhancement in the production of πμ pairs and thus to determine, in a model-independent way, the number of πμ atoms produced. New possibilities to check the predictions of the low-energy QCD would be available after the installation of the DIRAC setup on the 450 GeV SPS proton beam. Simulations show that the number of detected ππ atoms will be 15 times higher than the one at 24 GeV, the number of $K^+\pi^-$ atoms 25 times higher and the number of $K^-\pi^+$ atoms 32 times higher. This enhancement in atom yields allows obtaining simultaneously |a0-a2| with a precision of about 1.5% and about 5% for |a1/2-a3/2| within 12 months of data taking. The measurement of the Lamb shift in ππ and πK atoms would take another run. These results would provide the crucial check of low-energy QCD predictions. Migration from PS to PS2 with the 50 GeV beam would also provide a significant gain in the mesonic atom production. The required statistics and achievable accuracy are under investigation.

2.) Heavy Ion Physics

2.1) Introduction

Large experimental and theoretical efforts worldwide are devoted to the investigation of strongly interacting matter under extreme conditions. The goal of these activities is to explore, in the laboratory, the properties of such matter as function of temperature and density. The conditions probed range from dense and relatively cold nuclear matter, as present in core-collapse supernovae and in the interior of compact stars, to matter at the highest temperatures accessible in heavy-ion reactions, where hadrons melt, releasing the elementary building blocks, thus forming quark-gluon plasma as it existed in the early universe. To date there are no conclusive predictions for the properties of the phases of strongly interacting matter from QCD. The non-perturbative nature of the strong interaction has so far prevented an *ab initio* description of nuclear and quark-gluon matter in a major part of the nuclear phase diagram.

The experiments address fundamental aspects of strong interaction physics such as the equation-of-state of nuclear matter, the phase transition from hadronic to partonic matter, the structure of hot and dense quark-gluon plasma, and the restoration of chiral symmetry as well as its relation to the origin of hadron masses and their modification in a hot and dense medium. From the explorative measurements at the SPS and the eight years of systematic investigations at RHIC it is evident that a new state of matter is formed in such experiments. From a careful analysis of the emission pattern of produced particles, it is concluded that this matter forms a nearly perfect liquid and not the long conjectured weakly interacting gas of quarks and gluons. The particle yields and event-by-event fluctuations measured in heavy-ion collisions exhibit intriguing features at low SPS energies, which have been interpreted as signatures for the onset of deconfinement. However, in order to draw firm conclusions a more precise and comprehensive data set is required.

The upcoming heavy-ion experiments with ALICE at the LHC will form quark gluon matter with much higher initial temperatures and over substantially larger space-time volumes than previously achieved. The high beam energy will enable full exploitation of hard probes like jets and heavy quark production. The initial temperature may be high enough to observe a transition from a strongly interacting liquid-like state to weakly interacting plasma of quarks and gluons.

Hadronic and partonic matter at the highest baryon densities will be probed with unparalleled precision with the Compressed Baryonic Matter (CBM) experiment at FAIR. The goal of the CBM research programme is to explore in detail the QCD phase diagram in the region of large baryon-chemical potentials. Any new development has to be viewed within this framework. Nvertheless less exclusive measurements with lower statistics may be conducted before FAIR is finalized.

2.2) Summary of the talks

Critical Point and Onset of Deconfinement - Ion Program of NA61/SHINE at the CERN SPS (Marek GAZDZICKI), Abstract [47]

The NA61/SHINE experiment at the CERN SPS aims to discover the critical point of strongly interacting matter and study properties of the onset of deconfinement. These goals will be reached by measurements of hadron production properties in nucleus-nucleus, proton-proton and proton-lead interactions as a function of collision energy and size of the colliding nuclei. Furthermore, NA61/SHINE will perform numerous precision measurements needed for neutrino (T2K) and cosmic-ray (Pierre Auger Observatory and KASCADE) experiments. This contribution summarizes physics arguments for the NA61/SHINE ion program and presents the status and plans of the experiment for the next 5 years.

Rare probes of Quark-Gluon Matter (Marco VAN LEEUWEN), Abstract [41]

The goal of high-energy heavy ion experiments is to study strongly interacting matter at high density and temperature. The expected transition from a hot hadron gas to a deconfined Quark Gluon Plasma is of particular interest in this context. Indications so far are that this transition already takes place in fixed target experiments at 30-60 AGeV beam energy, which in the SPS energy range. A high-statistics measurements of two low cross section observables in Pb+Pb collisions is suggested ro investigate open charm production and high-pt di-hadron correlations. They have provided significant insight at higher energies (RHIC, sqrt(s)=200 GeV). This should be done at two SPS energies: one above and one below the expected deconfinement phase transition. Exploratory di-hadron measurements at SPS have found a transition from correlation structures very similar to those found at RHIC at the highest SPS energy (158 AGeV) to a striking depletion of the 'near-side' structure at the lower SPS energies (20 and 30 AGeV). Also a more detailed study of this transition is planned to unravel its origin. A data sample of 50-100M events which can be collected in two dedicated runs (one at each energy) of about 3 months with the NA61 experiment would represent a significant (factor 10-100) increase of the currently available data sample. Charm production is a good probe of hot QCD matter because the mass of the charm quark is much larger than the expected temperatures of the medium, so that charm quarks are expected to be dominantly from hard scatterings between initial state partons in heavy ion collisions. Measurements of yields and spectra will provide unique new insight in the nature of the hot QCD matter at SPS. So far, no direct charm measurement has been performed at SPS.

Reflections about EXChALIBUR, the exclusive 4pi detector (Gyoergy VESZTERGOMBI), Abstract [17]

EXChALIBUR stands for EXClusive HAdron and Lepton Instrument for Basic Universal Research. The goal is to identify the technical limits in the quest for the ideal particle physics detector within 5 to 10 years. The aim of this detector is to provide full 4pi coverage which can be assured only by fixed target arrangements, by definition. This proposal is an implicit continuation of large acceptance detectors as NA61/SHINE at SPS and CBM at FAIR. The detector should be able to record and reconstruct in full phase-space particle types: gamma, electron, muon, pion, charged K, K_S, proton, neutron (together with K_L), deuteron, lambda (K_S, $Omega^-$). Due to the insolvability of QCD explicit solution for any hadron-hadron or lepton-hadron process are missing. Much of the knowledge in experimental QCD is based on inclusive measurements, which of course gives only the fraction of the possible information. The real understanding of the code came after "exclusive" mapping along the chain, where we are now. The SPS energy range is full of mysteries which were completely forgotten after the closure of ISR. Due to the fact that in this region the multiplicities are still relatively modest one have more chance to identify characteristic features.

Search of the QCD critical point: study of dimuon pair production at the SPS in the energy range 40-160 GeV/nucleon (Gianluca USAI), Abstract [91]

This presentation summarizes first ideas on a new NA60-like experiment, focusing on the required detector changes. After completion of its physics program in 2004, the apparatus and in particular the large muon spectrometer, based on a toroidal magnet and various sets of MWPCs, is still standing in the high-luminosity ECN3 hall. The possibility to re-use some of the still in-place detectors will be discussed together with the possibility to use a new beam line in a different location.

The detection of lepton pairs played a very important role in the study of strongly interacting matter at high temperature and/or baryon density in ultra-relativistic heavy ion collisions since the very beginning. Fundamental achievements, as the discovery of anomalous J/psi suppression and the study of the low and intermediate mass continuum connected with chiral symmetry restoration. As of today (beginning of 2009), the field is expected to evolve in two different directions. Despite LHC, the study of the QCD phase diagram remains almost unexplored in the region of moderate temperature and high baryon density. In this regime, lattice QCD studies foresee the occurrence of a critical point. The search for such a critical point largely motivated the fixed-target CBM experiment at the forthcoming FAIR facility, with a maximum beam energy of about 40 GeV/nucleon. It would be extremely interesting to extend the lepton measurements made by the NA60 experiment at the CERN SPS by performing an energy scan from the SPS topmost energy down to 40-50 GeV/nucleon, close to the maximum FAIR energy. This would permit the study of leptonic observables in a region of increasing baryon density, close to the possible position of the QCD critical point. The theoretical description of this region, in terms of phenomenology of leptonic probes, is still at a rather preliminary stage. The leptonic yield should be considerably enhanced at lower energies. A pioneering measurement performed by CERES at 40 GeV/nucleon indeed seems to suggest this trend. Another key observable, J/psi suppression, exhibits a threshold- like behavior at top SPS energy, when studied as a function of the centrality of the collision. The extension of its systematic study towards lower energy could reveal detailed information on the nature of the observed threshold behavior, and allow a more direct connection with the underlying physics mechanism.

3.) Acknowledgement

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