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STUDIES OF FLUCTUATION PROCESSES IN NUCLEAR COLLISIONS

PROGRESS REPORT

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PREFACE

This report summarizes the progress on grant No. DE-FG05-89ER40530 during the period May 1, 1994 to February 28, 1995.

Work has continued for extending the Boltzmann-Langevin (BL) model by incorporating the memory effect associated with finite duration of binary collisions. In collaboration with J. Randrup, we applied this extended BL model to study the early evolution of the unstable nuclear matter in the spinodal zone and investigated the influence of the memory effect on transport properties of the unstable collective modes. Also, using this non-Markovian transport model we investigated the collisional relaxation of the giant monopole vibrations in nuclei. Four papers have appeared in Nucl. Phys. A and Z. Phys. A; two papers have been accepted for publication, both in Phys. Rev. C; and one paper has been submitted to Phys. Rev. C for publication. Several seminars were presented at various institutions.

Most of the work was done in collaboration with M. Belkacem, A. Bonasera Y. B. Ivanov, V. N. Kondratyev, and J. Randrup. Their collaboration has been very stimulating and much appreciated.

The secretarial and accounting duties for this grant have been performed by Gloria Julian, CPS, of the TTU Department of Physics, and I wish to express my appreciation. I also wish to thank the theory groups at LBL, Berkeley; INT, Seattle; GANIL, Caen; and LNS-INFN, Catania for their hospitality during my visits.

1. MEMORY EFFECT IN BOLTZMANN-LANGEVIN MODEL

We summarize the recent progress by incorporating the memory effect associated with finite duration of binary collisions into the Boltzmann-Langevin (BL) model. According to this model, the evolution of the phase-space density $f(r,p)$ is determined by a stochastic transport equation [1,2],

$$\frac{\partial}{\partial t} f + \{h(f), f\} = K(f) + \delta K. \quad (1.1)$$

Here, the l.h.s. describes the Vlasov propagation in terms of an effective one-body Hamiltonian $h(f)$. In the r.h.s. $K(f)$ is a binary collision term and δK denotes its stochastic part which is characterized by a correlation function. In the standard BL model, the binary collisions are treated in a Markovian approximation by assuming that the duration time τ_d of collisions is much shorter than the mean-free-time τ_λ between collisions, $\tau_d \ll \tau_\lambda$. This yields, the Boltzmann-Uehling-Uhlenbeck (BUU) form with on-shell binary scattering for the collision term, and the stochastic collision term can be treated as a white noise with a local space-time correlation function. The standard description provides a good approximation for heavy-ion collisions up to about 200 MeV/n when the system does not involve fast collective modes.

On the other hand, when the system possesses fast collective modes, for example in high frequency collective vibrations or in rapidly growing unstable modes, the Markovian approximation breaks down and memory effect due to finite duration of collisions becomes important. The finite duration time allows for a direct coupling between binary collisions and the collective modes, which gives rise to an appropriate quantum statistical description of the collective modes, whereas in the standard BL treatment transport properties of the collective modes exhibit a

classical character. In this case, a non-Markovian treatment should be carried out by including the finite durations of the binary collisions, in analogy with treatment of the quantal Brownian motion [3]. The non-Markovian binary collision term can be expressed as,

$$K(f) = \int d\mathbf{p}_2 d\mathbf{p}_3 d\mathbf{p}_4 \int_0^t d\tau \tilde{W}(12;34;\tau) [\tilde{f} \tilde{f}_2 f_3 f_4 - f f_2 \tilde{f}_3 \tilde{f}_4]_{t-\tau} \quad (1.2)$$

where $f_j = 1 - f_j$, and $\tilde{W}(12;34;\tau)$ is a binary collision kernel which should be calculated by taking into account for the variation of the mean-field in time. The stochastic collision term becomes a color noise characterized by a non-local correlation function. It is convenient to introduce its frequency decomposition according to [2,3]

$$\langle \delta K(\mathbf{r}, \mathbf{p}, t) \delta K(\mathbf{r}', \mathbf{p}', t') \rangle = \int \frac{d\omega}{2\pi} e^{-i\omega(t-t')} C(\mathbf{p}, \mathbf{p}'; \omega) \delta(\mathbf{r} - \mathbf{r}') \quad (1.3)$$

where $C(\mathbf{p}, \mathbf{p}'; \omega)$ denotes the spectral density of the correlation function. The spectral density is given by the standard expression of the correlation function in the Markovian limit, except that the transition rate $W(12;34)$ in the standard expression is replaced by a frequency dependent rate,

$$W(12;34; \omega) = W(12;34) \frac{1}{2} [\delta(\Delta\epsilon - \omega) + \delta(\Delta\epsilon + \omega)] \quad (1.4)$$

with $\Delta\epsilon = \epsilon_3 + \epsilon_4 - \epsilon_1 - \epsilon_2$ and

$$G(\omega) = \exp\left[-\frac{1}{2}(\tau_d \omega)^2\right]. \quad (1.5)$$

In this expression, the factor $G(\omega)$, specified by the duration time τ_d , acts as a cut-off function for the off-shell scattering, and it modulates the frequency spectrum of the correlation function.

For a description of small amplitude fluctuations around a stable or an unstable equilibrium state characterized by a Fermi-Dirac function $f_0(\epsilon)$, we can linearize the BL eq. (1.1). As a result, the small fluctuations of the phase-space density

$$\delta f(\mathbf{r}, \mathbf{p}; t) = f(\mathbf{r}, \mathbf{p}; t) - f_0(\epsilon) \equiv \chi(\mathbf{r}, \mathbf{p}; t) \frac{\partial}{\partial \epsilon} f_0 \quad (1.6)$$

is determined by a linearized transport equation,

$$\frac{\partial}{\partial t} \delta f + \{\delta h, f_0\} + \{h_0, \delta f\} = \int d\mathbf{p}_2 d\mathbf{p}_3 d\mathbf{p}_4 \delta W [\tilde{f}^0 \tilde{f}_2^0 f_3^0 f_4^0 - f^0 f_2^0 \tilde{f}_3^0 \tilde{f}_4^0] + \delta K_0. \quad (1.7)$$

In this expression, the transition rate is given by

$$\delta W = \int \frac{d\omega}{2\pi} e^{-i\omega t} W(12;34) \Delta\chi(\omega) Z(\omega) \quad (1.8)$$

where $Z(\omega) = [\delta(\Delta\epsilon - \omega) - \delta(\Delta\epsilon + \omega)]/2\omega$ and $\Delta\chi(\omega) = \chi_3(\omega) + \chi_4(\omega) - \chi_1(\omega) - \chi_2(\omega)$ with $\chi_j(\omega) = \chi(\mathbf{r}, \mathbf{p}; \omega)$ as the Fourier transform of the distortion function $\chi(\mathbf{r}, \mathbf{p}; t)$.

A paper on the formal aspect of this topic has recently appeared in Z.Phys A [2], and the work on a second paper is currently in progress.

2. EFFECT OF MEMORY TIME ON AGITATION OF UNSTABLE MODES IN NUCLEAR MATTER (with J. Randrup)

The early evolution of the unstable nuclear matter in the spinodal zone has been recently addressed in the framework of the BL model in refs. [4,5]. The system is mechanically unstable and the density fluctuations generated by the stochastic collision term may be amplified by the self-consistent mean-field, leading towards catastrophic transformation of the system into an assembly of nuclear clusters. In this work, we consider this problem on the basis of the extended BL model described in part 1 of this report and investigate the effect of finite duration on transport properties of the unstable modes [6].

In the application of the linearized BL eq. (1.7) to nuclear matter, it is convenient to perform a Fourier transform with respect to position,

$$\delta f(\mathbf{r}, \mathbf{p}; t) = \sum \frac{1}{\sqrt{V}} \delta f_k(\mathbf{p}, t) e^{-i\mathbf{k} \cdot \mathbf{r}} \quad (2.1)$$

where V is the volume of the system. Then, the linearized BL equation can be solved for $\delta f_k(\mathbf{p}, t)$ either by employing the response function approach or by the RPA treatment [7,8]. For each wave number k , there are two collective modes with frequencies $\pm \Omega_k$ determined by a dispersion relation. These frequencies are imaginary for the unstable modes and real for the stable modes. The fluctuating phase-space density can then be expanded in terms of the RPA modes,

$$\delta f_k(\mathbf{p}, t) = \sum A_k(t) f_k(\mathbf{p}) \quad (2.2)$$

where $A_k(t)$ denotes the amplitude associated with the RPA mode $f_k(\mathbf{p})$.

Substituting the expansion (2.2) into the linearized BL equation, it is possible to deduce equations for the stochastic evolution of the amplitudes $A_k(t)$. It is convenient to express these equations in terms of the correlation functions $\sigma_k^2(t) = \langle A_k(t) A_k(t)^* \rangle$. Keeping only the growing modes in the spinodal region or the positive modes in the stable region, we obtain,

$$\frac{d}{dt} \sigma_k^2 + i(\Omega_k - \Omega_k^*) \sigma_k^2 = -\Gamma_k \sigma_k^2 + 2D_k. \quad (2.3)$$

Here, the quantities Γ_k and D_k denote the collisional damping width and the diffusion coefficient associated with the mode. These transport coefficients can be expressed as

$$2D_k = \int_0^t ds e^{-i\Omega_k s} \int \frac{d\omega}{\pi} e^{i\omega s} C_k(\omega) \quad (2.4)$$

$$\frac{1}{2} \Gamma_k = \int_0^t ds e^{-i\Omega_k s} \int \frac{d\omega}{\pi} e^{i\omega s} \tilde{C}_k(\omega) \quad (2.5)$$

where the quantities $C_k(\omega)$ and $\tilde{C}_k(\omega)$ are determined by the spectral density $C(\mathbf{p}, \mathbf{p}'; \omega)$ of the correlation function of the stochastic collision term. The quantity $\tilde{C}_k(\omega)$ is related to $C_k(\omega)$ as

$$C_k(\omega) = N_k \coth \frac{\omega}{2T} \tilde{C}_k(\omega) \quad (2.6)$$

where N_k is a normalization factor. This relation reflects the quantal fluctuation-dissipation relation between the damping width Γ_k and the diffusion coefficient D_k .

For temperature T and the energy exchange $\hbar\omega$ are small in comparison to the Fermi energy, $\hbar\omega$, $T \ll \epsilon_F$, it is possible to factor out the ω dependence in $C_k(\omega)$ and $\tilde{C}_k(\omega)$ [9]. Then the transport coefficients can be expressed as a product of their classical value and a correction factor. As a result, the solution of eq. (2.3) for the density correlation function can be given as

$$\sigma_k^2(t) = \overset{o}{\sigma}_k^2(t) \cdot \chi_k(t) \quad (2.7)$$

where $\overset{o}{\sigma}_k^2(t)$ denotes the correlation function obtained without the memory effect and $\chi_k(t)$ is a time dependent enhancement factor due to the memory effect, which strongly depends on temperature and the frequency of the mode. In the spinodal region for the fastest growing modes at typical temperatures, this enhancement factor is about 50-100%. As an example in fig. (2.1), the enhancement factor is shown as a function of time for the most unstable mode corresponding to density $\rho=0.3\rho_0$ at temperature $T=4$ MeV in part (a) and $T=6$ MeV in part (b).

A paper on this topic is in press in Phys. Rev. C [6] and another one has been submitted to Phys. Rev. C [8] for publication.

Figure 2.1

3. NON-MARKOVIAN APPROACH TO DAMPING OF GIANT MONOPOLE RESONANCES IN NUCLEI (with M. Belkacem and A. Bonasera)

The linear response treatment of the BL model summarized in part 1 of this report provides a basis for a description of collective vibrations in nuclei. In particular, the collisional relaxation rate τ_R of an isoscalar vibration with a frequency ω can be calculated using the expression,

$$\frac{1}{\tau_R} = \frac{\int dr dp_1 dp_2 dp_3 dp_4 W Z(\omega) (\Delta\chi)^2 f_1^0 f_2^0 (1-f_3^0)(1-f_4^0)}{2 \int dr dp \chi^2 \frac{\partial}{\partial \epsilon} f_0} \quad (3.1)$$

where the quantities $Z(\omega)$ and $\Delta\chi$ are defined in eq. (1.8) for the linearized collision term with memory effect. In a previous study, this expression has been used to estimate the relaxation rate of giant quadrupole vibrations [10].

In this work, using the expression (3.1), we calculate the relaxation rate of giant monopole vibrations [11]. In the scaling description of the monopole vibrations with a velocity field of the form $\phi = r^2/2$, the Fermi surface remains spherical but oscillates radially with the monopole frequency. Therefore, the relaxation rate and hence the collisional width $\Gamma = \hbar/\tau_R$ can be estimated by taking $\chi = p^2$ for the distortion function. When the collective energy $\hbar\omega$ and temperature T are small as compared to the Fermi energy, $\hbar\omega, T \ll \epsilon_F$, two-body transitions in eq. (3.1) are concentrated in the vicinity of the Fermi surface. In this case, the momentum integrals can be calculated analytically [9]. For an isotropic cross-section σ and uniform nuclear density ρ , we find

$$\Gamma \cong \hbar V_F \sigma \rho \left[\left(\frac{\hbar\omega}{\epsilon_F} \right)^2 + \left(\frac{2\pi T}{\epsilon_F} \right)^2 \right] \left(\frac{\hbar\omega}{4\epsilon_F} \right)^2. \quad (3.2)$$

In fig. (3.1), the dotted line shows the result of this analytical approximation to the collisional width at zero temperature as a function of the atomic mass number of nuclei. We take the nuclear matter parameters as $\rho = 0.16 \text{ fm}^{-3}$, $V_F = 0.28c$, $\epsilon_F = 37 \text{ MeV}$ and the total cross-section $\sigma = 40 \text{ mb}$. For the mass-dependence of the resonance energies for $A \geq 70$ we use the formula,

$$\hbar\omega = 31.2 A^{-\frac{1}{3}} + 20.6 A^{-\frac{1}{6}} \text{ MeV} \quad (3.3)$$

and for $A < 70$ we take $\hbar\omega = 17.5 \text{ MeV}$.

In order to check the accuracy of the analytical approximation, we carry out numerical evaluation of the momentum integrals in eq. (3.1) by the Monte-Carlo method with the same nuclear matter parameters. The result of this calculations are shown in fig. (3.1) by dashed-dotted line. This result indicates that the analytical expression (3.2) provides a good approximation for eq. (3.1) in the nuclear matter limit, but it gives rise to a very small collisional width. We also incorporate the surface effects into the calculations in a local density approximation by parametrizing the nuclear density distribution $\rho(r)$ in terms of a Fermi function. The integrands in eq. (3.1) depend on r through the Fermi energy,

$$\epsilon_F(r) = \frac{\hbar^2}{2m} \left[\frac{3\pi}{2} \rho(r) \right]^{\frac{2}{3}}. \quad (3.4)$$

We repeat the Monte-Carlo evaluation of eq. (3.1) by including the surface effects with the isotropic cross-section $\sigma = 40 \text{ mb}$, and with an energy-angle dependent cross-section as parametrized in ref. [12]. These results with the isotropic cross-section and with the energy-angle dependent cross-section are indicated by dashed line and solid line in fig. (3.1), respectively. The calculated widths including surface effects with energy-angle dependent cross-

section are about a factor of 2 to 4 larger than those obtained with constant cross-section, but account only for a small fraction of the experimental damping widths of the giant resonances, which are indicated by solid dots in fig. (3.1).

A paper on this topic has been accepted for publication in Phys. Rev. C [11].

Figure 3.1

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APPENDIX I

Papers

"Stochastic Multi-Fluid Models for Intermediate Energy Heavy-Ion Collisions," S. Ayik, Y. B. Ivanov, V. N. Ruskikh and W. Norenberg, Nucl. Phys. A578 (1994) 640.

"A Bohr-Mottelson Model of Nuclei at Finite Temperature," D. Boilley, Y. Abe, S. Ayik and E. Suraud, Z. Phys. A349 (1994) 119.

"Simplified Nuclear Boltzmann-Langevin Simulation," J. Randrup and S. Ayik, Nucl. Phys. A572 (1994) 489.

"Long-Range Correlations in Boltzmann-Langevin Model," S. Ayik, Z. Phys. A350 (1994) 45.

"Effect of Memory Time on the Agitation of Unstable Modes in Nuclear Matter," S. Ayik and J. Randrup, Phys. Rev. C (1994), in press.

"Non-Markovian Approach to Damping of Giant Resonances in Nuclei," S. Ayik, M. Belkacem and A. Bonasera, Phys. Rev. C (1994), in press.

Seminars

"Memory Effect in Boltzmann-Langevin Model," presented at INFN-LNS, Catania, Italy (May 1994); Workshop on Hot and Dense Nuclear Matter, INT, Seattle (September 1994); GANIL, Caen, France (November 1994); and University of Rostock, Rostock, Germany (December 1994).

Conference Contribution

" β -Decay Probing the Electron Bulk Correlations," V. N. Kondratyev and S. Ayik, IV Int. School on Nuclear Physics, Kiev, Ukraine, 1994..

"Stochastic Approaches to Dynamics of Heavy-Ion Collisions: The Case of Thermal Fission," D. Boilley, E. Suraud., Y. Abe and S. Ayik, RIKEN Symposium on Nuclear Dynamics at Finite Temperature, Tokyo, Japan (1994).

"On the Relation Between Boltzmann-Langevin and Boltzmann-Uehling-Uhlenbeck Models," (Abstract). Y. B. Ivanov and S. Ayik, Fifth International Conference on Nucleus-Nucleus Collisions, Taormina, Italy (1994).

APPENDIX II
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