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Nuclear Theory

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The Nuclear Theory Program, in the NSD at LBNL, seeks to address important problems at the frontier of nuclear science to achieve a deeper understanding of the physical nature of quantal many-body systems at and below the hadronic level. This involves developing and applying theories and methods for prediction, analysis, and interpretation of experiments. While the current research program is primarily focused on high-energy nuclear collisions, significant efforts remain in the areas of compact stellar objects, macroscopic nuclear properties, and chaos studies. The main themes are briefly described below.

QCD Studies at the Partonic Level

A number of critical issues in heavy-ion collisions at RHIC energies and beyond are being addressed on the basis of a QCD-inspired partonic description. While the studies of initial partonic conditions in a collision are being continued, the focus has recently been on large p_T jets as probes of the dense matter, in particular the modification of the effective jet fragmentation function due to the energy loss suffered by the leading parton in a dense medium. Single inclusive spectra at large p_T in normal and direct photon-tagged central events were shown to be very sensitive observables for measuring the effective energy loss. Similar energy-loss effects of the initial produced charmed quarks have also been studied, as has the Cronin effect due to initial multiple parton scattering needed to extract the parton energy loss from inclusive particle spectra.

The effect of high gluon densities in small-x QCD on the evolution of gluons has been investigated. Renormalization group methods have led to a new and general evolution equation for gluons at small x which includes high-density effects to all orders in the gluon density. Current investigations focus on the first non-linear term in the density expansion, corresponding to fusion of two gluon ladders, in order to better understand the size of the area from which gluons are emitted, a major source of conceptual difficulty in existing models. Fusion of more gluon ladders can also be treated and these contribution are essential to the experimental observables at the HERA/LHC kinematic regions.

A number of studies have been directed towards heavy-quark production, both in the initial nucleon-nucleon collisions and in the quark-gluon plasma phase. Heavy quark production has been studied with perturbative QCD, including more detailed studies of next-to-leading logarithm resummation near the production threshold. The knowledge gained from pp physics can help us understand heavy-quark production in heavy-ion collisions at RHIC and LHC although medium effects such as energy loss by heavy quarks moving through the matter and shadowing of the nuclear parton distributions may play an important role. In particular, the spatial dependence of shadowing has been examined for charm production at RHIC. Further studies of related hard processes are underway. If a quark-gluon plasma is produced, the quarks and gluons in the plasma phase may acquire a mass, thus enhancing thermal charm production, an additional source of charm in these collisions.

Quarkonium suppression and dilepton production are especially interesting topics in light of recent CERN SPS data from NA38 and NA50. The J/ψ production ratios relative to Drell-Yan production in Pb+Pb collisions have been shown to be inconsistent with J/ψ suppression by hadrons alone. Plasma production increases the suppression but cannot easily account for any apparent thresholds in the data. It has also been recently shown that part of the intermediate mass dilepton enhancement may be due to Drell-Yan production in secondary meson-baryon interactions.

Manifestations of higher-twist effects on heavy quark production are also studied. The enhancement in the very high Q^2 data at HERA was shown to be larger than could be accounted for in the intrinsic charm model although this effect may contribute to the total enhancement. Charm baryon production by a $\Sigma-$hyperon beam is being studied in the context of this model. A quantum-mechanical final-state coalescence model is under development.

Disoriented Chiral Condensates

Further investigations of phenomena related to disoriented chiral condensates are being carried out. After calculating dilepton production from DCC states, investigations are continuing of how to observe this rather unique signal. It appears that the CERES detector at the CERN SPS should be able to resolve the signal and the calculations are therefore being refined. The hadronic signals for DCC production are also being studied in an attempt to ascertain the degree of degradation due to rescattering in the expanding hadronic phase. It is planned to investigate how the coupling to other degrees of freedom affects the formation and lifetime of DCC states and, furthermore, whether DCC formation can be studied in peripheral heavy-ion collisions.

Moreover, to illustrate how the measurement of the isospin domain structure depends on the ability to zoom in on limited parts of the phase space, wavelet-type methods have been employed for the analysis of pion field configurations obtained by idealized dynamical simulations.

In order to facilitate dynamical simulations of DCC phenomena in the complicated collision environment, a semi-classical transport formulation of the linear sigma model has is been made, leading to a description in terms of individual quasi particles moving with medium-modified effective masses self-consistently with the evolving local order parameter. Of special interest is the possibility of spontaneous particle creation in the superstrong field generated by the expansion-induced quench of the chirally restored matter.

In-Medium Effects and Collision Dynamics

The studies of dilepton production in heavy ion collisions are being continued. In particular, the contribution to the dilepton yield from $\pi-\rho$ collisions has been calculated and a quite sizable contribution was found. Currently, this channel is being incorporated into the transport treatment in order to see if the excess reported by CERES can be accounted for. Moreover, the production of dileptons from the coherent deceleration of heavy ions is also being investigated and the initial results indicate a surprisingly large contribution at SPS energies. This calculation will be extended to BEVALAC energies as well, in order to see to what degree this effect can account for the DLS data.

The photon production cross section has been calculated as a function of the ρ–meson mass and has been shown to be considerably enhanced when the mass of the ρ is reduced. However, calculations with a simple hydrodynamical model for the heavy-ion reaction dynamics suggest that the resulting photon spectrum is still within the upper limit given by experiment.

The momentum dependence of the kaon optical potential has been calculated based on a dynamic picture of the $\Lambda(1405)$. The attraction felt by antikaons at rest disappears at rather moderate momenta (near 200 MeV), calling into question the interpretation of current subthreshold K^- data from GSI. At the same time the relevant cross sections for the reaction $\pi(\Sigma,N)K^-$ are increased due to in-medium corrections. This may provide an alternative explanation of the enhanced subthreshold K^- production, as will be checked with a transport calculation.

Studies of hadron properties at finite temperature have also been made with the non-linear sigma model (with symmetry breaking and an anomaly term added), to determine the temperature dependence of η and η' masses for temperatures up to 150 MeV. The scattering from a heat bath consisting mainly of pions, as obtained by evaluating the relevant one loop diagrams at finite temperature, was found to change the masses by only a few MeV.

It is planned to extend the calculation of chemical equilibration rates to the strange sector and to include the relevant cross section into a transport model.

The confrontation between the recently developed quantum-Langevin molecular dynamics model and experimental data is being steadily broadened. After demonstrating that quantum fluctuations have a significant effect on both intermediate-mass fragment yields for nuclear collisions and on the critical properties of noble gases, application has recently been made to the production of hypernuclei by means of Ξ absorption on C and good qualitative agreement with the (very limited) data was obtained.

The effort to include the collective spin-isospin modes in transport treatments of heavy-ion collisions is also being continued In particular, the recent implementation of the in-medium properties into a transport code has made it possible to make more direct contact with data from heavy-ion collisions.

Compact Stars

We have started investigating 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 milliscond 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 measureable 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.

Low-Energy Macroscopic Phenomena

The long-range aim of this work is to develop a quantitative understanding of the macroscopic properties of nuclei (binding energy, surface energy, density, compressibility, neutron matter, etc.). Using the semi-classical

Thomas-Fermi method, we have recently achieved such a description which yields the binding energy (or mass) of a nucleus as a function of N, Z, and the nuclear shape. The model has been generalized to include angular momentum as well and an approximate description of ground-state, super-deformed and fission-isomeric rotational bands, and the associated moments of inertia has been achieved. Work in progress includes a study of the dependence of the nuclear binding energy on the diffuseness of the nuclear surface. This degree of freedom has an important bearing on the question of which super-heavy nuclei are likely to be the most stable.

The development of a macroscopic theory of nuclear dynamics continues based on the parallel between a transition from ordered to chaotic nucleonic motions and the transition from an elastic to a dissipative collective nuclear response. Recent work focuses on the two essential refinements in with the inclusion of shell effects and of fluctuations around the mean dynamical trajectories. With these improvements the dynamical studies should provide a useful guide to experimental attempts to extend the limits of known elements and isotopes. When heavy nuclei collide at intermediate and high energies, transient systems are formed that have unusual physical properties, being small quantal many-body systems far from equilibrium. Such processes may thus reveal novel aspects of transport theory and their study is a requisite for the analysis and interpretation of low-energy heavy-ion experiments. This has motivated a continuing series of investigations.

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