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40 years of development of Quantum Chromodynamics

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ABSTRACT BOOK

PLENARY SESSION

Spin Structure Functions from the Deep Inelastic Scattering

Seonho Choi

Seoul National University, Seoul 151-747 Korea

The Quantum Chromo-Dynamics(QCD) governs the quarks and gluons which form the nucleons. One of the most interesting features of the QCD would be the modification of the coupling constant as a function of the *scale* in which the observations are made. For example, at very small scale, the coupling constant (α_S) converges to zero producing so-called the asymptotic freedom, which enables the application of the usual perturbation method to the system of quarks and gluons. However, at large scale, the coupling constant gets large enough so that the perturbation calculation no longer converges, creating the non-perturbative region.

One of the important goals of modern nuclear physics is the understanding of the QCD at every scale, from perturbative to non-perturbative region. Using the dual nature of the length and momentum, the perturbative region corresponds to the high momentum scale with the non-perturbative region to the low momentum scale. Explaining the spin structure of the nucleon in terms of those of quarks of gluons is a key test of our knowledge of the QCD.

While the perturbative QCD is the natural choice at very high Q^2 region, in Q^2 region covered by the various experiments, one of the most successful tools have been the formalism of the Operator Product Expansion[1, 2] (OPE) where the corresponding operators for physical processes can be expanded in terms of the increasing order of the coupling constant, α_S. The OPE has produced several QCD sum rules at large momentum scale, most of which are well verified experimentally. However, at small Q^2 region, the theoretical tools are quite limited. At exactly $Q^2 = 0$ point, we can rely on another QCD sum rule. Just above $Q^2 = 0$, the chiral perturbation theory (χPT) can be used up to $Q^2 \simeq m_\pi^2$. In the intermediate region, the lattice QCD calculation may be the only available method.

At Jefferson Lab, an extensive spin physics program has been carried out to measure spin structure functions of neutrons and protons at various momentum scales. Using polarized electron beams on polarized nucleon targets (NH_3 for the proton, ND_3 or ^3He for the neutron), the spin structure functions g_1 and g_2 were extracted from $Q^2 \sim 0$ to $Q^2 = 5$ or 6 GeV^2 range. From these spin structure functions, a few QCD sum rules have been tested with the most surprising results for the spin polarizabilities, γ_0 and δ_{LT}[3].

Still, a new experiment or analysis of the data taken in earlier experiments are in progress. The presentation will give a short overview on the existing measurements of the spin structure functions and then more emphasis will be given to the new experimental results from Jefferson Lab.[4, 5] The future of the spin structure of the nucleon in connection with the Generalized Parton Distributions and the transversity will be mentioned briefly.

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The muonic hydrogen Lamb shift and the proton radius

Antonio Pineda [a)]

[a)] Grup de Física Teòrica, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain

Recently the muonic hydrogen lamb shift has been measured with unprecedented accuracy [1], allowing for a precise determination of the proton radius. This determination is 5 sigma away from the previous CODATA value [2] obtained from (mainly) the hydrogen lamb shift and the electron-proton scattering. Within an effective field theory formalism [3], I will define the proton radius [4] and briefly review [5] some aspects of the theoretical prediction for the muonic hydrogen lamb shift, studying both the pure QED-like computation and the hadronic effects.

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Form factors from lattice QCD

Dru Renner

Jefferson Lab

Precision computation of hadronic physics with lattice QCD is becoming feasible. The last decade has seen high-precision calculations of many simple meson properties and the last few years have seen precision calculations of baryon masses. As computational power continues to increase, the next few years should see the first precise calculations of a variety of more demanding hadronic properties. With this in mind, I will discuss current lattice QCD calculations of generalized parton distributions with an emphasis on the prospects of well-controlled calculations for these observables as well. I will do this by way of several examples: the pion and nucleon form factors at low Q^2 and the lowest x-moment of the nucleon parton and generalized-parton distributions.

Nuclear forces: Theory and applications

Evgeny Epelbaum

Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Understanding the properties of atomic nuclei and nuclear dynamics from QCD remains to be a major challenge. Complementary to first attempts along these lines based on lattice QCD, an effective field theory (EFT) approach has been developed and applied to a variety of nuclear bound states and reactions [1, 2, 3, 4]. This method exploits the separation of scales exhibited in nuclear systems and is formulated in terms of pions and nucleons (and possibly the $\Delta(1232)$ isobars) which are the proper degrees of freedom for this kind of problems. As the pion is the pseudo-Goldstone boson of the approximate chiral symmetry of QCD, its interactions are of derivative nature. This allows to derive the nuclear forces in a systematic way by using chiral perturbation theory.

In this talk I review the status of nuclear chiral EFT and discuss selected applications focusing on current topics such as the structure of three-body forces and their effects in few-body systems. I also discuss the discretized version of this approach which treats pions and nucleons as point-like particles on an Euclidean space-time lattice. This allows to evaluate the path integral by Monte Carlo sampling and to access the properties of heavier systems [5].

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The experimental quest for in-medium effects

Romain Holzmann

GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

The QCD vacuum is characterized by nonzero expectation values of various quark and gluon operators. Most notable is the $\bar{q}q$ condensate which signals the spontaneous breaking of chiral symmetry. In a cold, strongly interacting medium the chiral condensate is expected to be modified, and that already by about 30% at nuclear saturation density. Supposing, as suggested by QCD sum rules, that vector meson properties are indeed related to the QCD condensates, changes of the latter should be evidenced in the vector meson decays $\rho, \omega, \phi \to e^+e^-$. Likewise, hadronic many-body approaches imply a broadening and/or shift of the light vector mesons in an ambient nuclear medium. In fact, also in those models the pion dynamics and nucleon resonance formation are closely linked to the phenomenon of chiral symmetry breaking. For a recent review of this field see [1, 2], for a look onto future lines of exploration see [3].

Experimentally, in-medium properties are studied either in heavy-ion collisions (probing hot and dense hadronic matter) or in proton- and photon-induced reactions on nuclei (probing cold nuclear matter). Whereas medium modifications are expected to be stronger in HIC, all measured observables represent an average over the complete space-time evolution of the collision. In contrast, using reactions with elementary projectiles, the system does not cross a steep density and temperature profile, and observed quantities correspond to more well defined conditions. In both cases, lepton pair (e^+e^- or $\mu^+\mu^-$) decays of vector mesons are ideal probes since electrons and muons are not affected by strong final state interactions.

Particularly promising observables are the spectral shape of the dilepton invariant mass distribution as well as the nuclear modification of the observed yields. Two competing mechanisms have to be considered, however, when discussing nuclear modifications : Multi-step production mechanisms can enhance the particle production, while absorption of the produced hadrons reduces the yields. In fact, results from measurements focusing on the spectral distribution of dielectrons produced off nuclei in photon- and proton-induced reactions are not conclusive yet. For the ρ meson, the CLAS experiment at JLab reported a slight broadening and no shift of the pole mass in photo-production, while the E325 experiment at KEK found a shift but no broadening in proton reactions. For the ω and ϕ mesons, on the other hand, various experiments (CBELSA-TAPS, SPring-8, ANKE, CLAS, and NA60) have observed a non-trivial target mass scaling of the produced yields, which, with the help of model calculations, has been related to a sizable collisional broadening inside the nuclear medium (see [2] and references therein). The HADES spectrometer at GSI has recently added high-quality data on e^+e^- production in proton-induced reactions at low momenta relative to the nuclear medium where sensitivity is expected to be highest. These new results reveal strong medium effects on both, the spectral shape and the yield of the emitted dileptons. In my presentation I will give an overview of the various experimental investigations.

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New Heavy Exotic Hadrons

C. P. Shen [a] for the Belle Collaboration

[a] Department of Physics, Nagoya University,
Nagoya, 4648602, Japan

We review recent studies on exotic states at the Belle experiment. The results include: (1) The measurement of the cross sections of $\gamma\gamma \to \omega\phi$, $\phi\phi$, and $\omega\omega$ for masses that range from threshold to 4.0 GeV. In addition to signals from well established spin-zero and spin-two charmonium states, there are clear resonant structures below charmonium threshold, which have not been previously observed. We report a spin-parity analysis for the new structures [1]; (2) No $X(3872)$ signal is observed in $\eta J/\psi$ and $\gamma\chi_{c1}$ modes in B decays. A narrow peak at 3823.5 MeV/c^2 (named as ψ_2) to $\gamma\chi_{c1}$ with a significance of 4.2 standard deviations including systematic uncertainty is observed in $B^\pm \to K^\pm\gamma\chi_{c1}$; (3) The bottomonium states $h_b(1P)$, $h_b(2P)$ and $\Upsilon(1D)$ are observed in the reaction $e^+e^- \to \pi^+\pi^- + X$ [2]. The $\Upsilon(1D)$ is also observed in $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1D) \to \pi^+\pi^-\gamma\chi_b(1P) \to \pi^+\pi^-\gamma\gamma\Upsilon(1S)$; (4) The observation of two narrow structures (named as $Z_b(10610)$ and $Z_b(10650)$) in the mass spectra of the $\pi^\pm\Upsilon(nS)(n = 1, 2, 3)$ and $\pi^\pm h_b(mP)$ $(m = 1, 2)$ pairs that are produced in association with a single charged pion in Y(5S) decays [3].

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The Quark-Gluon Plasma, from SPS to RHIC and LHC

Jean-Paul Blaizot [a)]

[a)] IPhT-CEA Saclay, 91191 Gif-sur-Yvette cedex, France

I present a short overview of the studies of ultra-relativistic heavy ion collisions during the last twenty five years. Focussing on a few selected examples, I discuss the evolution of ideas of concepts as well as the major experimental progress and discoveries that have been realized. I also discuss the new perspectives that the first results from the LHC are opening up.

Lattice QCD at finite density and temperature

Harvey B. Meyer [a)]

[a)] Johannes Gutenberg Universität Mainz, Institut für Kernphysik, J.J. Becher Weg 45, 55099 Mainz, Germany

I review the latest calculations in finite temperature QCD on the lattice, including the chiral aspects of the phase transition, quark number susceptibilities and their comparison with the hadron resonance gas model. I also attempt to summarize the state of our knowledge of the QCD phase diagram at small to moderate baryon chemical potential.

Results of Nucleon Resonance Extraction via Dynamical Coupled-Channels Analysis from Collaboration@EBAC

Hiroyuki Kamano[a]

[a)] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

An understanding of the spectrum and structure of the excited nucleons (N^*) is a fundamental challenge in the hadron physics. The N^* states, however, couple strongly to the meson-baryon continuum states and appear as very broad resonances with decay widths of a few hundred MeV in the πN and γN reaction cross sections. Such strong couplings to the meson-baryon continuum states will affect significantly the N^* properties (mass spectrum and quark-gluon substructures etc.) and cannot be neglected in extracting information on the N* states from the data and giving physical interpretations. It is thus well recognized nowadays that the comprehensive study of all relevant meson production reactions with πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$, ... final states is necessary for a reliable extraction of the N^* states.

To address this issue, we have been exploring the nature of the N^* states through a comprehensive analysis of the world data of πN, γN, $N(e,e')$ reactions in the resonance region [1, 2, 3, 4, 5, 6, 7, 8]. The analysis is performed with a dynamical coupled-channels (DCC) model [9], within which the couplings among relevant meson-baryon channels including the three-body $\pi\pi N$ channel are fully taken into account so that the scattering amplitudes satisfy two-body and three-body unitarity. This work is a collaboration which originally started as a five-year project at the Excited Baryon Analysis Center (EBAC) of Jefferson Lab in 2006.

In this talk, I will review the development of the DCC analysis by collaboration at EBAC and present the final results from the latest 8-channel (πN, ηN, $\pi\Delta$, ρN, σN, $K\Lambda$, $K\Sigma$, γN) analysis [10] performed in 2010-2012."

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Nucleon sea and the five-quark components

Jen-Chieh Peng [a], Wen-Chen Chang [b]

[a] Department of Physics, University of Illinois, Urbana, IL 61801, USA
[b] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

We have generalized the approach of Brodsky *et al.* [1] for the intrinsic charm quark distributions in the nucleons to the light-quark sector involving intrinsic $\bar{u}, \bar{d}, s$ and $\bar{s}$ sea quarks. We compare the calculations with the existing $\bar{d} - \bar{u}$, $s + \bar{s}$, and $\bar{u} + \bar{d} - s - \bar{s}$ data. The good agreement between the data and the calculations is interpreted as evidence for the existence of the intrinsic light-quark sea in the nucleons [2]. The probabilities for the $|uudu\bar{u}\rangle$, $|uudd\bar{d}\rangle$, and $|uuds\bar{s}\rangle$ five-quark Fock states in the proton have also been extracted [3]. Implications on the intrinsic charm quark distributions in the nucleons will also be presented.

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Transverse Momentum Distributions: an experimental update

L.L. Pappalardo

Universita' degli Studi di Ferrara, Dipartimento di Fisica, Via Saragat 1, 44122 Ferrara, Italy

For a long time, transverse-spin effects in hard processes have been considered by the hadron physics community to be negligibly small. It took a while until it was realized that theory allows for unsuppressed transverse polarization effects in the nucleon. In particular, it was recognized that the leading-twist transversity distribution function contributes substantially to single transverse-spin asymmetries in Semi-Inclusive DIS (SIDIS) processes as well as to double transverse-spin asymmetries in Drell-Yan (DY) production. The so-called *Collins effect* [1], which involves a spin-dependent fragmentation function (the Collins function), has been recently exploited to access the transversity function in SIDIS [2, 3]. When the intrinsic transverse momentum of the quarks is taken into account, several new (transverse momentum dependent) parton distribution functions (TMDs) are needed to describe the transverse-spin structure of the nucleon. In fact, transverse spin and transverse momentum of quarks couple naturally, resulting in a variety of azimuthal asymmetries both in SIDIS and in hadron-hadron scattering processes. In the last decade TMDs have been recognized as crucial ingredients for a complete understanding of the nucleon structure. Describing correlations between the quark transverse momentum and the quark or the nucleon spin (i.e. spin-orbit correlations), they allow for a 3-dimensional description of the nucleon (nucleon tomography) in momentum space, and could provide insights into the yet unmeasured quark orbital angular momentum. Noteworthy, the interpretation of hard processes in terms of TMDs has been put on a solid basis by the proof of a non-collinear factorization theorem for SIDIS and DY [4]. At leading twist eight TMDs enter the SIDIS cross section in conjunction with a fragmentation function [5]. Among them, particularly interesting is the Sivers function, describing the correlation between the quark transverse momentum and the transverse spin of the nucleon. Similarly to the Collins effect, it causes measurable azimuthal asymmetries in the direction of the final-state hadrons (*Sivers effect*) [6]. The interest on this TMD suddenly increased after it was demonstrated to be linked to the quark orbital angular momentum, the main still unmeasured contribution to the nucleon spin. Another very intriguing TMD is the Boer-Mulders function [7], describing the correlation between the quark transverse polarization and transverse momentum in an unpolarized nucleon. It gives rise to azimuthal modulations in the cross section of unpolarized SIDIS and DY processes, observed already many years ago. In the last years, many transverse-spin and transverse-momentum effects have been measured in SIDIS (mainly by the HERMES and COMPASS experiments), in hadron-hadron collisions (experiments at RHIC), in unpolarized Drell-Yan processes (experiments at Fermilab), and in e^+e^- annihilation (BELLE and BABAR). An overview of the main experimental results concerning transverse phenomena in hard hadronic processes is presented, with a particular emphasis on the SIDIS experiments.

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Probing QCD at high p_T

Mikko Voutilainen

Department of Physics, University of Helsinki
P.O.Box 64, FIN-00014 University of Helsinki, Finland

We review recent experimental work on probing QCD at high p_T at the Tevatron and at the LHC. The Tevatron has just finished a long and illustrious career at the forefront of high energy physics, while the LHC now has its physics program in full swing and is producing results at a quick rate in a new energy regime. Many of the LHC measurements extend well into the TeV range, with potential sensitivity to new physics. The experimental systematics at the LHC are also becoming competitive with the Tevatron, making precision measurements of QCD possible.

Measurements of inclusive jet, dijet and isolated prompt photon production can be used to test perturbative QCD predictions and to constrain parton distribution functions, as well as to measure the strong coupling constant. More exclusive topologies are used to constrain aspects of parton shower modeling, initial and final state radiation. Interest in boosted heavy resonances has resulted in novel studies of jet mass and subjet structure that also test perturbative QCD predictions and parton shower models. At the highest mass scales, measurements of dijet mass and dijet angular distributions are sensitive probes of new physics.

QCD collinear factorization, its extentions and the partonic distributions

Lech Szymanowski

National Center for Nuclear Research (NCBJ), Warsaw, Poland

I summarize basic facts about the QCD factorization theorems. I start with a reminder of the standard form of the QCD factorization applied for the description of inclusive DIS in terms of the integrated partonic distribution functions (PDFs) and for the description of some hard exclusive processes which involve non-forward generalizations of PDFs: GPDs, GDAs, TDAs. Then I discuss a form of the QCD factorization relevant for the description of semi-inclusive DIS or Drell-Yan processes in terms of the unintegrated, transverse momentum dependent partonic distributions (TMDs). Finally, I discuss the open problem of TMD factorization breaking in hadroproduction of hadrons with high p_T.

Diffractive Processes

A.D. Martin

IPPP, Physics Department, Durham University, DH1 3LE, UK

A) Alternative s- and t-channel definitions of diffractive processes:

1 Elastic or quasi-elastic scattering caused, via s-channel unitarity, by the absorption of components of the wave functions of the incoming particles. Optical theorem. Eikonal formalism. Low-mass diffractive dissociation.

2 A process characterised by a large rapidity gap caused by t-channel Pomeron exchange. Mueller optical theorem. High-mass diffractive dissociation.

B) Why study diffraction?
Intrinsic interest. 40% of $\sigma_{\rm tot}$ at the LHC comes from diffractive processes. Exclusive diffractive processes can probe New Physics. Important for interpreting cosmic ray data. Diffraction is a quantum effect – interference is important – there is no probabilistic picture. Can we construct a Monte Carlo which includes diffraction and which merges 'soft' and 'hard' high energy interactions?

C) Partonic description of soft high energy proton interactions [1].
The QCD/BFKL/'hard' Pomeron may be continued smoothly to describe data in the 'soft' domain. The model embodies the main features of the BFKL approach, including diffusion in $\ln k_t$ and an intercept consistent with resummed NLL($1/x$) corrections. Contributions from multi-Pomeron exchange diagrams are crucial. A small number of physically motivated parameters are able to reproduce the available total, elastic and proton dissociation data.

D) Survival probability of large rapidity gaps [2].
Topical example: double-diffractive exclusive Higgs production at the LHC, $pp \to p + H + p$.

E) A Monte Carlo (SHERPA-SHRiMPS [3]) is described, which is based on the above 'BFKL' multi-Pomeron approach. The Monte Carlo smoothly incorporates both soft and hard high-energy interactions, and allows for diffractive processes. It is found to give a good description of pp and $p\bar{p}$ data through the CERN-ISR to LHC energy region.
SHRiMPS = Soft Hard Reactions involving Multi-Pomeron Scattering

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Hard probes of the Quark Gluon Plasma

David d'Enterria [a)]

[a)] CERN, PH Department, CH-1211 Geneva 23, Switzerland

The production of particles with large transverse momentum p_T and/or high mass ("hard probes") in high-energy heavy-ion collisions takes place in early-time partonic scatterings with large momentum transfer Q^2 and constitute experimentally and theoretically well-controlled "tomographic" probes of the hottest and densest phases of the reaction. A concise review of the experimental and phenomenological progress in the study of hard probes (jets, high-p_T hadrons, heavy-quarks, and electroweak bosons) in nucleus-nucleus collisions and in reference proton-proton collisions at LHC energies will be presented.

New experimental tools for exploring in-medium parton propagation in QCD

William K. Brooks, Hayk Hakobyan, and Miguel Arratia

Universidad Técnica Federico Santa María
Valparaíso, Chile

Atomic nuclei can be employed as spatial analyzers of the propagation of partons in-medium and of the hadronization process. The study of semi-inclusive deep inelastic scattering on nuclei using fully-identified final state hadrons began with the HERMES program in the late 1990s, and is now continuing at Jefferson Lab. In the Jefferson Lab measurements, electrons and positive pions were measured from a 5 GeV electron beam incident on targets of liquid deuterium, carbon, iron, and lead using CLAS in Hall B. The broadening of the transverse momentum of positive pions has been studied in detail as a function of multiple kinematic variables, and interpreted in terms of the transport of the struck quark through the nuclear systems. New insights are being obtained from these data concerning the roles of current and target fragmentation, characteristic time scales of the processes, and quantum interferences, in the interpretation of what is observed.

Another new probe of parton propagation through nuclear systems is provided by the proton-lead collisions planned for the LHC later this year. The initial tests and plans for proton-lead collisions at the LHC will be described, and the physics that could be obtained from an extended p-Pb run will be discussed; topics include gluon shadowing, nuclear parton distribution functions, and estimates of the saturation scale in cold nuclear matter.

These studies of the parton propagation and hadronization processes expose important connections between the DIS data, deuterium-gold collisions at RHIC, proton-nucleus interactions in Fermilab experiment E-906 at 120 GeV, and proton-nucleus collisions at the LHC with multi-TeV beams. They are providing new tools for understanding the fundamental QCD processes at play. In addition, they may help to constrain the interpretation of the jet quenching seen in heavy ion collisions at the LHC and at RHIC. The DIS measurements will be extended in the next few years with the approved JLab experiment E12-06-117, and later will be pursued at the future Electron-Ion Collider.

Chiral Properties of QCD and Lattice Simulations

Chris Sachrajda [a] (RBC-UKQCD and FLAG Collaborations)

[a] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK

There is a strong symbiotic relation between the communities performing lattice simulations and those using chiral perturbation theory. In lattice simulations the light-quark masses can be varied and I will review some examples of where the lattice data can be compared with the expectations of chiral perturbation theory. Moreover the prediction of chiral perturbation theory can be used to guide extrapolations of lattice results obtained at unphysical values for the light-quark masses. The unknown couplings of the chiral expansion can be determined and I will present examples of this for the spectrum and decay constants [1, 2, 3]. Since lattice computations are necessarily performed in a finite volume, and the dominant finite-volume correction is due to the propagation of the light pions, chiral perturbation theory can be used to estimate these corrections. I will also discuss the use of *hard-pion chiral perturbation theory* in which the external pions are hard, but nevertheless the chiral logarithms can be evaluated.

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Recent Results from BESIII Experiment

Yajun Mao [a] for BESIII Collaboration

[a] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

BESIII has collected the world largest data samples for J/ψ, ψ, and ψ''. Light hadron spectroscopy, charmonium spectroscopy and charmonium decays are studied with those data samples. In the study of light hadron spectroscopy, $p\bar{p}$ threshold enhancement and X(1835) are confirmed; 3 new resonances X(2120), X(2370) and X(1870) are observed. In the study of charmonium spectroscopy and charmonium decays, we report new measurements of the resonant parameters of the spin-singlet states, η_c, η_c, and h$_c$, and their production rates in ψ' transitions; we also report observations of many new decay modes of J/ψ, ψ', χ_{cJ}, and η_c, and improved measurements of many existing modes.

Hybrid Mesons

B. Ketzer [a)]

[a)] Technische Universität München, Physik Department, James-Franck-Straße 1, D-85748 Garching, Germany

Despite many years of experimental and theoretical investigations, the meson spectrum is still far from being understood. On the one hand, the constituent quark model has been quite successful to explain the properties of mesons with pseudoscalar and vector quantum numbers. Many radial and orbital excitations of quark-antiquark ($q\overline{q}'$) systems predicted by the model, on the other hand, have not yet been observed experimentally or assigned unambiguously. In addition, a much richer spectrum of mesons is expected from QCD, in which quarks interact which each other through the exchange of colored self-interacting gluons. Owing to this particular structure of QCD, states are expected in which an excited gluonic field contributes to the quantum numbers J^{PC} of the meson. States with a valence color-octet $q\overline{q}'$ pair neutralized in color by an excited gluon field are termed hybrids. The observation of such states, however, is difficult because they will mix with ordinary $q\overline{q}'$ states with the same quantum numbers, merely augmenting the observed spectrum for a given J^{PC}. Gluonic excitations, however, may also give rise to states with "exotic" quantum numbers $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$, which are not allowed in pure $q\overline{q}'$ systems. The lowest-lying hybrid multiplet is expected to contain a state with exotic quantum numbers $J^{PC} = 1^{-+}$ [1]. The search for hybrid states has been a central goal of hadron spectroscopy in the last 20 years [2]. Recent and upcoming high-statistics experiments are expected to shed new light on the existence of such states in nature. In this talk the present experimental evidence for hybrid meson states (e.g. [3, 4]) and future directions will be discussed.

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Chiral perturbation theory and final-state interactions in meson decays

Bastian Kubis

Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D–53115 Bonn, Germany

Final-state interactions in three-meson decays are of high importance for various reasons. From a close investigation of the corresponding Dalitz plots, we may learn something about meson–meson scattering, a prominent example of recent years being the extraction of pion–pion scattering lengths from the cusp effect in $K \to 3\pi$ decays [1]. Due to its small excess energy, this process can be analyzed in a variant of non-relativistic effective field theory [2] that has been developed specifically for this purpose, and extended to systematically include even radiative corrections [3].

On the other hand, a precise analysis of rescattering effects is of high importance to understand the fundamental transition operators driving the decays, due to the way they enhance and shape the decay probabilities. A low-energy example for this occurs in the analysis of $\eta \to 3\pi$ decays, which play a central role in precision determinations of the light quark mass ratios. We have analyzed the Dalitz plot parameters for this decay [4] and in particular could reconcile the precise experimental values for the $\eta \to 3\pi^0$ slope parameter α with chiral predictions.

To obtain reliable descriptions of final-state interactions also at somewhat higher energies, one has to go beyond perturbative treatments and resort to dispersion-theoretical analyses (see e.g. Ref. [5] for recent work also on $\eta \to 3\pi$). These allow one to develop rigorous, model-independent descriptions of meson decays beyond the applicability range of chiral perturbation theory, as recently demonstrated for the three-pion decays of the lightest isoscalar vector mesons, ω and ϕ [6]. Perspectives and physics issues to extend these methods even to heavy-meson decays will also be discussed.

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Quark matter in compact stars

Thomas Klähn

Institute for Theoretical Physics, University of Wrocław, Poland

The interior of neutron stars provides densities of several times the saturation density of nuclear matter. The question whether these conditions are sufficient to obtain a deconfined quark gluon plasma in the cores of neutron stars can be considered to be completely undecided. Besides the lack of a unique measurable signal indicating the presence of quark matter, this situation comes from the great freedom which the number of available models and model parameterizations provides. Combining neutron star phenomenology and the analysis of HIC data, e.g., the elliptic flow allows to tighten the constraints on the EoS of dense matter. I will demonstrate how in particular the recent measurement of the two solar mass neutron star PSR J1614-2230 provides a very valuable tool within this approach [1]. Moreover, knowing that only one of both scenarios (quark matter cores exist or not) can be realised has interesting implications for our understanding of heavy ion collisions and the search for signatures of the QCD phase transition. A further problem in investigating dense quark matter at the low temperatures as found in compact stars is the inaccessibility of this phase space domain for techniques as LQCD which have been developed to actually solve QCD. Worse, the same domain is not accessible to perturbative approaches as well, since in particular the phase transition region is characterised by the breaking of chiral symmetry. Consequently, most models applied to gain any insight at all are phenomenological and motivated by but not strictly derived from QCD. Therefore, I will use the second part of my presentation to briefly discuss an approach to the quark matter equation of state which is based on an application of the Dyson-Schwinger formalism in-medium. As this approach allows to derive non-perturbative equations of motion from the QCD-action there is some confidence that within reasonable approximations one will find solutions of these equations wich describe key features of QCD, in particular dynamical chiral symmetry breaking and the confinement/deconfinement phase transition in medium. The same approach has proven very successfully in vacuum and first results regarding the equation of state at finite densities promise interesting future insights which will hopefully trigger further analysis of the dense matter equation of state close to QCD[2, 3].

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Probing the Quark Sea and Gluons: the Electron-Ion Collider Projects

Rolf Ent

Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606

EIC is the generic name for the nuclear science-driven Electron-Ion Collider presently considered in the US. Such an EIC would be the world's first polarized electron-proton collider, and the world's first $e-A$ collider. Very little remains known about the dynamical basis of the structure of hadrons and nuclei in terms of the fundamental quarks and gluons of Quantum Chromodynamics (QCD). A large community effort to sharpen a compelling nuclear science case for an EIC occurred during a ten-week program taking place at the Institute for Nuclear Theory (INT) in Seattle from September 13 to November 19, 2010. The EIC science case and the initial detector design ideas are well documented in a report on this joint BNL/INT/JLab program [1].

The critical capabilities of a stage-I EIC are a range in center-of-mass energies from 20 to 70 GeV and variable, full polarization of electrons and light ions (the latter both longitudinal and transverse), ion species up to A=200 or so, multiple interaction regions, and a high luminosity of about 10^{34} electron-nucleons per cm^2 and per second. The physics program of such a stage-I EIC [2] encompass inclusive measurements ($ep/A \rightarrow e' + X$), which require detection of the scattered lepon and/or the full scattered hadronic debris with high precision, semi-inclusive processes ($ep/A \rightarrow e'+h+X$), which require detection in coincidence with the scattered lepton of at least one (current or target region) hadron; and exclusive processes ($ep/A \rightarrow e'+N'/A'+\gamma/m$), which require detection of all particles in the reaction.

The main science themes of an EIC are to i) map the spin and spatial structure of quarks and gluons in nucleons, ii) discover the collective effects of gluons in atomic nuclei, and (iii) understand the emergence of hadronic matter from color charge. In addition, there are opportunities at an EIC for fundamental symmetry and nucleon structure measurements using the electroweak probe. To truly make headway to image the sea quarks and gluons in nucleons and nuclei, the EIC needs high luminosity over a range of energies as more exclusive scattering probabilities are small, and any integrated detector/interaction region design needs to provide uniform coverage to detect spectator and diffractive products. This is because $e-p$ and even more $e-A$ colliders have a large fraction of their science related to what happens to the nucleon or ion beams.

As a result, the philosophy of integration of complex detectors into an extended interaction region faces challenging constraints. Designs feature crossing angles between the protons or heavy ions during collisions with electrons, to remove potential problems for the detector induced by synchrotron radiation. Designs allocate quite some detector space before the final-focus ion quads, at the cost of luminosity, given that uniform detection coverage is a must for deep exclusive and diffractive processes. The integrated EIC detector/interaction region design at JLab focused on establishing full acceptance for such processes over a wide range of proton energies (20-100 GeV) with well achievable interaction region magnets. The detector design at BNL uses the higher ion beam energies to achieve good detection efficiency for instance for protons following a DVCS reaction, for proton beam energies starting from 100 GeV. Following a recommendation of the 2007 US Nuclear Science Long-Range Planning effort, the DOE Office of Nuclear Physics (DOE/NP) has allocated accelerator R&D funds to lay the foundation for a polarized EIC. BNL, in association with JLab and DOE/NP, has also established a generic detector R&D program to address the scientific requirements for measurements at a future EIC.

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Time-Reversal Violation in the Nucleon and the Nucleus

U. van Kolck [a,b]

[a] Institut de Physique Nucléaire, Université Paris-Sud, CNRS/IN2P3, F-91406 Orsay, France
[b] Department of Physics, University of Arizona, Tucson, AZ 85721, USA

Various experimental proposals promise significant advances in sensitivity to time-reversal (T) violation through measurements of electric dipole moments (EDMs) of the nucleon and light nuclei [1]. The smallness of T-violation effects from the weak-interaction phase and the QCD vacuum angle suggests that Standard Model operators of effective dimension six (such as quark EDMs, and quark and gluon color-EDMs) might be important. The question then arises whether the dominant source of T violation, if any, can be inferred from measurements of hadronic and nuclear T-violating form factors (TVFFs).

I present some of the recent progress in establishing the framework to answer this question. I argue that the answer is yes, because each T-violation source breaks chiral symmetry in a different way, and thus produces different pion-nucleon interactions and, ultimately, different relations among observables. The chiral Lagrangian that incorporates all sources of dimension up to six [2] involves seven dominant interactions. I give results for the TVFFs of the nucleon [3], deuteron [4, 5], helion and triton [5]. I end with a discussion of the gaps that still exist in relating T-violating sources at the electroweak scale and nuclear observables.

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