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WHETHER IT IS POSSIBLE TO PUMP ENERGY INTO ATOMIC NUCLEI BY HIGH ENERGY HADRONIC OR NUCLEAR PROJECTILES

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1. INTRODUCTION

What might happen when two massive nuclei smash together at extremely high energies - say at about hundreds GeV per nucleon? Nobody knows it for sure up to now; the answer should be found in experiments, therefore!

But, the consensus conclusion is, based on theretical 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.

According to quantum chromodynamics, quarks and gluons can exist in some bound states - hadrons, as a hadronic gas[1]; a specific form of the hadronic gas is known as the intranuclear or nuclear matter - a collection of nucleons in atomic nuclei. Many physicists believe it can be transformed into a plasma consisting of quarks and gluons. Under some conditions the transition

$$\text{Hadronic gas} \rightleftarrows \text{Quagma} \qquad (1)$$

is predicted, therefore. Two transitions are considered: a) deconfinement transition; b) chiral transition. The calculations of the thermodynamics of quark-gluon systems were performed within the frames of two approaches - continuum approach[2-4] and lattice approach[5,6].

The transition (1) is expected to be realized at intranuclear matter density ε much higher as the intranucleon matter density ε_N is. The mean intranuclear matter density is $\langle \varepsilon_0 \rangle \approx 0.17\ \mathrm{GeV/fm^3}$; the intranucleon matter density is $\varepsilon_N \approx 0.5\ \mathrm{GeV/fm^3}$.

The burning questions arose, therefore: How it is possible to pump energy into a nucleus and create the quagma state of intranuclear matter?; Whether the condition necessary for the creation can be reached or not in hadron-nucleus or nucleus-nucleus collisions.

In my opinion, the passage of a single hadron and then the passage of a nucleus through intranuclear matter should be first recognized accurately by experiments, in order to obtain answers to the questions above. The subject matter in this paper are, therefore: a short review of experimental information about hadrons and nuclei passages through intranuclear matter; a short analysis of experimental data on hadron-nucleus and nucleus-nucleus collisions at various energies, from the point of view of their applicability for the problems in question.

The purpose is to establish some conditions at which quark-gluon matter might be obtained in laboratories, in high energy collisions of massive nuclei, and whether it is possible to obtain it this way at all. In contrast to other works, where the problem was discussed theoretically - on the basis of models containing free parameters, the discussion here is on the purely experimental ground, without application of any of such models. Conclusive data on hadron-nucleus collisions were obtained by means of the target nucleus applied as fine detector of the properties of the nucleon emission and particle production processes in hadron-nucleus collisions[7-12]. Appropriate data on nucleus-nucleus collisions, obtained by various groups of physicists, compared with the hadron-nucleus collision data from our experiments provide information which allows one to conclude about the mechanism of the nucleus-nucleus collision process. This way conclusions can be obtained concerning the passages of high energy nuclei through intranuclear matter.

2. EXPERIMENTAL DATA AND THE ANALYSIS OF THEM IN AN ASPECT OF THE PROBLEMS IN QUESTION

The passages of hadrons through intranuclear matter have been studied in experiments in pion-xenon nucleus collisions at 2-9 GeV/c momentum[7-12] - in the xenon bubble chambers, in proton collisions with nuclei in emulsions at 4.5 GeV/c momentum[13], at 300 GeV/c momentum[14], at 200 and 400 GeV/c momenta[15], and in pion collisions with atomic nuclei in emulsions at 50 and 200 GeV/c momenta[15]. The characteristic property of the passages is the accompaniment of intensive emission from target nuclei of fast nucleons - with kinetic energies from about 20 up to about 500 MeV - without ejection of particles which could be produced, without produced pions in particular[8,13].

As concerns the passages of nuclei through nuclei, the experimental data are indirect and less conclusive. They can be obtained from comparison of characteristics of the emission of fast nucleons from target nuclei in nucleus-nucleus collisions and corresponding characteristics of such nucleons emitted from the target nuclei in hadron passages through intranuclear matter observed in hadron-nucleus collisions. First direct information about "nonpion production interaction process observed in ^{16}O-emulsion interaction at 2.1 GeV/c/n and ^{12}C-emulsion interaction at 4.5 GeV/c/n" is published this year[16].

1. Hadron-Nucleus Collisions

There are no indications that superdence intranuclear matter is or can be produced in hadron-nucleus collisions. Incident hadrons lose their kinetic energies, in passing through intranuclear matter, proportionally to the intranuclear matter layer thickness λ covered - similarly as electically charged particles lose their energy in materials due to the ionization energy loss, but here the energy loss is due to the nuclear forces; the energy loss ΔE_h is[9]:

$$\Delta E_h = \epsilon_h \cdot \lambda, \qquad (2)$$

where ϵ_h is the hadron h energy loss in GeV/(nucl/S),for pions $\epsilon_h = \epsilon_\pi = 0.180$ GeV/(nucl/S) and for protons $\epsilon_h = \epsilon_p = 0.360$ GeV/(nucl/S), $S \approx 10$ fm², λ is in nucleons/S. For the mean thickness $\langle\lambda\rangle$ in nucleons/S of the target nucleus, the mean energy loss $\langle \Delta E_h \rangle$ GeV is:

$$\langle \Delta E_h \rangle = \epsilon_h \cdot \langle\lambda\rangle; \qquad (3)$$

for the maximum thickness, λ_{max} in nucleons/S, of the target nucleus - when the hadron passes through the nucleus along its diameter:

$$\Delta E_{hmax} = \epsilon_h \cdot \lambda_{max} = \epsilon_h \cdot D. \qquad (4)$$

At energies of the incident hadrons lower than $\epsilon_h \cdot D(A)$, where D(A) is the target nucleus diameter for a nucleus with the mass number A, the energy loss ΔE_h is lower.

The observed effect which the hadron energy loss in intranuclear matter is accompanied by is the emission of the fast nucleons; the emission is determined for a given hadronic projectile by the target nucleus size and nucleon density distribution in it. In particular - the mean number $\langle n_p \rangle$ of the emitted protons equals:

$$\langle n_p \rangle = \frac{Z}{A} \langle \lambda \rangle S \left(1 - e^{-\frac{\langle \lambda \rangle}{\langle \lambda t \rangle}}\right), \qquad (5)$$

where $\langle \lambda \rangle$ in nucleons/S is the mean thickness of the target nucleus, $\langle \lambda_t \rangle$ in nucleons/S equals $\langle \lambda_t \rangle = 1/\sigma_t$ and σ_t is the total hadron-nucleon cross section in S per nucleon, $S \approx 10\ fm^2$. The relation (5) holds for all hadrons up to energies met in experiments, where accelerator beams or cosmic ray particles were applied[7,8].

The mean and maximum values of energies lost by pions and protons in their passages through intranuclear matter are given in the Table.

Table. Mean and maximum energies of pions and protons lost in their passages through intranuclear matter; the kinetic energies E_h of the incident hadrons are larger than $E_h = \epsilon_h D$, where D in nucleons/S is the target nucleus diameter and ϵ_h in GeV/(nucl/S) is the energy lost by a hadron on the intranuclear matter layer as thick as 1 nucl/S, $S \approx 10\ fm^2$; for pions $\epsilon_h = \epsilon_\pi = 0.180$ GeV/(nucl/S), for protons $\epsilon_h = \epsilon_p = 0.360$ GeV/(nucl/S)[9]

Reaction	Energy GeV	Energy lost GeV	
		mean	max
Pi + C	≥ 1.5	0.5	1.5
Pi + Al	≥ 1.7	0.7	1.7
Pi + Cu	≥ 2.5	1.1	2.5
Pi + W	≥ 3.8	1.8	3.8
Pi + Ta	≥ 3.8	1.8	3.8
Pi + Pb	≥ 4	1.9	4
p + C	≥ 2.1	1	2.1
p + Al	≥ 3.4	1.5	3.4
p + Cu	≥ 5	2.2	5
p + W	≥ 7.6	3.6	7.6
p + Ta	≥ 7.6	3.5	7.6
p + Pb	≥ 7.9	3.7	7.9

The energies lost in hadron passages are taken away from the target nucleus - by the emitted nucleons, and so - in the passages without particle production the incident hadron energy cannot be pumped into the target nucleus.

In any type events, when particles are created, the energy cannot by pumped into the target nucleus as well. The angular and energy characteristics of the emitted nucleons are the same in stoppings and in any type events[8].

As has been seen in experiments, using the target nuclei as fine detectors of the properties of the particle production process in statu nascendi[7,17], the particle and resonance production process goes through intermediate objects or "generons" created in 2 → 2 type quasiendoergic reactions; these objects decay into usually observed particles and resonances after having left the parent nuclei[7]. Quasilinear intranuclear cascade of the intermediate objects or generons develops in the target nucleus massive enough[7], and this way the energy of the incident hadron is removed from the volume of the target nucleus additionally.

Within the frames of the picture of the collision process of hadrons with atomic nuclei[18], obtained in experiments[7-11], the quagma state of the intranuclear matter cannot be obtained in hadron-nucleus collisions; the matter inside the nucleus cannot be compressed this way.

But, the intermediate objects or generons can be considered as some kind of the excited matter inside the nucleon[7]; the intermediate objects can collide again with the downstream nucleons in the target nucleus and their kinetic energy might be transferred partly to them for an excitation and partly to the primary intermediate object for additional excitation as well. In target nuclei massive enough two, three, or more collisions may happen. It seems to be possible to pump energy large enough to some single nucleons only, the excited nucleons escape the parent nuclei, however. Maybe, at extremely high energies, the excited nucleons in the unidimensional cascade of generons[7,18] can interact and fuse together into the quagma outside the nucleus; this way, many excited nucleons may appear near one to another and fuse together into the quagma. But, will they fuse together? It should be proved experimentally; it may happen at extremely high energies. In such cases, the characteristics of the outcome in hadron-nucleus collisions should differ from corresponding characteristics of the outcome in usual hadron-nucleus collisions - without quagma production.

In order to identify the transition (1), one should analyse some physical quantities: the multiplicity of the produced particles, the transverse momentum of some collision reaction products, the composition of the products, or some other quantities reflecting the internal state of the produced quagma, and to investigate them in dependence on the projectile momentum.

If the obtained dependence will show some irregularity at higher energies, it will indicate that quagma is produced.

II. Nucleus-Nucleus Collisions

The knowledge about relativistic nucleus-nucleus reactions is mainly from experiments at the LBL Bevalac/19,20/, JINR Synchrophasotron/21/, in Cosmic Rays/22,23/; average multiplicities of the secondary particles were studied at Berkeley and Dubna/24-26/.

Our experimental data at present on heavy nuclei collisions are limited and we are free to speculate about what the process looks like when we go up in energy. A qualitative picture of the heavy ion collision process may be traced/27,28/ from comparatively low energy to relativistic energies, this picture is fragmentary and incomplete, however.

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 desintegrated; the heavily ionizing products of the collision reaction are distributed almost isotropically. At higher energies, at some tens GeV per nucleon, in central collisions of nuclei - of Mg and Ag for example, one observes the heavily 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 particles from the projectile may be observed as well.

The analysis of the 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/27/; 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/27/ is separated from the distribution of participant protons/27/ and produced pions. The Berkeley and 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.

Now, in result of the nucleus-nucleus collision studies, it can be concluded that:

a) Nucleus-nucleus collision may be considered as a composition of the hadron-nucleus collisions, in a first approximation;
b) No any peculiarities have been observed in energy-dependences of characteristics of the outcomes in nucleus-nucleus collisions, which could be an indication on an existence of the phase transition.

In the light of the results presented above, we are in the position to think that the passage of a high energy nucleus through intranuclear matter should look like the passage of a beam of high energy nucleons through the nucleus, and each of the beam nucleons behaves itself as single hadron does in passing through intranuclear matter - as has been described above and in the related papers/7,17,18/.

But, in high energy nucleus-nucleus collisions much more generons may be produced and fuse together into the quagma, at energies high enough; the events in which quagma might be produced will occur more plentifully. In the target nucleus system, the picture observed when quagma generated will be similar to that in hadron-nucleus collision without quagma generation, but the observed outcome should be expected more intensive and spectacular; in the center of mass system, two centers of produced quagma may appear frequently!

The detection of the quagma produced in nucleus-nucleus collisions should be realized in the same way as it is proposed in the case when production occurs in hadron-nucleus collisions.

3. CONCLUSIONS AND REMARKS

The experimental data on the hadron-nucleus collisions allow one to conclude that probably it is impossible to pump the energy high enough to colliding nuclei in order them to fuse together and transform into quagma state directly. The quagma might be produced only via intermediate objects or generons, or highly excited nucleons/7,18/, in the way described above - when many generons produced in hadron-nucleus or in nucleus-nucleus collisions fuse together into the quagma state outside the collision region.

Within the frames of the picture presented above, the most intensive production of the quagma should be expected at extremely high energies in central nucleus-nucleus collisions, if it can be produced at all.

In my opinion, the investigations of the "nonpion production" interaction processes in hadron-nucleus/7,18/ and in nucleus-nucleus collisions/16/ should be analysed, as related to the problem in questions, as well, additionally to the experiments in which quagma is expected to be found. Lately, some "unusual"/16/ events were observed in the collisions of ^{16}O and ^{12}C with emulsion nuclei at 2.1 and 4.5 GeV/c/nucleon where there is no pion production/16/; such events were observed in pion-^{131}Xe collisions at 2-9 GeV/c momenta/7,8,18/.

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REFERENCES

1. Chados A., Jaffe R.L., Johnson K.,Thorn C.B.,Weisskops V.F. - Phys.Rev., 1974, D9, p.3471.
2. Kapusta J. - Nucl.Phys., 1979, B148, p.461.
3. Stöker H. - Nucl.Phys., 1984, A418, p.587c.
4. Heinz U., Subramanian P.R., Greiner W. - In: BNL 51921, RHIC Workshop, BNL, Brookhaven, 1985, p.327.
5. Wilson K. - Phys.Rev., 1974, D10, p.2445.
6. Kogut J. et al. - Phys.Rev.Lett., 1983, 50, p.393.
7. Strugalski Z. JINR, E1-81-576, E1-81-577, Dubna, 1981; E1-82-287, Dubna, 1982; E1-85-578, Dubna, 1985; E1-86-579, Dubna, 1986.
8. Strugalski Z., Pawlak T., Peryt W., Pluta J. JINR, E1-11975, Dubna, 1978; Strugalski Z., Pawlak T., Pluta J. JINR, E1-82-718, E1-82-719, E1-82-841, Dubna, 1982; E1-83-234, Dubna, 1983; E1-85-888, Dubna, 1985.
9. Strugalski Z. JINR, E1-12086, Dubna, 1979; E1-83-850, Dubna, 1983; E1-84-194, Dubna, 1984.
10. Strugalski Z., Pawlak T., Pluta J. JINR, E1-84-855, Dubna, 1985.
11. Strugalski Z. - Second International Conf. on Nucleus-Nucleus Collisions, Visby, Sweden, June 10-14, 1985, vol.I, p.107; International Conf. of Particles and Nuclei, PANIC'87, Kyoto, Japan, 1987, vol.2, p.102.
12. Miller K., Pawlak T., Peryt W., Pluta J., Strugalski Z. JINR, E1-87-362, Dubna, 1987.
13. Sumbera M., Vokal S. - Acta Phys.Slov., 1982, 32, p.265.
14. Ghosh D. et al. - Hadronic J., 1980, 3, p.915.
15. Ghosh D. et al. - Proc. XVIII International Cosmic Ray Conf., Bangalore, India, 1983, HE-1-19, p.35.
16. Ghosh D., Roy J., Sangupta R. - Proc. XX International Cosmic Ray Conf., Moscow, USSR, 1987, vol.6, p.388.
17. Strugalski Z. JINR, E1-85-231, Dubna, 1985.
18. Strugalski Z. XX International Cosmic Ray Conf., Moscow, USSR, 1987, vol.5, p.46.
19. Nagamiya S. - Nucl.Phys., 1984, A418, p.239c.
20. Pugh H.G. Proc. of the Fourth International Conf. on Ultra Relativistic Nucleus-Nucleus Collisions, Helsinki, Finland, Lecture Notes in Phasics, Springer Verlag, 1984, 221, p.143.
21. Baldin A.M. - Nucl.Phys., 1985, A447, p.203.
22. Burnett T.H. - Nucl-Phys., 1985, A447, p.189c.
23. Jones W.V. - Nucl.Phys., 1984, A418, p.139c.
24. Fung S.Y. et al. - Phys.Rev.Lett., 1978, 40, p.292.
25. Aksimenko A. - Nucl-Phys., 1979, A324, p.266.
26. Bartke J. et al. JINR, E-13038, Dubna, 1980.
27. Otterlund I. Lund Univ.Report, LUIP 8011, Lund, 1980.
28. Andersson B. et al. Lund Univ.Report, LUIP 8602, Lund, 1986.

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Возможно ли накачать энергию в атомные ядра
с помощью адронов и ядер высоких энергий

Обсуждается, можно ли накачать энергию в атомные ядра адронами или ядрами высоких энергий. Обсуждение ведется на чисто экспериментальной основе, без привлечения моделей. Анализируются условия, при которых может быть получена квагма в столкновениях адрон-ядро и ядро-ядро.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Whether It Is Possible to Pump Energy into
Atomic Nuclei by High Energy Hadronic
or Nuclear Projectiles

In this paper, it is discussed whether it is possible to pump energy into atomic nuclei by high energy hadronic or nuclear projectiles. The discussion is performed on the purely experimental ground, without application of models. The conditions are considered at which quagma might be obtained in hadron-nucleus and nucleus-nucleus collisions.

The investigation has been performed at the Laboratory of High Energies, JINR.

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