СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-97-257

Z.Strugalski*

WHERE AND HOW THE QUARK-GLUON MATTER SHOULD BE SEARCHED FOR?

---

*Permanent addresses:
Z.Strugalski, Institute of Atomic Energy,
A-23, PL 05-400 Otwock-Swierk, Poland;
Z.Strugalski, ul.Brzozowa 5/9 m.3,
PL 00-258 Warsaw, Poland

1997

1. INTRODUCTION

Firstly, when the problem in the title appeared, nobody knew for sure what might happen when two heavy nuclei smash together at energies of the order of hundreds of GeV per nucleon. But, the consensus conclusion was, based on theoretical speculations, that if enough energy is pumped into a nucleus, normally considered as a loosely bound collection of nucleons, it will eventually transform into a new state: nucleons will lose their separate identity and fuse together into the quark-gluon plasma or quark-gluon matter, or «quagma».

The burning questions arose, therefore: a) How it is possible to pump energy into a nucleus and create the quagma state of intranuclear matter, and whether the condition necessary for such creation can be reached or not in hadron-nucleus or nucleus-nucleus collisions? b) How can the state be detected and studied, if generated?

There is an opinion that the whole Universe could have been in such a state a few microseconds after the initial Big Bang, and the quagma may still exist in the cores of neutron stars. If synthetic quagma is produced, it will be short-living state exploding in some 10^{-22} s into particles — into several thousands of particles, if uranium nuclei collided. As it is expected, the explosion should be accompanied by intensive flashes of gamma quanta and by an overabundance of strange particles.

In my opinion, the passage of a single hadron through intranuclear matter should be first recognized accurately in order to obtain experimentally based answers to the questions above. The subject matter in this paper are, therefore, mainly: a) A short review of experimental information about hadron passage through intranuclear matter; b) A short review of experimental data on hadron-nucleus and nucleus-nucleus collisions at various energies; c) A discussion about the topics in question above.

2. THE PICTURE OF THE HADRON-NUCLEUS NUCLEAR COLLISION PROCESSES — EXPERIMENTALLY BASED

It was not found necessary to repeat here a description of many experimental facts underlying the picture; the facts were described in many works of my co-workers and myself [1–8]. The picture may be treated as the experimentally prompted one.

When a high energy hadron h is incident on an atomic nucleus A, or, in other words, on a intranuclear matter layer of a thickness λ in nucleons per some area S units, [nucl/S], there may start various processes as it traverses this layer. This hadron may traverse the intranuclear matter layer without causing particle production or it can come into particle-producing reaction with one of the downstream nucleons met at any depth. In traversing intranuclear matter layer, the hadron loses always almost fluently its kinetic energy and it is deflected slightly from its initial course. The deflection is a result of the multiple scattering from objects in interanuclear matter of the rest mass as large approximately as the pion rest mass [9]. Such a passage is always accompanied by «fast» nucleon emission (kinetic energy from about 20 to about 500 MeV). The nucleon emission is a visible effect due to hadron energy loss in intranuclear matter. When the intranuclear matter layer is thick enough, the observed number of the emitted nucleons is as large as the number of nucleons met by the hadron within the cylindrical volume $\pi D_0^2 l$ centered on the hadron course l in intranuclear matter, where D_0 is the nucleon diameter — as large approximately as the nuclear interaction range R_h is. The fast nucleon emission is a phenomenon occurring independently of the particle-producing reactions of the hadron in intranuclear matter. The nucleon multiplicity distribution can be described quantitatively and simply by the formula without free parameters in terms of the target nucleus size and nucleon density distribution in it [4]. On the background of the fast nucleon emission process, single hadron-nucleon collisions leading to the particle production occur plentifully in intranuclear matter. The particle production in hadron-nucleus collisions starts in result of a single particle-producing head-on $2 \rightarrow 2$ type collision of the hadron with one of the nucleons met in intranuclear matter. The occurrence of the particle-producing collisions is determined by hadron-nucleon elementary collisions cross section σ_{in} [S/nucl]; the mean free path for such collisions in intranuclear matter is a measurable quantity and $<\lambda_{in}> \approx 3/\sigma_{in}$ nucl/S. The particle production in hadron-nucleon collisions, in nucleon-nucleon collisions in particular, is mediated by intermediate objects created first in a $2 \rightarrow 2$ type endoergic reaction in the early stage of the collision [10].

The intermediate objects, we called them «generons», move along the incident hadron course in intranuclear matter and behave themselves in it as usual hadrons do it, before the decay into finally observed resonances and particles after having left the parent nucleus; the lifetime of the generons is large enough, larger than about 10^{-22} s, them to be possible to traverse the most massive atomic nuclei. In traversing intranuclear matter, generons can collide with the downstream nucleons and produce new generons, giving rise to development of quasi-linear cascade of generons in intranuclear matter [11]. It has been shown [12,13] that in average

$<m> = e^t$ particle-producing collisions happen when a hadron fell on the intranuclear matter layer of the thickness λ, where $t = \lambda/<\lambda_{in}>$. In the cascading process the kinetic energy of the incident hadron is distributed between the generons created. This way, various characteristics of the outcome in a particle-producing hadron-nucleus collision at an energy E are the composition of corresponding characteristics of the outcome (or yield) in some number m of hadron-nucleon collisions at the mean energy E/m.

In hadron-nucleus collisions the target nuclei are pierced and destroyed locally in a definite manner by the projectile hadrons — an almost cylindrical part of a nucleus of the diameter as large as about $2D_0$ centered on hadron course in intranuclear matter is moved away — at first, and then the residual part of the target-nucleus decays into nuclear fragments [14].

3. THE PICTURE OF THE NUCLEUS-NUCLEUS COLLISION PROCESS — EXPERIMENTALLY BASED

In 1948, Freier et al. communicated about the presence of helium and heavier nuclei among the particles of the primary cosmic radiation [15]. They made experiments at altitudes of about 90000 ft by means of free ballons, the primary particles being detected both by observation with an expansion chamber and by photographic emulsions. Accurate conclusive investigations of heavy nuclei collisions at high energies started with photographic emulsions exposed to cosmic radiation [16]. Collisions of nuclei H^1, He^4, Be^9, N^{14}, Si^{28}, Fe^{56} with different constituents of the emulsion H, CNO(S), AgBr(I) were studied by photographic method, single events were studied accurately. Collisions of heavy nuclei from accelerators with nuclei were studied intensively later by many groups of physicists, and now are under great interest as well [17—28]. But, the old cosmic ray data are of large valuability for the problem in question in this article. The data obtained at that initial investigations are conclusive by much and are supported in many points by the new accelerator data. The main properties of the nucleus-nucleus collisions, discovered at that time, are actual by much up today as well.

Qualitative picture of the heavy ion collision process has been traced [17,18] from comparatively low energy to relativistic energies, this picture is fragmentary and incomplete, however. Our knowledge about relativistic nucleus-nucleus reactions is from the experiments at the LBL Bevalac [19,20], JINR Synchrophasotron [21], and cosmic rays [22,23]; average secondary multiplicities were studied at Berkeley and Dubna [24—26].

At some hundreds MeV per nucleon the projectile as well as the target nucleus in a central nucleus-nucleus collision, in C + Ag for example, are totally disintegrated; the heavily ionizing collision reaction products are distributed almost isotropically. At higher energies, at some tens of GeV per nucleon, in central collisions of nuclei, of Mg and Ag for example, one observes the heavilly ionizing tracks distributed in the same manner as in the low energy reaction described above, but, additionally the shower of particles in the forward direction which may contain tracks of the projectile protons and of the produced pions is evidently seen; many He perticles from the projectile may be observed as well.

The analysis of experimental data on the nucleus-nucleus collisions at about 2—15 GeV/nucleon, and the comparison of them with the proton-nucleus collision data, indicate that the recoil and temperature of the spectators in nucleus-nucleus collisions may be only weakly dependent on the nature of the incident particle, on the incident energy and on the number of participating nucleons [17]; it may indicate that only some parts of the nuclei are involved in the nucleus-nucleus collisions. The angular distribution of the projectile spectator protons [17] is separated from the distribution of participant protons [17] and produced pions. The Berkeley data and the Dubna streamer chamber data [21,24] show the dependence of the produced pion mean multiplicity on the number of participant nucleons which act almost as the surface of the participant system.

From cosmic ray data [27], at mean energy of about 19 GeV per nucleon the number of produced pions n_π in collisions with atomic nuclei in emulsions depends on the number n_s of the shower particle multiplicity and on the number n_p on the number of the protons into which the incoming nucleus fragments: $n_s - n_p = n_\pi$, and $n_p = Z_i - Z_f$, where Z_f is the charge of the fragments with $Z \geq 2$, and Z_i is the charge of the incident nucleus. The studies of the multiplicities in central (Ca - Fe) + Em nuclei as a function of the incident energy [28] give, at about 19 GeV/nucleon in average, the mean number of the shower particles $< n_s > \approx 120$, when the number of participant nucleons is ~130.

In general, the multiplicities of the produced particles in nucleus-nucleus reactions should depend mainly on the number of participants. So, on the basis of the nucleon-nucleon collision data, in central nucleus-nucleus collisions, when about 400 participants are involved, thousands of produced pions should be observed, and hundreds of the target and projectile nucleons.

And so, it was stated in the first cosmic ray works and supported by the accelerator investigations that [2,3]:

1) In collisions of a heavy highly energetic nucleus with a resting nucleus, with relatively high frequency a fast secondary heavy nucleus or a number of alhpa-particles emerge from the encounter.

2) The fast secondary heavy nuclei are a parts of the incoming projectile nuclei — the fragments of them; they are produced in peripheral collisions between two nuclei — only a few of the nucleons of the primary fast nucleus, or of the target nucleus, being involved in the impact.

3) In the peripheral collisions, it may happen that the main groups of nucleons of the colliding nuclei are not sufficiently disturbed to be disrupted, a heavy nuclear fragment emerging from the encounter with a velocity little different from that of the incoming particle, whilst a fragment of the struck nucleus is given little velocity — and remains intact in the emulsion.

4) In the head-on collisions between two similar nuclei both of them are totally dispersed into their component nucleons (as one can see on the photos 16—14 and 16—19 in the book of Powell et al.).

5) In such collision events, and when the primary nucleus is moving with great velocity, the number of secondary products of the impact — mesons and other particles — are observed.

4. MECHANISMS OF ENERGY TRANSFER FROM HADRONIC AND NUCLEAR PROJECTILES INTO TARGET NUCLEI IN COLLISIONS AT HIGH ENERGIES

In result of investigations of the projectile energy transfer to target nuclei [30—32], the following mostly important assertions may be stated, for the target nuclei at rest in the laboratory system:

1. In the hadron-nucleus collisions the projectile energy is transferred into the target nucleus in its passage through layers of the intranuclear matter, anyhow; this energy transfer depends on the path length covered by the projectile and/or its successor; in the passage, definite tube-shaped relatively small volume of the target nucleus is involved only. The energy transfer realized this way is limited and independent of the projectile energy, at energies high enough, and amounts no more than about 8 GeV for the proton projectile — it is as twice higher as for the pionic projectile.

Often, on the background of the projectile passage, the energy is transferred to the downstream nucleons in some particle-producing collisions. As a result of these collisions, intermediate objects, or generons, are created in 2 → 2 type endoergic reaction. If the target nucleus is massive enough, the generons may collide with the downstream nucleons and produce new — secondary generons in ones turn. This way, the intermediate objects may fuse together in some intranuclear cascading process of the generons in intranuclear matter. The energy transfer in this cascading is practically not limited, it depends on the projectile energy only; the intranuclear cascade of the generons is localized around the incident hadron course within the tube of relatively small volume V in the terget nucleus

$$V = \pi R_h^2 l \tag{1}$$

with the radius as long as the strong interacting range R_h centered on the hadron path l in the nucleus [30]. The finally formed intermediate objects, which may be in fact treated as some large quark-gluon bags (inside of the large bags, the quark-gluon matter is in expected highly excited state and the quark-gluon phase transition may be realized), decay into the so-called generated hadrons after having left the parent nucleus, after about 10^{-22} s.

2. In the nucleus-nucleus collisions, i.e., in the collisions of weakly bound nucleons beam with the target nucleus, the energy transfer process is similar for any of the beam nucleons treated as the projectile in a hadron-nucleus collision. The outcome in the nucleus-nucleus collision is then a composition of appropriate nucleon-nucleus collisions at various impact parameters; the screening should be taken into account.

And so, the experimentally revealed mechanism of the projectile energy transfer to the target nucleus, suggests some ways for production of the expected highly excited states of intranuclear matter, and for realization in experiments the quark-gluon matter phase transitions, at least inside some limited regions inside of the target nuclei. Some additional support of such picture of the incident hadron energy transfer to nucleons in the particle-producing hadron-nucleon collisions in intranuclear matter has been obtained in the investigations of the particle production process in hadron-nucleus collisions [33].

5. HOW TO OBTAIN OBJECTS OF HIGHLY EXCITED QUARK-GLUON MATTER IN LABORATORIES

In one of the previously performed experimental works [34], it has been suggested that the results of analysis of data on the hadron-nucleus collisions allow one to conclude that: 1) Probably it is impossible to pump the energy much enough to colliding nuclei in order them to fuse together and transform from the collection of nucleons into quark-gluon matter — or quagma state, directly; 2) The objects of quagma in an excited state might be produced only via generons, in the generon cascade in massive nucleus [11,34,35] — when many generons produced in hadron-nucleus or in nucleus-nucleus collisions could fuse together into quagma excited state.

Within the frames of the pictures presented above, the most intensive production of such objects of the excited quagma should be expected at extremely high energies in central hadron-nucleus collisions with massive target nuclei, when produced generons could fuse together — in a «generon cascading process». But, it is observed that the collimated beams of nucleons going out from the encounter, in collider experiments are lightly dispersed and the short range strong interaction cannot collect them together; additionally, the electrical forces of each electrically charged nucleons are acting for engrowing this dispersion. So, the generons cannot fuse together. So, the generons cannot fuse together into the quagma. It might happen, eventually, at energies by much larger than the energies of today particles from colliders, and even from cosmic rays.

One real way in which objects of highly excited quark-gluon matter might be produced is the natural one — when firstly produced generon collides with downstream nucleon in intranuclear matter and the intranuclear cascade of generons develops, in which the generons fuse naturally together, in colliding with downstream nucleons, and form many-generons-objects or large quark-gluon matter bags [36]. The generons produced in hadron-nucleus (in nucleon-nucleus) collisions with nucleons inside the target nucleus first of all — on mostly massive nuclei with hadrons of extremely high energies — are massive objects of extremely excited intranucleon matter; in fact, they consist of extremely excited quark-gluon matter or quagma.

In conclusion, the object of extremely excited quark-gluon matter may be produced: 1) in extremely high energy nucleon-nucleon (hadron-nucleon) collisions; 2) in extremely high energy nucleon (hadron) collisions with the heaviest nuclei.

In the light of this conclusion — *signals of the existence of the excited quark-gluon matter created in all central particle-producing hadron-nucleon and hadron-nucleus collisions are often observed; the most intensive signals are in the collisions of the hadrons with the heaviest target nuclei.*

The observable appearance of the «produced» hadrons — many pions, kaons, jets, and others — characterizes the quagma phase transitions.

6. HOW TO STUDY THE PHASE TRANSITION IN THE EXCITED QUARK-GLUON MATTER?

The studies of the quagma phase transitions may be, therefore, realized by many ways: all of them are consisting in the many-sided versatile experimental analysis of the yields from nucleon-nucleon (hadron-nucleon) collisions at various projectule energies — from the hadron generation threshold up to the extremely high met in experiments.

The collected many-sided experimental data about the excited quagma changes will provide conclusive information about the quark-gluon matter phase transition.

7. CONCLUSIONS AND REMARKS

In analysing experimental data, experimental facts, and results on experimentally discovered mechanisms of hadron-nucleus and nucleus-nucleus collisions, and on energy transfers from hadronic and nuclear projectile to target-nuclei, I found myself in a position to state that:

1. Proceed from the standard model of fundamental particles and interactions, the objects of excited quark-gluon matter or plasma should be searched for there (at such conditions) where they exist in their normal state of being — in hadrons, in nucleons in particular first of all.

2. The atomic nuclei as objects normally existing as losely bound collection of nucleons cannot be transformed directly into a new state of being — when nucleons will lose their separate identity and fuse together into a new state — into the quark-gluon matter or quagma.

3. The quark-gluon matter or quark-gluon plasma can be transited into highly excited state only in hadron-hadron particle-producing collisions, in nucleon-nucleon particle-producing collisions first of all, and in hadron-nucleus central particle-producing collision on heavy nuclei, and may be mostly effective and impressible — in generon-nucleon cascading process in massive target-nuclei.

4. The characteristics of the transition in the quark-gluon-matter may be obtained from the yields of the particle-producing hadronic and nuclear collisions — simplest of all — from the nucleon-nucleon and nucleon-nucleus collisions at various energies — from the hadron production threshold up to extremely high.

REFERENCES

1. Strugalski Z. — Energy and Angular Spectra of Protons Emitted in Pi$^-$ + Xe Interactions at 3.5 GeV/c. Sov. J. Nucl. Phys., 1974, v.20, p.504.
2. Strugalski Z. — Proc. 18th ICRC, Bangalore, India, August 22 to September 3, v.V, 1983, p.194.
3. Strugalski Z., Pawlak T., Pluta J. — Experimental Study of the Pion-Xenon Nucleus Collisions without Particle Production at 3.5 GeV/c Momentum; General Data. JINR, E1-82-718, E1-82-719, E1-82-841, Dubna, 1982; E1-83-234, Dubna, 1983; E1-85-888, Dubna, 1985; references in them.
4. Strugalski Z. — Formulas for Description of Nucleon Emission Intensity in Hadron-Nucleus Collisions. JINR, E1-86-578; E1-86-579, Dubna, 1986.

5. Pawlak T., Peryt W., Strugalska-Gola E., Miller K., Strugalski Z. — Characteristics of Atomic Nuclei Employed as Tergets in High Energy Nuclear Collisions. JINR, E1-86-643, Dubna, 1986.
6. Strugalski Z., Pawlak T., Peryt W., Alrohiah M., Mousa M., Sharkawy El S., Sredniawa B., Miller K., Pluta J. — Experimental Study of Hadron Passage through Intranuclear Matter., JINR, E1-88-211, Dubna, 1988.
7. Strugalska-Gola E., Strugalski Z. — Observations of Fast Hadron Passages through Intranuclear Matter. JINR, E1-94-296, Dubna, 1994.
8. Strugalski Z., Mulas E., Strugalska-Gola E., Wojcichowski A. — Hadrons as Probes for Exploration into Intranuclear Matter. JINR, E1-96-121, Dubna, 1996.
9. Okhrimenko L.S., Słowinski B., Sredniawa B., Strugalski Z. — π^0 Meson Production in Collisions of π Mesons with Xenon Nuclei at 2.34 and 3.5 GeV/c and the Problem of an Effective Target of Interaction. JINR, R1-9807, Dubna, 1976.
10. Strugalski Z. — Hadron-Nucleus Collisions: Picture, Descriprion Procedure, Cross-Sections; Nucleon Emission, Average Particle Multiplication; Produced Particle Multiplicities, Energy and Angular Spectra, Pseudorapidity Distributions. JINR, E1-81-154, E1-81-155, E1-81-156, Dubna, 1981.
11. Strugalski Z. — Study of the Particle Production Process Using Nuclear Targets: Method, Intermediate Objects. JINR, E1-81-576, E1-81-577, Dubna, 1981; E1-82-287, Dubna, 1982; E1-85-578, Dubna, 1985; E1-86-579, Dubna, 1986.
12. Strugalski Z. — Free-Parameterless Model of High Energy Particle Collisions with Atomic Nuclei. JINR, E1-82-401, Dubna, 1982.
13. Sredniawa B., Strugalska-Gola E. — On the Characteristics of the Particle Production Process in Hadron-Nucleus Collisions: Multiplicities and Dispersions. JINR, E1-84-411, Dubna, 1984.
14. Strugalski Z. — On the Emission of Target Fragments in Hadron-Nucleus Collisions. JINR, E1-84-195, Dubna, 1984.
15. Freier P., Lofgren E.J., Ney E.P., Oppenheimer F., Bradt H.L., Peters B. — Phys. Rev., 1948, v.74, p.213.
16. Powell C.F., Fowler P.H., Perkins D.H. — The Study of Elementary Particles by the Photographic Method, Pergamon Press, London, 1959; references in it.
17. Otterlund B.I. — Lund University Report, LUIP 8011, Lund, 1980.
18. Andersson et al. — Lund University Report, LUIP 8602, Lund, 1986.
19. Nagamiya S. — Nuclear Physics, 1984, v.A418, p.239; references in it.
20. Pugh H.G. — Proc. of the Fourth Intern. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions, Helsinki, Finland, Lecture Notes in Physics, Springer Verlag, 1984, v.221, p.143.
21. Baldin A.M. — Nucl. Phys., 1985, v.A447, p.203; references herein.
22. Burnett T.H. — Nuclear Phys., 1985, v.A447, p.189.

23. Jones W.V. — Nuclear Phys., 1984, v.A418, p.139.
24. Fung S.Y. et al. — Phys. Rev. Lett., 1978, v.40, p.292.
25. Aksinienko A. — Nuclear Phys., 1979, v.A324, p.226.
26. Bartke J. et al. — JINR, E1-13038, Dubna, 1980.
27. Wosiek V. — Acta Physica Polonica, 1978, v.B9, p.191.
28. Gagarin G. et al. — Proc. of the 16th ICRC, Kyoto, Japan, 1979.
29. Daniel and Perkins (unpublished); Dainton A.D., Kent D.W. — Phil. Mag., 1950, v.41, p.963.
30. Strugalski Z. — Mechanism of Energy Transfer from Hadronic and Nuclear Projectile into Target Nuclei in Collisions at High Energies. JINR, E1-94-321, Dubna, 1994; references in it.
31. Strugalska-Gola E., Strugalski Z. — The Picture of the Disintegration Mechanism of Nuclei — from Nucleus-Nucleus Collision Experimental Data at High Energies. JINR, E1-97-176, Dubna, 1997; references in it.
32. Strugalski Z., Strugalska-Gola E. — Energy Changes in Massive Target Nuclei, Induced by High Energy Hadronic Projectiles. JINR, E1-97-130, Dubna, 1997.
33. Mulas E., Strugalska-Gola E., Strugalski Z. — Investigations of the Particle Production Process in Hadron-Nucleus Collisions: Intensities of Particles. JINR, E1-90-460, Dubna, 1990; references in it.
34. Strugalski Z. — Whether it is Possible to Pump Energy into Atomic Nuclei by High Energy Hadronic or Nuclear Projectiles? JINR, E1-87-740, Dubna, 1987.
35. Strugalski Z. — XX International Cosmic Ray Conference, Moscow, USSR, 1987, v.5, p.46.
36. Strugalski Z. — Physical Meaning of the Yields from Hadron-Nucleon, Hadron-Nucleus, and Nucleus-Nucleus Collisions Observed in Experiments. JINR, E1-95-23, Dubna, 1995; references in it.

Received by Publishing Department
on August 22, 1997.