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A lot of theoretical and experimental effort is devoted to study the strong interaction in extreme conditions. The experiments ALICE at CERN and PHENIX and STAR at RHIC explored the strong interaction at low density and high temperature. In this region the situation on the theory side is satisfactory, too. However, lattice calculations applicable at low density cannot be used at high density. At high density the existing experimental data is scarce and have rather bad statistics (NA61 at CERN). New experimental facilities (NICA at JINR, PANDA and CBM at FAIR) will be finished soon to explore this region more precisely.

In this project the main objective of our investigations was
"to understand the properties of hadrons (especially the charmed ones) and hadronic matter at high density and low temperature" and "to give predictions for these forthcoming experiments".

In the application we emphasized specially three points: 1) develop our transport model for investigating antiproton-nucleus collisions, 2) calculate the phase diagram using the linear sigma model and calculate hadron properties in the medium, 3) extract a K^-N potential. I think all of these goals have been achieved.

2. Transport model

We have considered the equilibration in a relativistic heavy ion collision using our transport model. We applied periodic boundary conditions to close the system in a box. We found that the thermal equilibration takes place within the first 20-40 fm/c which time is comparable to the duration of a relativistic heavy ion collision. The chemical equilibration is a slower process. The nonstrange degrees of freedom approximately equlibrate in 50-100 fm/c, but for the strangeness the equilibration time is from 100 to 300 fm/c depending on the density and on the bombarding energy. We also studied the propagation of broad resonances within our approach. We found that in our model the mass distributions of the resonances always follow the spectral function corresponding to the given density, so there is no memory effect in contrast to the exact treatment [1].

One of our main aim is to calculate specific channels at the energies of CBM/FAIR, PANDA/FAIR and NICA/JINR . To reach this goal we had to include the relevant cross sections in our transport model. Since at higher energies the cross sections of hadron-hadron collisions are not known experimentally (except pion, kaon, proton and antiproton, other hadrons cannot be used as target or projectile), we developed a statistical bootstrap model to calculate hadron-hadron cross sections at the few GeV energy range. The model based on the assumption that in a collision first a fireball is formed which decays sequentially to the hadronic final states. The model successfully described several available data [2].

We also carried out BUU transport calculations for strangeness production at the HADES/GSI energy region in π+A and p+A reactions. We proposed a new production mechanism for the doubly strange Ξ^- baryon in subthreshold nuclear collisions via a two-step process, in which singly strange hyperons and hyperon resonances play an important role. We found that the yield of Ξ baryons is very sensitive to anisotropies of the underlying hadronic processes. The new mechanism could contribute to the understanding of the high Ξ multiplicities found in subthreshold p+A and A+A collisions by the HADES collaboration [3].

We calculated the dilepton and φ meson production at NICA and CBM energies. We have found that the dilepton spectrum is dominated by the φ meson at the φ mass region. This allows to study the effects of the medium on the φ and kaon properties[4].

We extended the transport model we developed here, to charmonium production in hadron (especially antiproton) induced reactions. In the investigations [5,6] the following picture has arised: The antiprotons annihilate close to the surface of the heavy nuclei. The charmonium travels through the nuclei contributing to the dilepton spectra. Crossing again the thin surface the rest of the charmonium states decay in vacuum. The higher lying charmonium states (ψ(3686) and ψ(3770) expected to have a mass shift in dense matter in the range of about 100 MeV. We found that in the dilepton spectra the ψ(3686) shows up with two peaks. One of the peak is the contribution of the vacuum decay and the other one is developed from the decay inside the nucleus around normal nuclear matter density. The peaks are clearly separated and can be observed at the PANDA detector at FAIR. By measuring the distance of the two peaks we can determine the mass shift of the ψ(3686) around normal nuclear matter density, therefore, we can get information about the gluon condensate at this density [6].

Moreover, we developed an Effective Lagrangian model for the angular distribution of dilepton (electron-positron pair) production in π-nucleon collisions. In our model, the electromagnetic interaction of hadrons is described by vector meson dominance via an intermediate ρ meson. Spin≥3/2 resonances are incorporated using a consistent interaction scheme, which ensures the elimination of unphysical lower-spin degrees of freedom. We identified the dominant contributions in the energy range of the HADES experiment and investigated the angular distribution of di-electrons in terms of an anisotropy coefficient sensitive to the transverse or longitudinal polarization of the virtual photon decaying to the lepton pair. We have investigated the connection between the angular distribution and the polarization of intermediate baryon resonances and vector mesons. This will provide new information about the electromagnetic transitions of the baryon resonances contributing to the process. We gave predictions for an anisotropy coefficient, which can be studied by the HADES experiment. [7,8].

As a member of the CBM collaboration, we continued the planning of the details of the detector. We participated in the detector simulations concentrated on the φ meson and on the double strange hypernuclei [9].

3. Effective Field Theory

In an extension of the model beyond the originally included scalar, pseudoscalar, vector, and axial-vector nonets, we added a baryon octet and a baryon decuplet and calculated the tree-level baryon masses and possible two-body decuplet decays. The baryon masses were generated through spontaneous symmetry breaking. The model parameters were determined through a multiparametric minimalization process, which compares the calculated physical quantities with their experimental values. It was found that our model described the experimental data well[10].

We developed further our extended version of the linear sigma model by including two parity-doublets of spin-1/2 baryons. We included the nucleonic states according to the so-called mirror assignment, that allows for chirally invariant baryon mass terms. We fitted the parameters of the baryonic sector of this model to the masses, decay widths and axial coupling constants of the nucleonic resonances, obtaining a good overall description of the data. The model gives a reasonable description of the vacuum phenomenology of the nucleon and the N(1440), N(1535) and N(1650) baryon resonance states [11]. We investigated the three-flavor version of the extended linear sigma model with four baryonic multiplets. We studied the influence of the axial anomaly on the decay N(1535)-> N η [12].

We also investigated the low energy limit of the two flavored (axial)vector extended linear sigma model. Accordingly, all the fields, except for the pions, are integrated out. The resulting low energy model that contains only pionic fields and interactions can be identified as a Chiral Perturbation Theory (ChPT) after expanding it in powers of (derivatives of) the pion fields. The main result of our calculation is that the correspondence between the low-energy constants of the ChPT and the coupling constants of the effective low-energy model is remarkably good [13].

We investigated at finite temperature and baryon chemical potential μ_B the chiral phase transition within an extended quark-meson model with $N_f = 2 + 1$ flavors that includes besides (axial-)vector mesons also Polyakov loop degrees of freedom. The Polyakov loops mimic some properties of the QCD confinement. The grand potential was calculated in the simplest possible approximation in which only the fermion determinant is included beyond tree-level and the effect of the mesonic fluctuations is neglected. The model was parameterized with a χ^2 minimization procedure applied on the tree-level decay widths and the vacuum scalar and pseudoscalar curvature masses which include the contribution of the constituent quarks. We included as an input the well-established value of the chiral transition temperature of the QCD at vanishing density. We determined he pressure and thermodynamical observables derived from it and compared them with available lattice results. It turned out that the best fit and a meaningful thermodynamics can only be achieved when the scalar states of the model corresponds to lowest lying states: a0(980), K0*(800), f0(500), and f0(980) particles. The agreement with the lattice results is rather good. We explored the μ_B–T phase diagram and found that our best parametrization of the model allows for the existence of the critical end point (CEP) of a first order transition line at rather large values of μ_B. By slightly changing the parameter set the critical point moves in the direction of the T=0 axes, and will soon disappear [14]. In our model we also calculated the isentropic curves and compared them with the lattice simulations[15]. The agreement is remarkable.

Moreover, we provide a general framework to treat coupled-channel systems in the presence of overlapping left- and right-hand cuts as well as anomalous thresholds. By suitable deformations of left-hand and right-hand cut lines we establish a framework of linear integral equations defined for real energies. We show that the scattering amplitude can be represented in terms of three phase shifts and three inelasticity parameters as expected from coupled-channel unitarity condition[16]. A general spectral representation is established for partial-wave amplitudes derived from t- and u-channel exchange processes. The representation is valid in the presence of anomalous thresholds, decaying particles and overlapping left-hand and right-hand cuts as often present in hadron physics. The results are illustrated by examples for meson-meson scattering and can provide reliable input information for in-medium hadron property calculations [17]

4. Antikaon-N potential

We performed exact, Faddeev-based calculations of the 1s level shift in kaonic deuterium with realistic $\bar{K}$ N potentials. This is the first exact calculation of the level shift in a hadronic atom, which uses realistic, multichannel hadron-nucleon interaction and goes beyond the conventional two-body picture. For the strangeness nuclear physics the main significance of the results is not as much in the obtained numbers, as in the first possibility to relate an important and hopefully measurable observable of the $\bar{K}NN$ system to the input $\bar{K}N$ interactions without relying upon uncontrollable approximations [18]. A new chiral based, multichannel and energy-independent KN potential was constructed, which reproduces all known experimental data at the same level of accuracy as the energy-dependent ones. In variational calculations of n>2 K-nuclear systems the new potential avoids the not easily (and not uniquely) surmountable difficulties arising from the energy-dependence of the two-body interaction. Using this potential we have shown, that the overall accepted scenario, according to which chiral based meson-baryon interactions lead to two-pole structure of the Λ(1405), is due to an unjustified approximation (on-shell factorization). When the equation is solved without this approximation, the T-matrix has only one pole in the energy region of the Λ(1405) [19]

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