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STUDIES OF FLUCTUATION PROCESSES IN NUCLEAR COLLISIONS

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TABLE OF CONTENTS

PREFACE	1
1. RELATIVISTIC BOLTZMANN-LANGEVIN MODEL FOR HEAVY-ION COLLISION	2
2. K^+ PRODUCTION FAR BELOW FREE NUCLEON-NUCLEON THRESHOLD	4
3. DAMPING OF COLLECTIVE VIBRATIONS IN A MEMORY-DEPENDENT TRANSPORT MODEL	10
APPENDIX I Publications, etc.	16
APPENDIX II Personnel	17
APPENDIX III Relativistic Boltzmann-Langevin Model for High Energy Heavy-Ion Collisions (reprint) <i>(Removed and cycled separately)</i>	18

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PREFACE

This report summarizes the progress on grant No. DE-FG05-89ER40530 during the period February 15, 1991 to February 29, 1992.

We developed the Boltzmann-Langevin model (BLE) further on the basis of Walecka-type field theory for describing the fluctuation dynamics at relativistic energies. In semi-classical limits, this gives rise to a set of coupled BLEs for the fluctuating distribution functions of interacting nucleons, deltas and pions. We investigated the kaon production mechanism at energies below the free nucleon-nucleon threshold in the framework of the BLE model, and compared the results with similar calculations done within the BUU model. Some results of the calculations are contained in this report. The principal investigator spent a fruitful summer (1991) at Michigan State University, where together with D. Boilley who is a graduate student at GANIL, we studied the damping properties of collective vibrations in a memory-dependent transport model. Two papers have been published (Anns of Phys. and Phys. Lett. B), two manuscripts have been submitted for publication (Nucl. Phys. A and Phys. Lett. B), and one manuscript is in preparation for publication. Several seminars and contributed talks were presented at various meetings.

Most of the work was done in collaboration with E. Suraud, M. Belkacem and D. Boilley of GANIL and P. G. Reinhard of the University of Erlangen. Their collaboration has been very stimulating, and is much appreciated.

The secretarial and accounting duties for this grant have been performed by Gloria Julian of the TTU Department of Physics, and I wish to express my appreciation. I also wish to thank the scientists at MSU-Cyclotron Laboratory, at GANIL, and at GSI for their hospitality during my visits.

1. RELATIVISTIC BOLTZMANN-LANGEVIN MODEL FOR HIGH ENERGY HEAVY-ION COLLISIONS

Recently an extension of the non-relativistic one-body transport has been proposed by incorporating dynamical fluctuations in a stochastic approximation [1–2]. In the semi-classical limit this gives rise to a Boltzmann-Langevin Equation (BLE) for the fluctuating phase-space distribution function and provides a consistent description of the gross properties of the collision dynamics. In the present work, we consider a further development of this approach towards the relativistic domain, in the framework of the Quantum Hadrodynamic Model, by including the delta resonance excitation and pion production in the spirit of ref. [3]. In a sufficiently dilute system, the dynamics is mainly determined by elastic and inelastic binary collisions between nucleons and deltas ($NN \leftrightarrow NN$, $NN \leftrightarrow N\Delta$, $N\Delta \leftrightarrow \Delta\Delta$, etc.), and pions are frequently created and absorbed through the decay and formation of deltas ($\Delta \leftrightarrow N\pi$). The residual two-body interactions play two different roles during the dynamical evolution of the system: (i) production dissipation by randomizing momentum distribution of the constituent particles via binary collisions, and in addition (ii) inducing fluctuations by propagating correlations, which spread the trajectories of single-particle densities in phase-space. These two effects of the residual interactions (i.e., dissipation and fluctuation) can be incorporated into the equation of motion for the single-particle densities [1] or for the one-body Green's functions [4]. In the semi-classical limit together with the quasi-particle approximation, we obtain a set of coupled relativistic BLE's for the phase-space distribution functions of nucleons, deltas and pions, $f_J(p, x)$ $J = N, \Delta, \pi$,

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial p} E_J \cdot \frac{\partial}{\partial x} - \frac{\partial}{\partial x} E_J \cdot \frac{\partial}{\partial p} \right] f_J(p, x) = K_J(f) + \delta K_J(p, x). \quad (1.1)$$

Here, the left-hand side describes the Vlasov propagation which is determined by the relativistic single-particle energies $E_J(p, x)$ of hadrons, and $K_J(f)$ is the collision term for each particle species. The collision term describes the effects of elastic and inelastic

scattering between nucleons and deltas, as well as production and absorption of pions. The additional term $\delta K_J(p,x)$ arises from correlations not accounted for by the collision term, and is referred to as the fluctuating collision term. As a matter of fact, such an additional term always arises in transport theory whenever we deal with a reduced dynamical description, and it describes the coupling to the remaining degrees of freedom due to correlations. In analogy with Brownian motion, we assume that eq. (1.1) describes a stochastic process in which the entire distribution function $f_J(p,x)$ for each J is a stochastic variable and $\delta K_J(p,x)$ acts like a random force. In such a stochastic description, the fluctuating collision term is characterized by a correlation matrix,

$$\langle \delta K_J(p,x) \delta K_{J'}(p',x') \rangle = C_{JJ'}(p,x;p',x') \delta^{(4)}(x-x') \quad (1.2)$$

which is assumed to be local in $x = (t,r)$ due to the localized collisions in space and time. Once the collision term K_J and the correlation matrix $C_{JJ'}$ are explicitly evaluated, eq. (1.1) becomes a well-defined stochastic transport equation for the fluctuating distribution function $f_J(p,x)$ for each hadron species, and it is referred to as the relativistic BLE. The collision term describes dissipation, that is, the approach toward equilibrium, and the fluctuating collision term together with its correlation matrix determines the fluctuations.

A brief description of the model has recently appeared in Phys. Lett. B [5], a copy of which is enclosed in the appendix of this progress report. A detailed description will be presented in a subsequent publication.

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2. K⁺ PRODUCTION FAR BELOW FREE NUCLEON-NUCLEON THRESHOLD (with M. Belkacem and E. Suraud)

We investigate the kaon production mechanism at energies below the free nucleon-nucleon threshold in the framework of the Boltzmann-Langevin Equation (BLE) (see section 1), and compare the results with similar calculations done within the Boltzmann-Uehling-Uhlenbeck (BUU) model [1], and estimate the K⁺ production cross-section in ⁴²Ca + ⁴²Ca collisions at the bombarding energy of 92 MeV/n [2].

The BUU model describes the average one-body distribution function in the independent binary collision approximation. On the other hand, the BLE approach [3-4] goes beyond the average description of the BUU by incorporating the effects of high order correlations in a stochastic approximation. These correlations give rise to large fluctuations in the local momentum distribution during the early stages of the collision process. Since the particle production mechanism at sub-threshold energies involves high energy tails of the momentum distribution, it is expected that the fluctuations in the momentum distribution play an important role for a proper description of the particle production cross-sections.

Kaons are produced predominantly in the elementary baryon-baryon collision, $B+B' \rightarrow B''+K+Y$, where B , B' and B'' are either a nucleon N or a delta Δ , and Y represents either a Λ - or a Σ -hyperon. The channels with pions, $\pi+B \rightarrow K+Y$, are also taken into account, but their contributions are negligible at bombarding energies below 1.0 GeV/n [5], hence these contributions are neglected in the present calculations. Because of small production cross-sections at energies below the nucleon-nucleon threshold, we use a perturbative approach and calculate the invariant K⁺ production cross-section according to

$$E \frac{d^3}{dp^3} \sigma = \sum_c \int 2\pi b db \int dt \int d^3r d^3p_B d^3p_{B'} |\mathbf{v}_B - \mathbf{v}_{B'}| E \frac{d^3}{dp^3} \sigma_c \cdot Z \quad (2.1)$$

where $\frac{d^3}{dp^3} \sigma_c(B+B' \rightarrow K)$ denotes the elementary cross-section in the channel "c" leading to a K⁺ production. In the BUU model, the factor Z is given in terms of the ensemble averaged one-body distribution function $f(\mathbf{r}, \mathbf{p}, t)$ by

$$Z \rightarrow Z_{\text{BUU}} = f(r, p_B, t) f(r, p_{B'}, t) [1 - f(r, p_{B''}, t)]. \quad (2.2)$$

In the BLE model, the K^+ production cross-section is evaluated using the same formula of eq. (2.1), but the factor Z is determined by the average over an ensemble of the solutions $f_\lambda(r, p, t)$ of the BLE,

$$Z \rightarrow Z_{\text{BLE}} = \overline{f_\lambda(r, p_B, t) f_\lambda(r, p_{B'}, t) [1 - f_\lambda(r, p_{B''}, t)]} \quad (2.3)$$

where the index " λ " refers to the events of the BLE, eq. (1.1). In either case, the formula of eq. (2.1) essentially represents the folding of the elementary cross-section with the momentum distributions of the colliding baryons in which the Pauli blocking of the final nucleon state is properly incorporated.

For an accurate calculation of the production cross-section in the BLE approach, a sufficient number of the solutions of eq. (1.1) is required. In our calculations, we determine the solutions of the BLE using an approximate method developed in ref. [6]. According to this method, the fluctuating events of eq. (1.1) are determined by following the fluctuations in a set of multipole moments of the momentum distribution. Here, we consider a single moment, namely the z -component of the quadrupole moment of the momentum distribution, $Q_{zz} = 3p_z^2 - p_x^2 - p_y^2$. The events of the BLE are generated iteratively by first calculating the fluctuations in the quadrupole moment during each time step, then by scaling the momentum distribution to a specific quadrupole deformation while preserving the conservation laws.

We carry out numerical calculations for K^+ production cross-section in $^{12}\text{C} + ^{12}\text{C}$ collisions in an energy range of 0.6 – 1.0 GeV/n in both the BLE and the BUU approaches. In the calculations, we use the same input data as Cugnon and Lombard [7]. Figure 1 shows the K^+ production cross-section as calculated in the BUU model. The dotted curve represents the cross-section for a compressibility of $K = 200$ MeV (soft) while the dashed-dotted curve corresponds to a compressibility of $K = 380$ MeV (stiff). The solid curve reflects the K^+ cross-section arising from the simulations with no mean field, and the points are from Cassing, et al. [8]. Figure 2 shows the K^+ cross-section as a function of the beam

energy calculated both in the BLE and the BUU models with a soft mean field. As seen, the calculations with fluctuations give larger cross-sections than those obtained in the BUU model, however, the difference tends to disappear for increasing beam energy.

In order to test the reliability of our numerical calculations of the BLE model, we simplify the calculations at the expense of introducing further approximations, and we develop an analytical model. We consider that the events of the BLE is characterized by a single collective variable and take the z-component of the quadrupole moment of the momentum distribution, Q , as the collective variable, $f_{\lambda}(r,p,t) \rightarrow f_Q(r,p,t)$, and assume that the distribution function $P(Q,t)$ of Q 's is a Gaussian determined by its mean value $\bar{Q}(t)$ and width $\sigma_Q(t)$. Then, the K^+ cross-section is evaluated according to eq. (2.1) with the factor Z now given by

$$Z \rightarrow Z_Q = \rho(r)^2 \int P(Q) dQ n_Q(p_B, t) n_Q(p_{B'}, t) [1 - n_Q(p_{B'}, t)] \quad (2.4)$$

where the one-body distribution function is approximated as $f_Q(r,p,t) = \rho(r) n_Q(p,t)$. The quantities, the mean value $\bar{Q}(t)$ and the width $\sigma_Q(t)$ of $P(Q,t)$, and the momentum distributions $n_Q(p,t)$ with fixed values of the quadrupole moment are extracted in the numerical simulations of the BLE with a reasonable number of events, and then they are used in eq. (2.1) to evaluate the K^+ production cross-section. In Figure 2, the analytical calculations are indicated by dots, and they are seen to be in good agreement with the numerical simulations. In order to estimate the K^+ production cross-section in $^{42}\text{Ca} + ^{42}\text{Ca}$ collisions at the beam energy of 92 MeV/n, we perform calculations with the analytical model. We obtain a total cross-section of $\sigma_K = 5.3 \times 10^{-7}$ mb which seems to be in good agreement with the measured cross-section of $\sigma_K = (2.4 \pm 1.5) \times 10^{-7}$ mb.

A paper on this topic is near completion and will be submitted to Phys. Lett. B for publication.

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FIGURE 1

Inclusive cross section of K^+ production in $^{12}\text{C} + ^{12}\text{C}$ collisions versus bombarding energy per nucleon. Points are from Cassing, et al. [8]. Our calculations are performed with a momentum-independent mean field.

FIGURE 2

Comparison between the numerical simulations of both the BUU (dashed line) and the BLE (solid line) approaches and the analytical model. The K^+ production cross section in $^{12}\text{C} + ^{12}\text{C}$ collisions is plotted as a function of kinetic energy in the laboratory per nucleon. The simulations are performed with a soft momentum-independent mean field.

3. DAMPING OF COLLECTIVE VIBRATIONS IN A MEMORY-DEPENDENT TRANSPORT MODEL (with D. Boilley)

In this work we calculate the spreading width of collective vibrations due to collisional damping in the basis of a semi-classical transport equation with a memory dependent collision term [1-3]. We obtain a simple analytical expression which provides a reasonable description for the observed damping widths of isoscalar and isovector giant resonances in medium mass and heavy nuclei at zero temperature, as well as at finite temperatures [4].

First, we consider the isoscalar vibrations and in the next step, we extend the treatment to the isovector modes. We assume that the spin-isospin averaged momentum distribution is determined by a Boltzmann-type transport equation with a memory dependent collision term as [3],

$$\frac{\partial}{\partial t} f(\mathbf{p}, t) \equiv K(f) = \int_0^\infty d\tau \int d^3p_2 d^3p_3 d^3p_4 \frac{W}{2\pi} (e^{i\tau\Delta\epsilon} + e^{-i\tau\Delta\epsilon}) \cdot [(1-f_1)(1-f_2)f_3f_4 - f_1f_2(1-f_3)(1-f_4)]_{t-\tau} \quad (3.1)$$

where all the occupation factors $f_j = f(\mathbf{p}_j, t)$ are evaluated at time $t-\tau$, $\Delta\epsilon = \epsilon_3 + \epsilon_4 - \epsilon_1 - \epsilon_2$ and W denotes the spin-isospin averaged transition rates. We linearize the memory dependent transport eq. (1) around a finite temperature equilibrium $f_0(\mathbf{p})$,

$$f(\mathbf{p}, t) = f_0(\mathbf{p}) + \delta f(\mathbf{p}, t) = f_0(\mathbf{p}) + \chi(\mathbf{p}, t) \frac{\partial}{\partial \epsilon} f_0 \quad (3.2)$$

where $\chi(\mathbf{p}, t) = \alpha_L e^{i\Omega t} p^L P_L(\theta)$ characterizes the multipolarity of the distortion of the momentum distribution from spherical equilibrium with $P_L(\theta)$ as a Legendre function, and Ω is the frequency of the harmonic vibrations.

We define the relaxation rate of the distorted momentum distribution as,

$$\frac{1}{\tau_s} = - \frac{\int d^3p \chi(\mathbf{p}) \delta K_s}{\int d^3p \chi(\mathbf{p}) \delta f_s}$$

$$= \frac{\int d^3p_1 d^3p_2 d^3p_3 d^3p_4 \frac{W}{4} [\delta(\Delta\epsilon - \Omega) + \delta(\Delta\epsilon + \Omega)] \Delta\chi \delta F}{\int d^3p \chi^2 \frac{\partial}{\partial \epsilon} f_0} \quad (3.3)$$

where δK_s is the linearized collision term, $\Delta\chi = \chi_1 + \chi_2 - \chi_3 - \chi_4$ with $\chi_j = \chi(\mathbf{p}_j)$ and the subscript "s" refers to the situation that τ_s is the relaxation rate for the isoscalar modes. Incorporating the memory effects in the transport eq. (3.1) enforces the energy conservation between the collective state, with energy $\hbar\Omega$, and the more complicated two particle-two hole states in the relaxation rate, and properly accounts for the available phase-space for damping. On the other hand, the Markovian approximation consists of replacing the proper energy conserving factors $\delta(\Delta\epsilon - \Omega)$ and $\delta(\Delta\epsilon + \Omega)$ with $\delta(\Delta\epsilon)$ in eq. (3.3); consequently, the resultant expression severely restricts the available phase-space for damping. In particular, at zero temperature all two-body collisions are Pauli blocked and hence the collisional width vanishes in the Markovian approximation. Using the fact that transitions are concentrated around the vicinity of the Fermi surface, and employing the standard coordinate transformation [5], the energy and angular parts of the momentum integrals in eq. (3.3) can approximately be factored as

$$\frac{1}{\tau_s} = \left[\frac{m}{2} \right]^3 \int d\epsilon_1 d\epsilon_2 d\epsilon_3 d\epsilon_4 Z f_1^0 f_2^0 (1-f_3^0) (1-f_4^0) \cdot I_s. \quad (3.4)$$

Here $Z = \frac{\partial}{\partial \Omega} [\delta(\Delta\epsilon + \Omega) - \delta(\Delta\epsilon - \Omega)]$ and the angular part of the integral with the notation of ref. [5] is given by

$$I_s = \frac{\int d\Omega_1 d\Omega d\phi (\cos \frac{\theta}{2})^{-1} W (\Delta P_L)^2}{\int d\Omega P_L^2} \quad (3.5)$$

with $\Delta P_L = P_L(\theta_1) + P_L(\theta_2) - P_L(\theta_3) - P_L(\theta_4)$. In order to describe the damping of isovector modes we generalize this treatment by distinguishing proton and neutron degrees of freedom in the relaxation process. For the relaxation rate of isovector modes, τ_v , we obtain an expression similar to eq. (3.4) with an angular part I_v corresponding to isovector distortions. In terms of the relaxation rates, we determine the spreading width of collective vibrations at finite temperatures using the relations, $\Gamma_s = \frac{\hbar}{\tau_s}$ and $\Gamma_v = \frac{\hbar}{\tau_v}$. Assuming

isotropic scattering cross-sections, the relevant energy and angular integrals in τ_s and τ_v can be evaluated analytically, and we find simple analytical formulas for the spreading widths. The formula for the width of isoscalar quadrupole and octupole vibrations ($L = 2,3$) is given by

$$\Gamma_s = \hbar \frac{4\pi^2}{2L+1} \sigma_s \rho v_F \left[\left(\frac{\hbar\Omega}{\pi\epsilon_F} \right)^2 \frac{3}{4} + \left(\frac{T}{\epsilon_F} \right)^2 \right] \quad (3.6)$$

where $\sigma_s = (\sigma_{pp} + \sigma_{nn} + 2\sigma_{pn})/4$ is the spin-isospin averaged cross-section and ρ , v_F denote the nuclear matter density and Fermi velocity, respectively. Similarly, the formula for the spreading widths of isovector dipole and quadrupole vibrations ($L = 1,2$) is given by

$$\Gamma_v = \hbar \frac{4\pi^2}{2L+1} \sigma_v \rho v_F \left[\left(\frac{\hbar\Omega}{\pi\epsilon_F} \right)^2 \frac{3}{4} + \left(\frac{T}{\epsilon_F} \right)^2 \right] \quad (3.7)$$

where $\sigma_v = \sigma_{pn}/2$ for $L = 1$ and $\sigma_v = (\sigma_{pp} + \sigma_{nn} + 2\sigma_{pn})/4$ for $L = 2$. The effect of partial cancellation between particle and hole amplitudes of the collisional damping is automatically incorporated into eqs. (3.6) and (3.7) for the widths [1]. In particular this cancellation becomes complete for the isoscalar monopole mode as seen from the fact the angular integral I_s in eq. (3.5) vanishes for $L = 0$. As a result, the spreading width of the monopole vibration vanishes in the linearized limit of the collision term in eq. (3.1).

We apply the formulas (3.6) and (3.7) to describe the damping of isovector giant dipole and isoscalar giant quadrupole resonances. In numerical calculations we use a Fermi momentum of $k_F = 1.34/\text{fm}$ to obtain the Fermi energy, the Fermi velocity and the nuclear matter density as $\epsilon_F = 37 \text{ MeV}$, $v_F = 0.28c$ and $\rho = 0.16/\text{fm}^3$. For the cross-sections, we use the free space values, $\sigma_{pp} = \sigma_{nn} \simeq 25\text{mb}$ and $\sigma_{pn} \simeq 50\text{mb}$, which give a spin-isospin averaged cross-section of $\sigma = 37.5\text{mb}$. Figure 1. shows the results of calculations and a comparison with the measured damping widths of dipole and quadrupole resonances at zero temperature as a function of the atomic mass number of nuclei. For the mass dependence of the resonance energies for spherical medium mass and heavy nuclei we use the formulas

$$\hbar\Omega_D = 80A^{-1/3} \text{ MeV}, \quad \hbar\Omega_Q = 64A^{-1/3} \text{ MeV}. \quad (3.8)$$

The mass dependence of the damping widths in the calculation, $A^{-2/3}$, arises entirely from

the mass dependence of resonance energies. As seen from the figure, except for light nuclei, calculations describe rather well the average trend of damping widths of giant dipole and giant quadrupole resonances over a broad mass range. Figure 2 shows the calculated spreading width of the giant dipole resonance in ^{108}Sn , in comparison with the experimental data as a function of excitation energy E^* which is related to temperature through the relation $E^* = a T^2$ with $a = \pi^2 A / 4 \epsilon_F$. Both the experimental and the calculated widths increase linearly with excitation energy, but the slope of the calculated curve is somewhat smaller than the experimental one.

Overall, our calculations provide a reasonable description for the gross properties of the damping widths of giant dipole and giant quadrupole resonances at zero and at finite temperatures. Some shortcomings of the calculations can be attributed to the escape width due to direct nucleon emission which has not been incorporated into the calculations yet.

A paper on this topic has been submitted to Phys. Lett. B for publication.

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FIGURE 1

The atomic mass number dependence of the damping width for the giant dipole resonance (upper part) and the giant quadrupole resonance (lower part).

FIGURE 2

The excitation energy dependence of the damping width for the giant dipole resonance in ^{108}Sn nucleus.

APPENDIX I

PAPERS

"Boltzmann-Langevin Equation Derived from Real-Time Path Formalism," P. G. Reinhard, E. Suraud and S. Ayik, Ann. Phys, (1991), in press.

"Relativistic Boltzmann-Langevin Model for High Energy Heavy-Ion Collisions," S. Ayik, Phys. Lett. B265 (1991) 47.

"Damping of Collective Vibrations in a Memory-Dependent Transport Model," S. Ayik and D. Boilley, Phys. Lett. B (1991), in press.

"Application of Boltzmann-Langevin Equation to Nuclear Collisions," E. Suraud, S. Ayik, M. Belkacem and J. Stryjewski, submitted to Nucl. Phys. A (1991).

SEMINARS

"Relativistic Boltzmann-Langevin Model," GSI, Darmstadt, Germany (1991); and GANIL, Caen, France (1991).

"The Boltzmann-Langevin Equation," Michigan State University, East Lansing, MI (1991).

"The Boltzmann-Langevin Approach," Workshop on Equilibrium and Non-Equilibrium Physics at Finite Temperature, Telluride, CO (1991).

CONFERENCE CONTRIBUTIONS

"Towards Stochastic Extensions of Quantal and Semi-Classical Dynamical Theories," P. G. Reinhard, E. Suraud, S. Ayik and M. Belkacem, Int. Workshop on Gross Properties of Heavy-Ion Collisions, Hirschegg, Austria (1991).

"Memory Effects in Damping of Collective Vibrations," S. Ayik and D. Boilley, Winter Workshop on Nuclear Dynamics, Jackson, WY (1992).

APPENDIX II PERSONNEL

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D. Boilley, Graduate Student

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APPENDIX III

(papers removed and cycled separately)—

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