Institute for Theoretical Physics I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Annual Report 2002

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Preambel

This small booklet reports on the scientific work at the Institut für Theoretische Physik I during the year 2002. As in the last years, we have tried to cover a broad spectrum of theoretical hadron and nuclear physics ranging from studies of nuclear and nucleon structure over relativistic heavy-ion reactions to the description of high-energy electromagnetic processes. In all of this work our guiding intention was to look for different manifestations of the same physics effects in widely different areas.

All of this research is being done by and with students and young post-docs. The students are from their start valuable members of the group. They contribute to the ongoing research in an important way and thus learn from the very beginning to stand their ground in an international research environment. They also all 'grow up' with computers and the internet and are used to working with the help of international data bases.

The students all participate in the European Graduate School Copenhagen-Giessen that we have founded together with our experimental colleagues at Giessen and colleagues from the Niels-Bohr-Institute and NORDITA. We are extremely grateful to DFG for funding of this school and – after a very successful review at the end of last year – look forward to the future operation of this school, including by then also partners from Finland. Within the European Graduate School we have created the first structured graduate education program for students after their diploma here at the JLU Giessen. The school has - through its lecture weeks which are also open to students from other German and European universities - achieved a very wide visibility in the field. This has also been recognized by the European Commission by granting a Marie Curie Training Site for Hadron Physics to Giessen.

Through this school we have organized last summer one of the first workshops on the future scientific program at GSI. We were thus all delighted to hear about the decision of the German federal government to fund a big new project at GSI. In the scientific preparation of this project scientists from Giessen, especially also from theory, have been involved from its very start and we will continue to contribute significantly also during the construction period of the new GSI facility.

Most of our research is funded by outside sources; we are thus used to compete for research grants on a national level. We are particularly grateful to GSI Darmstadt and to the BMBF for their continuing support. In addition, we have been supported by the Deutsche Forschungsgemeinschaft and the Forschungszentrum Jülich. Without the help of all these organizations our work - and education of students - would not have been possible. Last, but not least, our thanks go to the President of our university for his support in form of computer equipment, for which we have an everlasting need.

Ulrich Mosel

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Scientific Program

Exotic Nuclei and Hypernuclei

Investigations of the structure of exotic nuclei and hypernuclei have been our central research topics in nuclear structure physics during the past year. The strong evidence for a gradual transition from mean-field dynamics to a new kind of correlation dynamics predicted to appear in dripline nuclei, has been confirmed in recent experiments. Non-linearities due to multi-phonon admixtures in response functions of stable and exotic nuclei were investigated. The field theoretical methods developed for normal nuclear matter are being extended to the strangeness sector and applied in hypernuclear structure calculations.

Correlations in nuclear matter and hypernuclear matter

Short-range correlations lead to deviations of single particle properties from the strict mean-field picture of independent quasi-particles moving in a static potential well. Such non-stationary effects have far-reaching consequences not only for low-energy nuclear spectroscopy - especially in exotic nuclei - but also in sub-nuclear areas as particle production cross sections and color transparency. Short-range correlations in infinite symmetric nuclear matter have been studied in a transport-theoretical model. In addition to the static (Hartree-Fock) mean-field we include dynamical self-energies from the coupling of single particle states to intermediate 2p1h and 1p2h states, respectively. This leads to a self-consistent description of single particle spectral functions in the hole and particle sector, respectively. In symmetric infinite matter at saturation density we found the surprising and interesting result that correlation effects are dominated by phase space contributions while dynamics are well accounted for by assuming a constant average matrix element. The latter observation agrees well with the expectation that correlations are determined by the short-range nuclear interaction mediated by the vector mesons.

Deriving the in-medium interactions microscopically by solving the Bethe-Salpeter equations in ladder approximation the well defined diagrammatic structure of our interaction is most suitable for extensions of DDRH theory into the strangeness sector. A Dirac-Brueckner scheme for the full baryon octet has been formulated theoretically and is now implemented numerically. A most transparent interpretation of the results is obtained with a decomposition of the Dirac-Brueckner interactions into Lorentz invariants by a physically motivated expansion into meson exchange interactions. The method simplifies the numerical calculations considerably, making a solution of the full set of Bethe-Salpeter equations without a 3-dimensional reduction feasible in the near future.

Correlation dynamics in exotic nuclei and hypernuclei

In previous calculations we found strong evidence for a drastic change in nuclear dynamics at the driplines, evolving from mean-field dominance to a new kind of correlation dynamics at extreme proton-to-neutron ratios. The transition into a new dynamical regime is well illustrated for the single-nucleon halo systems ^{8}B,

^{11}Be and ^{19}C. Our calculations show that the halo particles are bound mainly by dynamical self-energies. The halo particles are found in wave packet-like configurations, being distributed equally over a large number of mean-field orbits. Recent FRS/GSI experiments for those nuclei and the neutron-rich oxygen isotopes $^{20-24}$O, measuring breakup momentum distributions for halo nuclei in conjunction with γ rays from core excitations, confirm the theoretical predictions on a quantitative level. The same theoretical methods have been used to describe the production and spectroscopy of exotic nuclei in heavy ion charge exchange reactions.

These findings deserve a systematic study of correlation dynamical effects in response functions and other non-static properties in β-unstable exotic nuclei. Since these are low-energy phenomena non-relativistic HFB and QRPA theory and refinements thereof, including admixtures of up to three phonon states, i.e. six quasi-particle configurations, are being used. Of particular interest is the appearance of low-energy dipole strength because such states are direct indicators for non-standard dynamical effects. Calculations of nuclear response functions for the A=100-140 Sn isotopic chains are showing a gradual increase of the multi-phonon effects with increasing neutron excess. Since the experimentally known cases (A=116-124) are well described, reliable predictions for the unstable regions can be expected from these calculations.

The structure of hypernuclei has been investigated in the field-theoretical DDRH approach. A re-consideration of separation energies in medium and heavy single Λ nuclei, measured recently at KEK, showed the necessity to extend the commonly used description to core-particle interactions. At the mean-field level they are most conveniently taken into account by a phenomenological spin-spin interaction. Also, on a more fundamental level the $\Lambda\omega$ tensor vertex was included the first time into the analysis. Both interaction effects together improve the agreement with the measured spectra considerably. With these new contributions the data are overall well described within the experimental uncertainties.

Hadron and quark physics

Understanding the interactions among hadrons and their internal quark structure is one of the central aims of modern hadron physics. An interesting aspect is the change of hadronic properties when a hadron travels through a hadronic medium with which it can interact. Obviously there is a mutual influence between the internal structure of hadrons and their interactions. Hence studying the in-medium behavior of hadrons in addition to their elementary reactions can also shed some light on the internal structure. All these aspects are studied in our group for various types of hadrons and hadronic emvironments.

Meson- and photon-nucleon interactions

We studied the following channels for elementary scattering reactions: (π, N), (γ, N), (η, N), (K, Λ), (K, Σ), $(2\pi, N)$ and (ω, N). Due to inelastic rescattering effects these channels should not be treated separately. To account for that these reaction channels are treated on a common footing by a coupled-channel K-matrix approach. Baryonic resonances are included as intermediate states in our approach. Hence the ingredients to describe meson-nucleon and photon-nucleon interactions are coupling constants and resonance masses. Our coupled-channel approach allows to highly constrain these input parameters as a large variety of channels (i.e. data) have to be explained with the same set of parameters. This allows for a deeper understanding of the properties of the relevant degrees of freedom. Recently we have extended the coupled-channel K-matrix approach by including spin-$\frac{5}{2}$ baryon resonances.

Internal Structure of Hadrons

Concerning the formation of hadrons out of quarks it is expected that the non-perturbative phenomena of confinement and chiral symmetry breaking are crucial for the understanding of these bound-state problems. Unfortunately, the derivation of these aspects from the underlying theory (QCD) is still missing. However, confinement can be described by treating the vacuum as a dielectric medium (chromodielectric or Friedberg-Lee model). In this picture the quarks are the sources of chromo-electric fields. The latter couple to the dielectric field. It is energetically favored that the chromo-electric fields are constrained to a narrow space region by the dielectric field. Quark-antiquark configurations form strings by this mechanism which is numerically rather involved. Recently we analyzed also three-quark configurations (nucleons). Also in this case strings appear which connect the three quarks. In general, it is an open question whether these strings form a Y- or a triangular Δ-shaped configuration. We have analyzed the total energy as a function of the distances of the three quarks. It has turned out that in our approach the valence quarks in a nucleon arrange in energetically favored Δ-type configurations.

Chiral effective models of hadrons

In an alternative approach we have studied the relation between spontaneous chiral symmetry breaking and hadronic properties. Here we focussed on mesonic states, especially rho-mesons. We utilized a chiral constituent quark model to obtain a low-energy representation of QCD (chiral perturbation theory). Presumably the method is insensitive to confinement as the unphysical quark production threshold is far away in energy. The obtained purely hadronic low-energy theory is extended to higher energies. Mesonic resonances can be recovered in that way. We obtain satisfying results for the mass of the rho meson and its coupling to pions and photons. In spite of the lack of confinement the model does not posses unphysical quark production thresholds. In addition, one obtains parameter-free results for the rho-meson properties. Having established a model which works fairly well in vacuum, the next step will be an extension to the finite temperature case.

In-medium properties of hadrons

Once hadrons are embedded in a nuclear environment their properties like masses and life times change due to the reactions with the particles from the background medium. The rho-meson is a promising probe for studying in-medium changes of hadrons because it couples to dileptons. Since the latter traverse the hadronic interaction region without further disturbance they carry information about in-medium properties of the initial rho-meson to the detectors. We study the properties of rho-mesons in infinite nuclear matter aiming at their in-medium mass distributions (spectral function). The most relevant channels for collisions between the rho-mesons and the nucleons from the medium are the formation of baryonic resonances in the 1.5 to 2 GeV region decaying back again into meson-nucleon states. In-medium changes of the meson properties in turn cause changes of the properties of the baryonic resonances. We tackle this self-consistency problem by a coupled channel approach for rho, eta and pion on the mesonic side and nucleonic resonances on the baryonic side, most prominently $N(1520)$, $N(1535)$ and $\Delta(1232)$. Our approach results in a significant broadening of the rho spectral function and the appearance of new structures (resonance-hole states). The baryonic resonances also obtain broadened spectral functions.

Equipped with our experience on dealing with non-trivial spectral information, i.e. off-shellness, in the hadronic sector, we start to investigate the influence of the off-shell properties of quarks on high energy reactions like deep inelastic scattering and Drell–Yan dilepton production.

Open charm and charmonium in the medium

In the last decade the interest in hadronic states with charm flavors $(c, \bar{c})$ has been rising continuously. This relates to the elementary charm production cross section in pN and πN reactions as well as to their interactions with baryons and mesons which determine their properties (spectral functions) in the hadronic medium. The charm quark degrees of freedom play an important role especially in the context of a phase transition to the quark-gluon plasma (QGP) where, due to color screening, charmonium $(c\bar{c})$ states should no longer be formed. However, the interactions of open charm mesons and charmonia with hadrons are not well known and large ambiguities persist by now. This uncertainty might be substantially reduced by experimental data from $\bar{p}$ induced reactions on nuclei, where charmonia can be formed on resonance with moderate momenta relative to the target nucleus. Such studies will be performed experimentally at the future high-energy antiproton storage ring (HESR) at GSI-Darmstadt.

Within detailed transport calculations – including dropping $D, \bar{D}$ meson mass shifts according to QCD sum rules – we find that for a heavy nucleus like ^{208}Pb the fraction of 'inside' charmonium decays to dileptons or $D + \bar{D}$ reaches $\sim 40\%$ for the $\Psi(3770)$, i.e. the first charmonium state above the $D+\bar{D}$ threshold, which at first sight looks promising. However, the in-medium effects in the $D + \bar{D}$ invariant mass spectra are hard to see experimentally since for invariant masses from the $D + \bar{D}$ threshold to the $\Psi(3770)$ pole mass the final spectrum is only slightly modified while at high invariant masses it is covered by the non-resonant background. The e^+e^- invariant mass spectra from the in-medium $\Psi(3770)$ show a decrease at small masses (below the $D+\bar{D}$ threshold) since these charmonia preferentially now decay via the $D+\bar{D}$ channel in the nucleus. Thus the net in-medium effect is not an 'enhancement' of lower mass dileptons as in case of the ρ and ω mesons, but a relative 'suppression'. If this suppression could be seen in experiment it might provide valuable information on the $D, \bar{D}$ self-energies in the nuclear medium.

Nucleus-nucleus Collisions

Collisions at high baryon density

The new GSI project aims with its Compressed Baryonic Matter (CBM) facility for the interesting and not much explored region of very high baryon densities between the experimentally determined freezeout curve and the expected phase-boundary to the quark-gluon plasma. The interest here stems from two aspects: one is the question of high-density correlations in 'classical' baryonic degrees of freedom, the other is that of chiral symmetry restoration at high baryon densities.

In order to investigate the former question we have extended our successful approach to calculate in-medium spectral functions within a transport-theoretical ansatz to high densities and intermediate temperatures. At all densities the collisional width of nucleons grows significantly with temperature. At a fixed temperature, however, the width is found to increase steadily at densities close to the equilibrium point and approaching a constant value at high densities. This saturation is due to the increased Paul-blocking at higher densities. The effect sets in at about $3\rho_0$, i.e. roughly at a density where a merging of individual nucleons might be expected and chiral symmetry restoration could set in.

The latter is of fundamental interest. Whereas lattice QCD calculations at zero baryon chemical potential indicate that a restoration of chiral symmetry goes along with the deconfinement phase transition at a critical temperature T_c, the situation is less clear at finite baryon density where QCD sum-rule studies show a linear decrease of the scalar quark condensate $\langle \bar{q}q \rangle$ – which is nonvanishing in the vacuum due to a spontaneous breaking of chiral symmetry – with baryon density ρ_B towards a chiral symmetric phase characterized by $\langle \bar{q}q \rangle = 0$. This decrease of the scalar condensate is expected to lead to a change of the hadron properties with density and temperature, i.e. in a chirally restored phase the hadrons might become approximately massless as suggested by Brown and Rho. Experimental studies on the excitation functions of hadrons from central $Au+Au$ or $Pb+Pb$ collisions are expected to shed some light on this issue especially in the energy domain of 10–20 A·GeV where the highest baryon densities should be encountered. This energy window – between the AGS and SPS range – is the domain of the future GSI accelerator SIS200, which has been approved very recently.

In order to bridge the gap from AGS (< 11 A·GeV) to SPS energies (>40 A·GeV) two different covariant transport calculations have been performed for central $Au + Au$ collisions from 2 – 160 A·GeV and confronted with experimental hadron spectra whenever available. We find that the excitation functions of pions, kaons, antikaons and hyperons from central $Au + Au$ (or $Pb + Pb$) collisions from the two hadronic transport models – when discarding any specific in-medium effects for the hadrons – are very similar: both approaches give an absorption of pions at lower bombarding energy and a relative increase of pion production for $E_{lab} > 10$ A·GeV. Kaons and antikaons from AA collisions are enhanced in central reactions relative to scaled pp collisions at all energies by a factor of ≥ 2 and well in line with the data. This also holds for the hyperon spectra. However, both models fail to reproduce the experimental excitation function for the K^+/π^+ ratio in central nucleus-nucleus collisions. Our systematic study in comparison to the most recent data from the NA49 Collaboration demonstrates that this failure is mainly due to an inadequate description of pion dynamics and cannot be related to an underestimation of strangeness production.

We have, therefore, also started investigations of the consequences of in-medium changes of pion spectral functions in the dense medium. Because pions freeze out at rather low densities, the effects are found to be small, but visible in the low-momentum parts of the spectrum. Effects on other reaction channels are presently studied.

Collisions at high temperatures

The prominent aim of experiments carried out in the high-temperature regime at the accelerators RHIC and – in the future – LHC is the search for a new state of matter, the Quark-Gluon Plasma. Here we concentrate both on conceptual and on practical aspects to help identify possible signatures.

Statistical description with anisotropic momentum distributions

The various experimental data at AGS, SPS and RHIC energies on hadron particle yields and ratios for central heavy ion collisions have been analyzed within a generalized statistical density operator, which allows for a well-defined anisotropic momentum distribution of each particle species, specified by a common streaming velocity parameter. A further numerical study of this two-fluid streaming analysis shows that the individual particle ratios are rather insensitive to a change of this intensive parameter. Hence, the fact that particle ratios are being sucessfully reproduced by a statistical treatment does not imply a clear evidence for the existence of a fully isotropic momentum distribution, i.e. for a state of almost complete thermal equilibrium, at hadrochemical freeze-out, but merely does represent an assumption.

Energy loss of high p_t hadrons by final state interactions

When discussing the parton jet-quenching phenomena in ultrarelativistic heavy ion collisions typically the materialization of high energetic transverse partons to hadronic jets is assumed to occur outside the reaction zone. On the other hand quantum mechanical estimates give a hadronization time on the order of only a few fm/c for jets materializing into hadrons with transverse momentum of $p_t \leq 10\,GeV$, which thus should well take place inside the fireball. Typical (in-)elastic collisions of these high p_t particles with the dominant low momentum hadrons of the fireball have a rather low invariant mass and are thus nonperturbative and large. The mean free path in the late hadronic stage is estimated to be $\lambda \approx 1 - 5\,fm$, resulting in a few collisions $L/\lambda = 0, 1, 2, \ldots$. We carried out an analysis within this collision number expansion by means of the FRITIOF collisions scheme for various hadrons. Here we have shown that the hadronic final state interactions can in principle (partially or fully) account for the modification of the (moderate) high $p_\perp$ spectrum observed for central collisions at RHIC. A possibility to distinguish between various proposed scenarios of high momentum depletion could be the precise measurements of p_t–distributions of charmed particles like the D–mesons.

Parton Boltzmann dynamics

We have developed a full microscopic Monte-Carlo simulation of real-time parton dynamics starting with early minijet production of (semi-)hard partons followed by a semiclassical kinetic transport description of Boltzmann type. The sampling of the minijets (with $p_t \geq 1 - 2$ GeV) are generated via pQCD. The kinetic transport describes at present $2 \rightarrow 2$ collisions. A detailed analysis shows that thermalization of parton matter can not be built up or maintained by this mechanism alone. In addition, some severe deficiencies in treating frequent collions have been analysed. For this a space-time cell subdivision method is now adopted, which will also allow to treat the important $2 \rightarrow n$ processes in a consistent way. The latter are thought to be responsible for a fast generation of entropy, which will be tested in the near future.

Phase Transition

A question of considerable interest for the experimental program at *RHIC* and *LHC*, is how the thermodynamical properties of hadronic matter will evolve at energy scales near and, in particular, above the expected deconfinement transition. There, matter forms a many-particle system of quarks and gluons – characterized by a large value of the coupling – which makes the theoretical description challenging. Perturbative results for the thermodynamic potential were calculated to a high order, but they turned out to have little predictive power. Numerical calculation within lattice QCD, on the other hand, have been restricted to zero baryon density until very recently, and they become computationally expensive when trying to consider physical quark masses.

An alternative, phenomenological, approach is to derive from available lattice QCD (LQCD) data a quasiparticle model, which then may be used to compute other relevant quantities not directly accessible in LQCD. Some years ago, we proposed to apply the model to obtain information about the equation of state at non-zero baryon density. Our predictions, e.g., for the phase boundary, have turned out to be in striking agreement with pioneering lattice simulations exploring the region of small baryon density.

Photonuclear Physics

The focus of our work on photonuclear reactions on nuclear targets has always been one in which we try to describe the many-body aspects consistently with other nuclear reactions. Our main technical contribution has thus been the first coupled channel description of final state interaction effects to replace the usual Glauber treatment. On the conceptual side we have carried through our earlier calculations of in-medium properties of hadrons and have shown for the first time how spectral changes of mesons imply corresponding changes of strongly coupled baryon resonances and vice versa. The search for such in-medium changes has been so far a domain of relativistic heavy-ion physics. We investigate the observability of such effects in elementary hadronic reactions on nuclei.

On the low-energy side we have continued our calculations of photon-induced meson-production on nuclei. Here we have in detail analyzed the data by the local TAPS group on η-meson production as well as on ρ production. We have shown that the η-data can be very well understood quantitatively if the momentum-dependence of the self-energy is taken into account. Another very detailed study has been performed on the feasibility of a search for in-medium changes of the ϕ meson, planned at the SPRING-8 facility in Japan. We have been able to show that in particular the final state interactions of the K and $\overline{K}$ mesons will inhibit the observation of any of such predicted spectral changes of the ϕ. An important, new side result of this study has been the finding that the inclusive ϕ-production cross sections contribute significantly to any yield in the low-momentum region; these cross sections are so far experimentally usually not available. Finally, our predictions for dilepton production on nuclei by photo-induced reactions have finally been taken up by a collaboration at JLAB in the USA. We eagerly await the evaluation of the data taken in 2002.

During the last year we have extended these studies to considerably higher energies up to the HERMES regime. Here, on top of the incoherent treatment of the final state interactions a coherent treatment of the initial-state shadowing phenomenon, experienced by high-energy photons impinging on nuclei, is essential. We have achieved such a treatment by a coherent Glauber description in the incoming channel. This led to the derivation of a new formula for the total incoherent cross section on nuclei allowing to separate the initial state and final state interaction so that we can combine now the coherent initial state with the incoherent final one. In the framework of this theory we have analyzed the incoherent vector meson production on nuclei in the HERMES experiment. We have found a significant contribution of final state side-feeding to this channel due to the coupled-channel effects inherent in our treatment. In particular we have shown that these data allow a reliable extraction of formation times only if these coupled channel effects are properly taken into account.

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