Nuclear Theory

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The main scientific themes pursued by the Nuclear Theory Group, recent accomplishments and future directions are briefly described below. During the past year, 53 publications in refereed journals and 7 publications in conference proceedings resulted from this work. An additional 9 articles were submitted for publication. A strong visitor program is in place, which provides connections to both theoretical and experimental activities in the division.

The ultimate goal of high-energy nuclear collisions is to study the phase transition from a color-deconfined quark-gluon plasma to hadronic matter. We have studied a number of possible signatures of the quark-gluon plasma. Other nuclear effects which could influence the interpretation of the data have also been investigated. Lessons learned from the current data, including the heavy-ion program at the CERN SPS, can be applied to higher energy heavy-ion collisions at RHIC and the LHC. At the heavy-ion colliders, hard processes such as dileptons, heavy quarks and quarkonium, and jets, are expected to be sensitive probes of dense matter.

CERN experiment NA50 has measured suppression of the J/ψ rate in pp, pA and AB collisions. All but the Pb+Pb data can be explained within the context of simple analytical models of absorption by either nucleons alone or nucleons and co-moving secondaries. However, in these models the treatment of the interaction dynamics is rather crude. The anomalous J/ψ suppression in Pb+Pb collisions has recently been addressed within the context of a dynamical simulation, which allows a more detailed study of how the J/ψ interacts in the dense hadronic environment. The simulation can explain all the data, including Pb+Pb if the J/ψ interaction cross section with co-movers is not too small because the number of secondaries increases faster than assumed in the analytical models. Other simulations have addressed the J/ψ pA data in the context of nucleon stopping and find satisfactory agreement with this mechanism. Baryon stopping has been studied assuming that gluon junctions provide the nucleon binding. The charmonium production rate from the final hadronic stage of heavy ion collisions has also been studied.

The quark and gluon distributions in the nucleus are different from those in a free proton. An evolution equation including gluon recombination effects has been derived for high density, small momentum fraction gluons. Phenomenologically, this “shadowing” should also be position dependent. The spatial dependence of nuclear shadowing has been studied in several scenarios. Charm, bottom, J/ψ and Drell-Yan production have been studied at the CERN SPS and at the future RHIC and LHC colliders. It was shown that the interpretation of the J/ψ suppression data could be significantly influenced by these effects.

Investigations into both the fundamental issues of parton energy loss inside dense matter and the phenomenological consequences in high-energy heavy-ion collisions have been carried out. Energetic charm and bottom mesons carry most of the heavy quark energy. Thus, energy loss will be directly reflected in the suppression of large p_T charm or bottom mesons. The influence of final-state interactions of charm quarks upon intermediate mass dileptons at the SPS has been investigated. In higher energy collisions, fragmentation of the heavy quarks has been included and the effect on the dilepton spectrum at the LHC examined. It was found that, contrary to previous expectations, bottom decays will dominate the dilepton continuum at the LHC.

High p_T jet production and propagation has been proposed as a means to investigate the properties of dense matter. The analysis of recent high p_T pion production data at the SPS has helped to narrow down the uncertainties in RHIC predictions due to other nuclear effects such as initial multiple scatterings.

Contributions to heavy quark production beyond leading order and leading twist have also been a subject of study. Near the heavy quark production threshold, soft gluon corrections can be resummed to all orders in perturbation theory. This resummation has now been carried out to next-to-leading logarithm and a complete calculation of the color structure in $q\overline{q} \rightarrow t\overline{t}$ production in the DIS scheme shows that these effects are important at the Fermilab Tevatron. Fast charm hadrons can be produced when the projectile wavefunction contains $c\overline{c}$ fluctuations, known as intrinsic charm. These charm quarks can coalesce with projectile valence spectators to produce large x_F charm hadrons. The coalescence mechanism introduces flavor correlations between the projectile and the final-state hadrons. The model can explain leading charm baryons such as $\Lambda_c^+(udc)$, $\Sigma_c^0(ddc)$, and $\Xi_c^+(usc)$ produced in Σ^-(dds)N interactions at the CERN SPS.

Calculations of dilepton production in heavy ion collisions are continuing. We have implemented the contribution of π–p scattering into a transport code, including the collisional broadening associated with it. We find only small modification of the resulting dilepton spectrum. However, our results agree well with the most recent (preliminary) data from CERES. We further try to provide a better estimate of the effect of baryons. To this end we concentrate on the contribution from the N*(1520) resonance, which has a particularly large coupling to photons. First results indicate that this channel will not change the resulting dilepton spectrum substantially. The calculation concerning dilepton production due to collective deceleration of the nuclei has been completed and the contribution has been found to be negligible.

The lifetime of a disoriented chiral condensate (DCC) in a hadronic environment has been calculated by extending the Lehmann-Symanzik-Zimmermann (LSZ)-reduction formalism to coherent states. It was found that neither higher resonances nor baryons affect the DCC lifetime considerably. For thermal pion densities at T=150 MeV, the lifetime is about 7 fm/c, comparable with the lifetime of the entire system, but at densities three times thermal, as indicated by some event generators, then the lifetime reduces to 1.5 fm/c which would render any detection of DCC states impossible.

For the purpose of making more realistic dynamical simulations of DCC formation, an apparently accurate test-particle method has been developed, simulating the linear σ model in terms of medium-modified quasi-mesons. This advance allows the treatment of realistic geometries, including the significant degree of expansion expected, and it makes it straightforward to take account of the complicated hadronic environment within which the chiral dynamics occurs.

Since both supercritical fields and parametric amplification may occur, the treatment of the chiral dynamics requires real-time quantum-field theory. This problem has been addressed within the mean-field approximation and the resulting insight has proven useful for testing and improving the test-particle simulations in the physically most interesting scenarios as well as providing results that are helpful to the practical data analysis.

Strangeness has been incorporated into the treatment of chiral condensates. At the high temperatures relevant to DCC formation, the strangeness degrees of freedom are agitated and the phase structure is affected significantly (chiral symmetry is harder to achieve). The order-parameter dynamics is richer and may enhance the production of kaons as well.

We have calculated the momentum dependence of the kaon optical potential based on a dynamic picture of the $\Lambda(1405)$. The attraction felt by antikaons at rest disappears at rather moderate momenta (~200 MeV) calling into question the interpretation of current subthreshold K^- data from GSI. At the same time we find that the relevant cross sections for $\pi+\Sigma\rightarrow K^-N$ are increased due to in-medium corrections. However, after implementing the potential as well as the in-medium modified cross section into a transport model, we find only moderate changes in the final K^- yield, leaving the GSI data still as a puzzle.

Increasing attention has been paid to the novel possibility of making extensive statistical analyses of individual RHIC events. As a first result, it was shown that event-by-event fluctuations are directly related to multi-particle inclusive distributions; specifically, the measured gaussian event-by-event fluctuations can be understood in terms of two-particle correlation functions. Furthermore, fluctuations and correlations of rapidity-dependent azimuthal moments of the pion distributions are being studied within the linear sigma model.

Explorations have started of a novel method for detecting the effect of compositional changes in neutron stars due to hyperonization, deconfinement, kaon condensation, etc., on structural changes (such as size and moment of inertia) which will reflect themselves in the time-structure of pulsar spin-down. Such changes are expected because the changing angular velocity and centrifugal force will change the density profile as well, introducing thresholds at which new baryon species can be populated. With each such threshold the equation of state will be softened. Therefore, the transformations will be reflected in the time-dependence of the rotation of the star. The most striking signal of a phase transition could be the spontaneous spin up of a millisecond pulsar that should otherwise be spinning down due to angular momentum loss from radiation. Estimated to be on for about 100 million years, this is a trivial signal to observe. In particular, the signal of a first-order phase transition is strongly registered in the braking index of pulsars - a measurable quantity. It is estimated that the signal will be present in about ten of the presently known pulsars if the phase transition does take place.

In the past year we have continued exploiting our Thomas-Fermi model to study nuclei under extreme conditions of size, deformation and angular momentum. We have worked out the dependence of the nuclear surface energy on the diffuseness of the nuclear surface, and (through a collaboration with A. Sobiczewski's group in Warsaw) this is leading to improved estimates of the properties of superheavy nuclei. We have also made a study of (hyperdeformed) fission saddle-point shapes which, combined with experimental work at the 88-Inch Cyclotron, has provided evidence for our prediction of the shape-dependence of the Wigner term in nuclear binding energies. Our work on the shapes and energies of very deformed nuclei at extreme values of angular momentum has stimulated experiments at the cyclotron searching for so-called Jacobi shapes. (A similar collaboration is under way with R. Broda's group in Krakow, working at the Legnaro Laboratory in Italy). We have continued our collaboration with J. Blocki, J. Skalski and others in Warsaw on chaos and nuclear dynamics, funded by a Polish-U.S. Sklodowska grant, recently renewed for a further three-year period. In the future we plan to increase still further our close contacts with experimental groups at the 88-Inch Cyclotron (regarding superheavies, fission, and high spin) as well as our contacts with Polish physicists.