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Новый механизм образования высокой плотности
при релятивистских столкновениях ядер

Предложен механизм реакции, который уже в момент фазы проникновения при столкновении обеспечивает условия для фазового перехода относительно плотности. В рамках этой релятивистской динамической модели рассматриваются возможные фазовые переходы первого и второго рода. Получено, что вторичный минимум в уравнении состояния ядерного вещества находится при $\rho/\rho_0 = 3.7$ с шириной впадины порядка ρ_0.

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A New Mechanism for Forming Highly Dense Nuclear
Matter in Relativistic Nucleus-Nucleus Collisions

A reaction mechanism is outlined which already during the diving phase of the collision provides the conditions for phase transitions with reference to the density. Within this relativistic dynamical model possible first- and second-order phase transitions are regarded. On this basis and in connection with experimental α-particle data the second minimum of the nuclear matter equation of state is found to be located at $\rho/\rho_0 = 3.7$ with a bump width of ρ_0.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1. INTRODUCTION

Present activities are concerned with the collision of heavy nuclei at high energies. The interest in this topic is due to the possibility that in a transient state of high energy collisions heavy nuclei may become compressed to more than their normal density ρ_0. If such a nuclear matter is formed in the laboratory, it will cast new light on studies pertaining to nuclear matter under unusual conditions which can not be realized at low energies. Such possibilities have been widely discussed as the formation of abnormal nuclear states (Migdal [1], Irvine [2]) and meson ($\pi-$, $\sigma-$) condensates (Migdal [3,4], Lee and Wick [5], Brown and Weise [6]). By field theoretical model calculations it is shown that compressed nuclear matter ($\rho/\rho_0 \gtrsim 2$) due to meson condensation may become unstable. It may then undergo a phase transition into a new form of matter with properties differing from those of the nuclear ground state considerable. At this time almost nothing is known about the stability of superdense nuclei. Estimations of Hofmann et al. [7] show that in dense nuclear matter there may exist at least metastable superdense nuclear states.

The increasing availability of high-energy heavy-ion projectiles made the production of abnormal nuclei an experimental possibility, and the above idea rapidly gained attention, but at present it is very difficult to extract these effects from the existing experimental material. Therefore there are two main tendencies in the theory which look for such phenomena to understand the experimental data.

The first group of models computes the "background" of the reaction as reliable as possible, i.e., the result, if all nucleons act incoherently. Any deviation between the data and calculation may point at coherent effects. On this basis, i.e., without coherency assumptions, the present models are

i) fireball model (Westfall et al. [8]),

ii) firestreak model - refinement of the first one (Meyers [9]),

iii) rows on rows as a microscopic collision model (Hüfner and Knoll [10]),

iv) hydrodynamical models(Amsden et al. [11]),

v) intranuclear cascade models on the Monte Carlo basis (Gudima and Toneev [12], Baz et al. [13], Bondorf et al. [14], Amsden et al. [15], Smith and Danos [16]),

vi) classical equations of motion (Bodmer and Panos [17], Wilets et al. [18]). One-particle inclusive spectra measured so far can be explained by these models nearly in the same quality although the basic concepts of these approaches are rather different. In the same way recent multiplicity measurements can be reproduced (Knoll et al. [19]).

The second group postulates the possibility to create nuclear shock waves which are up to now regarded as the only feasible way to produce bulks of strongly compressed nuclear matter (Chapline et al. [20], Scheid et al. [21], Wong and Welton [22], Baumgardt et al. [23], Sobel et al. [24], Kitazoe et al. [25]). They may appear in head-on collisions of two nuclei when their relative velocity is higher than that of nuclear sound wave. The basis of a description of shock wave phenomena is a hydrodynamical concept which requires a rapid randomization of energy and momentum. There are many papers dealing with the justification of the formation of such a collective motion with supersonic mass flow (Bertsch [26], Sobel et al. [24], Bodmer and Panos [16]). This flow yields a discontinuous front in such quantities as the density, pressure and temperature across the front surface. To get the shape and the propagation of the shock front, the hydrodynamical equations for the time-dependent motion must be solved, which is very

complicated to do in general. Instead of solving the equations, geometric models for the shocked region have been used to investigate how the produced dense matter propagates and finally disintegrates (Scheid et al. [21], Sobel et al. [24]).

In considering heavy ion collisions, it is clear that the dense nuclear matter formed will be in a highly excited state. So in the hot matter region a thermal excitation into baryonic resonances may be possible. The interplay with the intensity of shock waves has been studied using a thermodynamical theory of nucleons and their excited states (Hofmann et al. [27]).

The existence of phase transitions or collective instabilities in nuclear matter during a nuclear collision has two consequences, it influences the shock wave dynamics (Galitski and Mishustin [28]) and the dynamics of the scattering process itself (Gyulassy and Greiner [29]). In ref. 29 the scattering process is considered as the decay of a many-body state initially far from the equilibrium; they found that the cross section for an external particle to scatter in many-body system may become large by critical scattering when that system is near an instability threshold. Considering a system in thermal equilibrium Ruck et al. [30] have shown that these phenomena reduce the temperature and the mean free path appreciably, leading to an enhancement in the formation of nuclear shock waves thus improving the applicability of hydrodynamics. Their results further indicate that the second-order phase transition point where the pion condensate is formed is for sufficiently high densities $\rho \gtrsim 2\rho_0$ expected to survive a rather high degree of excitation ($T \sim 50$-100 MeV) of the nuclear system. A comparison of these values with the ones expected in heavy ion collisions (Baumgardt et al. [23]) shows that pionic instabilities are likely to occur in heavy ion collisions in spite of the high excitations.

All these models have been used to investigate where the particularities originated by the properties of nuclear matter under compression may be found in the experimental angular and energy distributions of the emitted particles.

One of the most important parameters for the possible onset of these coherent phenomena is the value of attainable particle number density ρ during the heavy ion reaction process. The finite size and shape of the dense zone, the character of its evolution and the time scale are also of great importance. The problem is how to produce dense regions. At present only two mechanisms for getting an increase in density are known:

i) incoherently interacting nucleons which make a basis for the microscopic scattering models iv-vi and

ii) shock waves assumed a priori.

First attempts to investigate the possibilities whether shock waves can be formed have been made in the framework of the models IV and V. In this connection, the time-dependent density evolution has been calculated in both models (Gudima et al.[31] and Amsden et al.[11]). It seems that on the level of nucleon constituents a formation of shock waves, over a sufficient large area, is impossible due to the density needed to form a shock wave.

For both mechanisms one can state the following fact, dense regions will not be instantaneously formed on contact of the two nuclei but need distances of some mean free paths (its order of magnitude is about 2 *fm*) to be established via dissipative processes, i.e., through collisional relaxation. This distance then is comparable with the target heavy ion radius. A phase transition should be possible at this point only because the conditions are then fulfiled. The above mentioned effects could, of course, act amplifyingly.

The aim of this paper is to propose a new mechanism for getting an increased density based on a microscopic consideration. The density necessary for a phase transition is produced at that moment if the projectile enters the target without any interaction resulting from a relativistic effect. The details for that can be found in former papers of the author. So, the relativistic determination of the density in a heavy ion model system consisting of two freely interpenetrating nuclei has been described in ref. 32. An estimation with justification of the probability that projectile particles can penetrate the target

without interaction has been given in ref. 33. After a short review concerning the conditions of creation and existence for phase transitions, the new reaction mechanism is outlined. A discussion of the results in connection with experimental data then follows. A short summary completes the paper.

2. *OUTLINE OF THE NEW REACTION MECHANISM*

First let us regard possible phase transitions within a relativistic dynamical model. Field theoretical model calculations mentioned above provide results which are often significantly different from each other. Some models predict the occurrence at approximately three times of normal nuclear density of a first-order phase transition (density isomers), in which the nuclear density changes discontinuously, whereas other models predict a different critical density and/or a second-order phase transition,with no discontinuous change in density. If we use a phenomenological description of nuclear matter, phase transitions of first and second kind can be described as secondary minima or bends, respectively, in the density-dependent ground-state energy per nucleon ϵ (ρ,T=0). Three possible phase transitions of nuclear matter are summarized in *fig. 1* (Stöcker et al.[34], Nix[35]). In the absence of these effects the energy would simply increase monotonically with density.

Let us consider a central high energy collision of a smaller projectile and a heavy target, for example, an α-particle on silver. The kinematically contracted projectile enters the target without interaction. As it has been pointed out in ref.[33], this process can take place with a rather large probability. According to the results in ref.[32], all nucleons in the overlap region between projectile and target feel, in their rest system, an enlarged neighbourhood of other nucleons which results during the diving phase in an increased density beyond the sum of the rest densities of projectile and target. The density becomes beam-energy-dependent. As *fig. 2* indicates, the attained density also depends on the com-

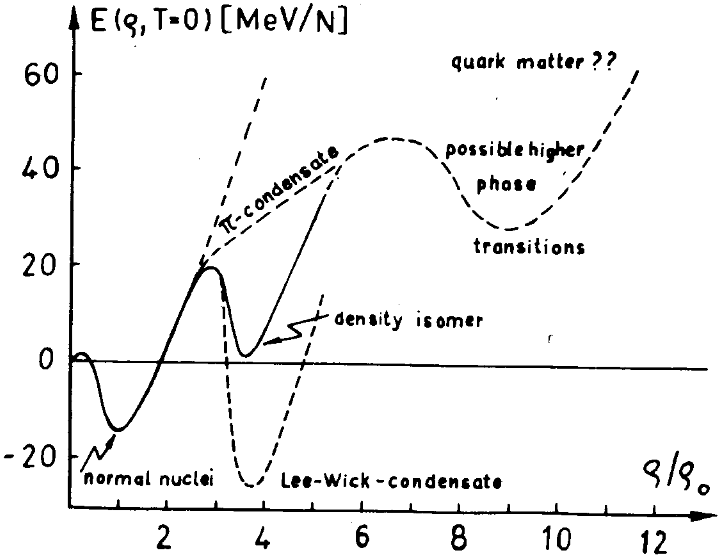

Fig. 1. Schematic illustration of various possible forms of the ground-state energy $\epsilon(\rho, T=0)$ *per nucleon upon nucleon number density (in units* ρ_0 *).*

bination of the colliding partners. Here an α-particle projectile which is the densest known complex particle provides the highest densities in the diving phase.

After the free diving N projectile nucleons interact with N target nucleons. If the density approaches the second order phase transition point ρ_c then for $\rho > \rho_c \gtrsim 1.64\rho_0$ (taken from Galitski and Mishustin/28/) the occurrence of a pion condensate should be possible whereby the pressure during the transition is positive ($p > 0$).

Let us consider its conditions of creation and existence during the heavy ion reaction. The diving phase is characterized by an extreme non-equilibrium state of the nuclear system. One part of the nucleons has momentum $\vec{p}_{CM}$ while the other has momentum $-\vec{p}_{CM}$. The excitation energy of the system can then be tied up in this ordered motion. The question arises whether pionic instabilities can also occur during the concerned diving phase. Gyulassy /36/ has found that in the case of a non-equilibrated state collective instabilities may be expected and over it, may actually be enhanced as the excitation energy increases.

The non-equilibrium state exists up to its thermalization about $(2-3)\tau_0$ (Gyulassy /36/) while the typical total interaction time during the collision is $\tau_{int} \approx (3-8)\tau_0$. Therefore, a substantial fraction of the collision process involves non-equilibrium dynamics.

Galitski and Mishustin /37/ have examined the behaviour of a classical pion field in nuclear matter if it is initially in a non-equilibrium state. The basic dissipation mechanism has taken to be a Landau type damping which

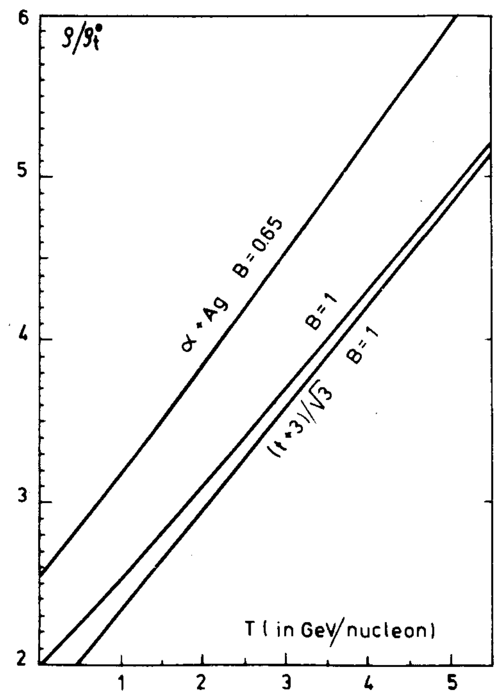

Fig. 2. Rest density (in units of the target density ρ_t° *) in a heavy ion reaction during the diving phase as a function of beam energy in units of GeV per nucleon. The curves reflect the cases: i)* α*-particle and silver (upper), ii) two nuclei with the same densities* (B ≈1) *and iii) the same as in ii) but the asymptotic behaviour for large energies (lower). The figure is taken from ref.* /32/

guarantees an effective mechanism to release an excess of excitation energy of the pion field into nucleon degrees of freedom. On that basis they have calculated the relaxation time of the pion field which amounts to $1.2\,\tau_0$.

In an independent estimation of the time for a formation of a pion condensate Ruck et al.[30] have found $\tau_{cond} \approx \tau_0/\Delta\rho$ with $\Delta\rho = (\rho-\rho_c)/\rho_0$. For beam energies per nucleon of several hundreds of *MeV* the quantity $\Delta\rho \approx 1$ and coincides with the former result. As the projectile crosses slowly the penetration distance, the scattering process then can be considered as adiabatic with respect to the pion degrees of freedom, also for the description of the collision dynamics parameters can be used characterizing the equilibrium of the pion condensate (Galitski and Mishustin[37]).

For larger beam energies the dwelling time, that specifies the duration of the diving phase of the collision, is shorter but $\Delta\rho$ becomes larger because the diving density ρ increases. So, for example, at 2 *GeV/N* we get $\tau_{cond} \approx 0.5\tau_0$ which coincides with the penetration time of an α-particle. If the beam energy becomes still higher, the penetration time does not change. The diving density ρ, however, grows continuously so that the condensation becomes faster. Altogether the available time should be sufficient for pionic instabilities to develop.

Furthermore, the authors Hofmann et al.[38] and Gyulassy[39] have estimated that a dense system of dimensions $\approx$ (2-3) *fm* could support a condensate. This is consistent with the dimensions of the overlapping region of an α-particle and a target.

As a result, the condensated stable density isomeric state which remains compact (with a structure of a nuclear spin-isospin lattice) moves nearly friction-free as frozen new phase (Hofmann et al.[38]). During the interpenetration of the condensate phenomena similar to shock waves or shock waves as an idealization (Baumgardt et al.[23]) should be formed. Therefore nucleons and fragments are ejected into preferential angles and give rise to beam energy dependent peaks.

If we assume a density isomer at $\rho/\rho_0 \approx 3$, the above picture does not work. For large enough bombarding energies per nucleon (between 1-2 *GeV*) the diving density approaches the phase transition region. The nuclear matter becomes unstable and collapses into the isomeric state: and due to the first-order transition a density region of negative pressure ($p<0$) exists. Then shock wave phenomena are impossible and therefore no preferential ejections of fragments are observable.

How can these considerations experimentally be checked? In *fig. 3* the analysis of the Dubna results and Schopper's experiments carried out by Stöcker et al.[34] under the assumption that shock waves eject matter into

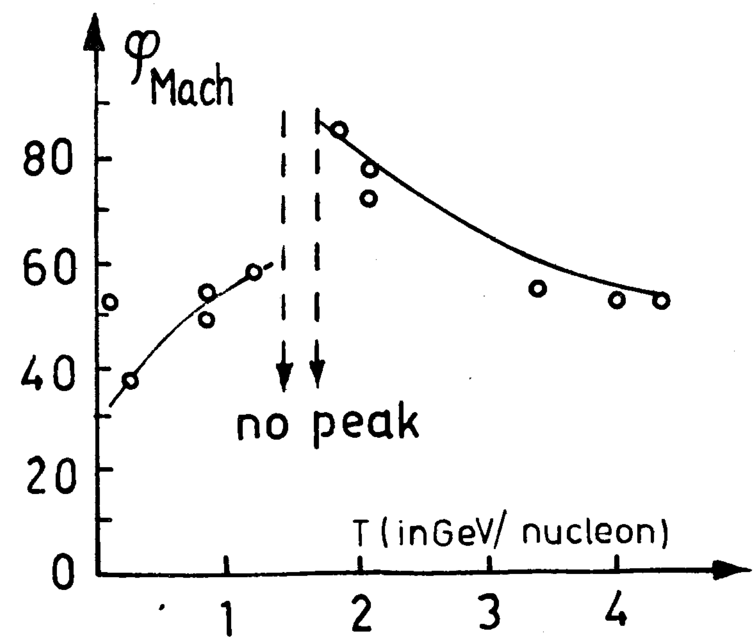

Fig. 3. Mach shock angles deduced from the measurement of the energy dependent position of the Mach shock peak (taken from Stöcker et al.[34]). The dashed lines indicate that at these energies (1.4 and 1.7 GeV/nucleon for α-particles on silver) no peaks in the angular distribution have been found.

preferential angles in dependence of the beam energy is given. At the energies 1.4 *GeV/nucleon* and 1.7 *GeV/nucleon* no peak could be seen. A similar result was published by Jakobsson et al.[40] measuring non-evaporated α-particles in the reaction $^{16}O + AgBr$. They found a characteristic shift of the $dN/d\Omega$ distribution of He nuclei, low energy protons and deuterons, from a broad forward-peaked shape at 0.2 *GeV/nucleon* to an almost isotropic distribution at 2 *GeV/nucleon*, which is in qualitative agreement with the results of Schopper et al. The interpretation of this behaviour in the framework of the above given mechanism is the following. The projectile particles enter the target without interaction. If the diving density approaches a special region, the phase transition can occur. Since the density depends on the state of motion, the transition, therefore, can take place only in a narrow beam energy range which gives rise to a reaction window for the transition. For incident energies $t < 1.3$ *GeV/nucleon* and $t > 1.9$ *GeV/nucleon* a first-order phase transition cannot occur because the supposition concerning the density is not fulfilled; it is too small and too large, respectively.

Taking into account the fact that the pressure is negative $(p<0)$ during the transition, we can deduce from the behaviour of the curve in *fig. 3* the position of the second minimum. The onset of the transition lies, according to *fig. 2*, at $3.3\rho_0$ whereas the minimum is situated at $3.7\rho_0$ so that we get a widths of the bump of about ρ_0 measured from the maximum.

If $t > 1.9$ *GeV/nucleon* the shock phenomena and connected with it a preferential ejection of particles should reappear, as is explained above.

The mechanism has been developed to deal with α-particles but it can, of course, also be extended to other projectiles with little difficulty.

The same mechanism could be applicable to a transition to the speculatively existing quark matter which may occur at a density that is 10 to 20 times normal nuclear density (Chapline and Nauenberg[41], Nix[35]). According to eq. (4) in ref.[32] this would correspond to beam energies per nucleon between 10 and 25 *GeV*.

3. SUMMARY AND CONCLUSIONS

The reaction mechanism for forming highly dense nuclear matter presented in this paper is attractive because of its simplicity. It was shown that the conditions for phase transitions with respect to the density are fulfilled just at that moment the projectile enters the target without interaction. This interpenetration can take place with a rather large probability. The increase in density during the diving phase of the collision beyond the sum of the rest densities of projectile and target is due to a relativistic effect and amounts to a growth rate of $0.7\rho_0$ per GeV/nucleon increase in beam energy. So, the onset of the phase transitions can already occur in the diving phase. There is no need to postulate shock waves as a supposition for the production of dense regions in the consequence of which than phase transitions can take place. These suppositions are automatically realized in the outlined mechanism. The available time during the diving phase should be sufficient for pionic instabilities to develop. If with increasing projectile energy the diving density approaches the critical density region of the first-order phase transition then the nuclear matter will collapse into the isomeric state. Since the density is beam energy-dependent, the transition, therefore, can take place only in a narrow beam energy range which gives rise to a reaction window for the phase transition. Without other complicated suppositions the presently known α-particle experiments can be interpreted. On that basis, the second minimum in the nuclear matter equation of state was found to be located at $\rho/\rho_0 = 3.7$ with a bump width of about ρ_0.

REFERENCES

1. *Migdal A.B. Phys. Lett., 1974, 52B, p.172.*
2. *Irvine J.M. Rep.Progr. Phys., 1975, 38, p.1385.*
3. *Migdal A.B. Zh.Eksp. Teor. Fiz., 1971, 61, p.2209.*
4. *Migdal A.B., Mavkin O.A., Mishustin I.N. JETP, 1974, 66, p.443.*
5. *Lee T.D., Wick G.C. Phys. Rev., 1974, D9, p.2291.*

6. Brown G.E., Weise W. Phys. Rep., 1976, 27C, p.1.
7. Hofmann J. et al. Phys. Rev.Lett., 1976, 36, p.88.
8. Westfall G.D., et al. Phys. Rev.Lett., 1976, 37, p.1202.
9. Myers W.D. Report LBL-6569, Berkeley, 1977.
10. Hüfner J., Knoll J. Nucl.Phys., 1977, A290, p.460.
11. Amsden A.A., Harlow F.H., Nix J.R. Phys. Rev., 1977, C15, p.2059.
12. Gudima K.K., Toneev V.D. JINR, E4-9765, Dubna, 1976.
13. Baz A.I. et al. IAE-2660, Moscow, 1976.
14. Bondorf J.P. et al. Phys. Lett., 1976, 65B, p.217.
15. Amsden A.A. et al. Phys. Rev.Lett., 1977, 38B, p.1055.
16. Smith R.K., Danos M. Proceedings of the Topical Conference on Heavy Ion Collisions, Fall Creek Falls State Park, Tennessee USA, 1977, CONF-770602, p.362.
17. Bodmer A.R., Panos C.N. Phys. Rev., 1977, C15, p.1342.
18. Wilets L. et al. Nucl.Phys., 1977, A282, p.341.
19. Knoll J., Hüfner J., Bonyssy A., to be published in Nucl.Phys., 1978.
20. Chapline G.E., et al. Phys. Rev., 1973, D8, p.4302.
21. Scheid W., Müller H., Greiner W. Phys. Rev.Lett., 1974, 32, p.741.
22. Wong C.Y., Welton T.A. Phys. Lett., 1974, 49B, p.243.
23. Baumgardt H.G. et al. Z.Phys., 1975, A273, p.359.
24. Sobel M.I. et al. Nucl.Phys., 1975, A251, p.502.
25. Kitazoe Y., Sano M., Toki H. Nuovo Cim. Lett., 1975, 13, p.139.
26. Bertsch G.F. Phys. Rev.Lett, 1975, 34, p.697.
27. Hofmann J., Scheid W., Greiner W. Nuovo Cim., 1976, 33A, p.343.
28. Galitskii V.M., Mishustin I.N. Phys. Lett., 1978, 72B, p.285.
29. Gyulassy M., Greiner W. Ann. of Phys., 1977, 109, p.485.
30. Ruck V., Gyulassy M., Greiner W. Z.Physik., 1976, A277, p.391.
31. Gudima K.K., Iwe H., Toneev V.D. JINR, P2-10769, Dubna, 1977.
32. Iwe H. JINR, E2-11964, Dubna, 1978.
33. Iwe H. JINR, E2-11965, Dubna, 1978.
34. Stöcker H., Scheid W., Greiner W. Talk at the Fall Creek Falls Meeting on Heavy -Ion Collisions, Tennessee USA, 1977, CONF-770602.
35. Nix J.R. Report LA-UR-77-2952, Los Alamos, 1977.

36. Gyulassy M., Talk at the Fall Creek Falls Meeting on Heavy-Ion Collisions, Tennessee USA, 1977, CONF-770602, p.457.
37. Galitskii V.M., Mishustin I.N. JETP Lett., 1977, 26, p.566.
38. Hofmann J. et al. Talk at Int. Topical Meeting on Multiparticle Production on Nuclei at Very High Energies, Trieste, 1976, June 10-15.
39. Gyulassy M. LBL-7704, Berkeley, 1978.
40. Jakobsson B., Kullberg R., Otterlund I. Nucl.Phys., 1977, A276, p.523.
41. Chapline G.F., Nauenberg M. Phys. Rev., 1977, D16, p.450.

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