The the JINR Scientific Works Competition 2021

PRESENTATION

The work is presented

“Observation of the Cold Superdense Baryonic Component of Nuclear Matter”

Section: Experimental Scientific-Research works

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The presented series of articles includes 8 publications:

1. Measurement of the Yields of Positively Charged Particles at an Angle of 35◦ in Proton Interactions with Nuclear Targets at an Energy of 50 GeV;
V. V. Ammosov, N. N. Antonov, A. A. Baldin, V.A.Viktorov, V. A. Gapienko, G. S. Gapienko, A. A. Golovin, V. N. Gres, A. A. Ivanilov, V. I. Koreshev, V. A. Korotkov, A. I.Mysnik, A.F.Prudkoglyad, Yu. M. Sviridov, A. A. Semak, V. I. Terekhov, V.Ya.Uglekov, M. N. Ukhanov, B. V. Chujko, and S. S. Shimanskii;
Physics of Atomic Nuclei, 2013, Vol. 76, No. 10, pp. 1213–1218.

2. PRODUCTION OF HIGH-PT CUMULATIVE PARTICLES IN PROTON-NUCLEUS INTERACTIONS AT 50 GeV;
V.V.Ammosov, N.N.Antonov, V.A.Viktorov, V.A.Gapienko, G.S.Gapienko, V.N.Gres’, V.A.Korotkov, A.I.Mysnik, A.F.Prudkoglyad, Yu.M.Sviridov, A.A.Semak, V.I.Terekhov, V.Ya.Uglekov, M.N.Ukhanov, B.V.Chuiko, A.A.Baldin, S.S.Shimanskiy;
Yadernaya Fizika I Inzhiniring 4 (2013)773–778(RUS) & nucl-ex_ arXiv.1410.5582 (ENG)

3. Production of Cumulative Particles and Light Nuclear Fragments at High pT Values beyond the Fragmentation Region of Nuclei in pA Collisions at a Proton Energy of 50 GeV;
N. N. Antonov, V. A. Viktorov, V. A. Gapienko, G. S. Gapienko, V. N. Gres’, M. A. Ilyushin, V. A. Korotkov, A. I. Mysnik, A. F. Prudkoglyad, A. A. Semak, V. I. Terekhov, V. Ya. Uglekov, M. N. Ukhanov, B. V. Chuiko and S. S. Shimanskii;
JETP Letters, 2015, Vol. 101, No. 10, pp. 670–673.

4. Spectra of Double-Cumulative Photons in the Central Rapidity Region at High Transverse Momenta1;
I. G. Alekseev, A. A. Golubev, V. S. Goryachev, G. B. Dzubenko,

A. G. Dolgolenko, N. M. Zhigareva, S.M. Kiselev, K. R. Mikhaylov,
E. A. Morozova, P. A. Polozov, M. S. Prokudin, D. V. Romanov,
D. N. Svirida, A. V. Stavinsky, V. L. Stolin, and G. B. Sharkov;
Physics of Atomic Nuclei, 2015, Vol. 78, No. 8, pp. 936–942.

5. Knockout of Deuterons and Tritons with Large Transverse Momenta in pA Collisions Involving 50-GeV Protons;
N. N. Antonov, A. A. Baldin, V. A. Viktorov, V. A. Gapienko, *, G. S. Gapienko,
V. N. Gres', M. A. Ilyushin, V. A. Korotkov, A. I. Mysnik, A. F. Prudkoglyad,
A. A. Semak, V. I. Terekhov, V. Ya. Uglekov, M. N. Ukhanov,
B. V. Chuiko and S. S. Shimanskii;
JETP Letters, 2016, Vol. 104, No. 10, pp. 662–665.

6. DENSE COLD BARYONIC MATTER;
A.V. Stavinskiy, D.Yu. Kirin, N.M. Zhigareva, K.R. Mikhailov, V.S. Goryachev, P.A. Polozov,M.S. Prokudin, D.V. Romanov, G.B. Sharkov, V.L. Stolin, O.A. Chernishov, A.A. Baldin, A.V. Konstantinov, A.I. Malakhov, S.S. Shimanskiy;
Acta Phys. Pol. B Proc. Suppl. 9, 325 (2016).

7. Observation of the Independence of the p/π Ratio from the Nuclear Size for Hadrons Knocked out with Large Transverse Momenta from a Nuclear Target by 50-GeV Protons;
N. N. Antonov, A. A. Baldin, V. A. Viktorov, A. S. Galoyan, V. A. Gapienko,
G. S. Gapienko, V. N. Gres', M. A. Ilyushin, A. I. Mysnik, A. F. Prudkoglyad,
D. S. Pryanikov, V. A. Romanovskii, A. A. Semak, V. I. Terekhov,
V. Ya. Uglekov, M. N. Ukhanov and S. S. Shimanskii;
JETP Letters, 2018, Vol. 108, No. 12, pp. 783–786.

8. Scaling Behavior of Spectra of Protons, Deuterons, and Tritons Produced with High Transverse Momenta in pA and 12CA Collisions;
N. N. Antonov, A. A. Baldin, V. A. Viktorov, A. S. Galoyan, V. A. Gapienko,
G. S. Gapienko, V. N. Gres', M. A. Ilyushin, A. F. Prudkoglyad, D. S. Pryanikov,
V. A. Romanovskii, A. A. Semak, I. P. Solodovnikov, V. I. Terekhov,
M. N. Ukhanov, and S. S. Shimanskii;
JETP Letters, 2020, Vol. 111, No. 5, pp. 251–254.

The work nominated for the competition is a series of articles published from 2013 to 2020 in scientific journals and conference proceedings under the theme No. 02-1-1087-2009 / 2023 on the topic "Research in the physics of relativistic heavy and light ions at accelerator complexes Nuclotron-NICA JINR and SPS CERN".

The presented works are aimed at elucidating the nature of cumulative processes. As a result of this study, evidences have been obtained for the existence of a cold superdense component of nuclear matter - in ordinary nuclei, nuclei of smaller mass (deuterons and tritons) are observed in the highly compressed state. And also, a physical program has been prepared to study the properties of the new state of nuclear matter in the planned experiments.

D.I. Blokhintsev in 1957, analyzing the experimental data on proton-nuclear collisions obtained at the synchrocyclotron of LNP JINR, came to the conclusion that the quasi-elastic scattering of protons by deuterons (contained in nuclei) can be described if we assume the existence in the nuclei of nuclei of a smaller mass in a compressed state. Those, in ordinary nuclei, there is a baryonic component with a density much higher than the average density of nuclear matter. Such experiments continued after 1957 at LNP JINR and ITEP. However, the huge interest in the study of multinucleon (multiquark) systems was initiated by the A.M. Baldina's article appeared in 1971. The existence of "cumulative processes" were predicted and in the same year were discovered in experiments with accelerated deuteron beams at the LHE JINR.

The cumulative processes studies in the following years have found many unusual effects such as: a strong A-dependence; isotopic symmetry of particles born in the cumulative kinematic region; increased yield of baryons and nuclear fragments in comparison to mesons; scaling behavior of cross sections. Most of the experimental data on cumulative processes were obtained in the region of nuclear fragmentation and transverse momenta of less than 1 GeV/c. These experimental data stimulated the emergence of many theoretical models that considered various multinucleon (multiquark) configurations in nuclei to explain the nature of the cumulative processes. Some considered various versions of multinucleon (multiquark) systems - fluctons, while others believed that nuclei contain point like nucleons with large relative momenta located at short distances (for example, short-range correlations - SRC).

In the 2000-th ITEP NRC "Kurchatov Institute" carried out studies to search for possiblity of the deep inelastic flucton-flucton fusion with emission of hard photons near an angle of 90^0 in the center-of-mass system of nucleon-nucleon interactions. This is a absolutely new mechanism for the formation of nuclei in the central region for pA- and AA-interactions. ITEP experiments were discontinued in 2012 after the accelerator failure.

Since 2004 the research with relativistic nuclei is being carried out at the IHEP NRC "Kurchatov Institute". At the SPIN set up since 2009 investigations of the features of particle production in the kinematic region outside the fragmentation region (p> 2 GeV/c) and with large transverse momenta (pT> 1 GeV/c) have begun. In this kinematic region, interactions in the initial and final states are suppressed. Research is carried out in the region up to the kinematic boundary and beyond the kinematic boundary of nucleon-nucleon interactions i.e. in the pre-cumulative and cumulative domains. The studies carried out in the new kinematic domain made it possible to confirm the main features of the cumulative processes observed in the nuclear fragmentation region. And also, to obtain evidence of direct knocking out of the lightest nuclear fragments (deuterium and tritium) from nuclei with transfer energy up to 6 GeV. Taking into account that the transferred energy is ~ 10 times greater than that observed in 1957 at LNP JINR one can state the observation of supercompressed light nuclei, and, consequently, a cold superdense baryonic component. These results force us to take a fresh look at the properties of nuclear matter located in the center of massive stars, its properties and the evolution laws.

Joint team from JINR and ITEP have prepared programs to studiy the properties of the cold superdense component in the cumulative processes at the accelerators of JINR, IHEP and others.

The main results obtained in the framework of the presented series of articles:

1. The main results obtained in the study of pre-cumulative and cumulative processes at the SPIN installation (IHEP, NRC "Kurchatov Institute"). The regularities found in the study of cumulative processes in the target fragmentation area have been confirmed.

1.1. The strong A-dependence of the cumulative particle production and the impossibility to describe the relative yield of the particles on different nuclei in standard MC generators were confirmed [1].

In cumulative processes a strong dependence on the atomic mass for the particle production cross sections of is observed. The dependence of the particle production cross sections can be represented as $\sigma \sim A^{\alpha}$. In pA - collisions, in the absence of the big contribution from the initial state (ISI) and final state (FSI) interactions, the dependence with α=2/3 is observed. This dependence indicates the proportionality of the collision cross section of the transverse area of the nucleus which depends on the atomic mass as $A^{2/3}$. If such the A-dependence is observed in pA-collisions, then nucleon-nucleon interactions are observed, in which the nucleons of the nucleus are smeared over the transverse area of the nucleus. If there is a significant contribution of ISI and FSI (for example, multiple secondary interactions) the dependence on atomic mass can be $\alpha \geq 1$. Research at the SPIN facility is carried out in the kinematic region where of ISI and FSI are suppressed. The proton beam with a momentum of 50 GeV/c and the intensity $\sim 5 \times 10^{12}$ protons per cycle interacted with thin (0.6 - 0.8 g /cm^2) nuclear targets made of carbon, aluminum, copper, and tungsten. The data of work [1] were obtained at a registration angle of 35^0 (lab.sist.). The positive charge particles with momenta from 1 GeV/c to 6.6 GeV/c were registered which corresponds to the interval of transverse momenta from 0.57 GeV/c to 3.76 GeV/c. I.e. the observation of the strong A-dependence with $\alpha \geq 1$ at the SPIN set up is an indication of interaction with a multinucleon (multiquark) configuration. Figure 1 shows [1] A-dependence for positive charge particles. During the taking this data the facility didn't use the time-of-flight particle identification system.

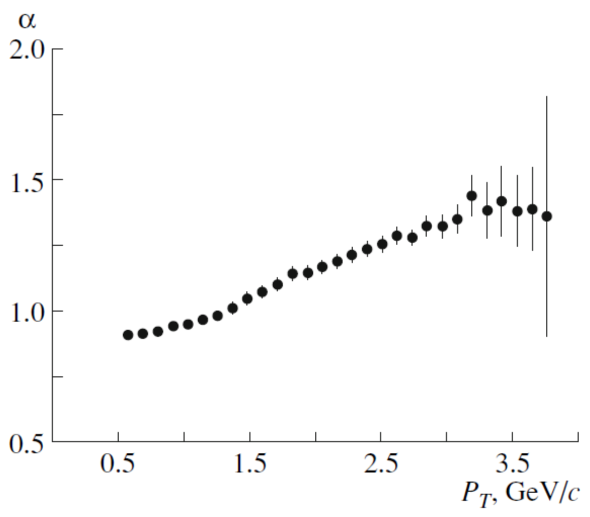
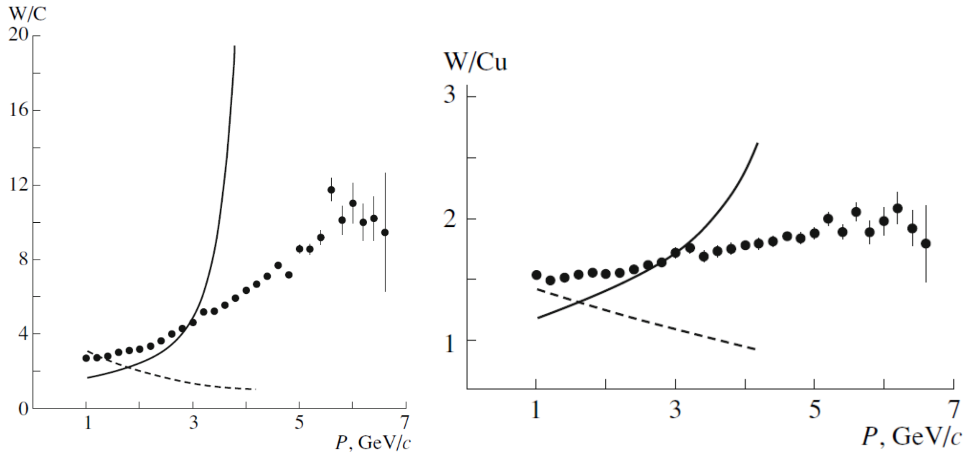


Fig.1 The exponent of A-dependence on the transverse momentum.

Fig. 2 shows a comparison of the obtained data [1] with the predictions of the MC generators. It can be seen that the MC generators without a special modification describe poorly the data obtained in the pre-cumulative kinematic region and have no predictions for the cumulative region where multi-nucleon (multi-quark) configurations are involved in the interaction.



(a) (b)

Fig.2 The ratio of the positive charge particle yields in the interactions of protons with tungsten and carbon (a), and also tungsten and copper (b). Points - this experiment [1]; curves: dashed line — UrQMD MC generator, solid — HIJING MC generator.

1.2. The dominance of the baryonic component over the meson component was confirmed. An indication of the locality of the processes for the positive charge particle production was obtained. The universality of the description the negative pion cross sections as proposed in [A] was confirmed.

Measurement of the negative particle yield at the SPIN set up made it possible to carry out additional studies [2]. Fig. 3 shows the ratios of the of positive and negative charge particle yields.

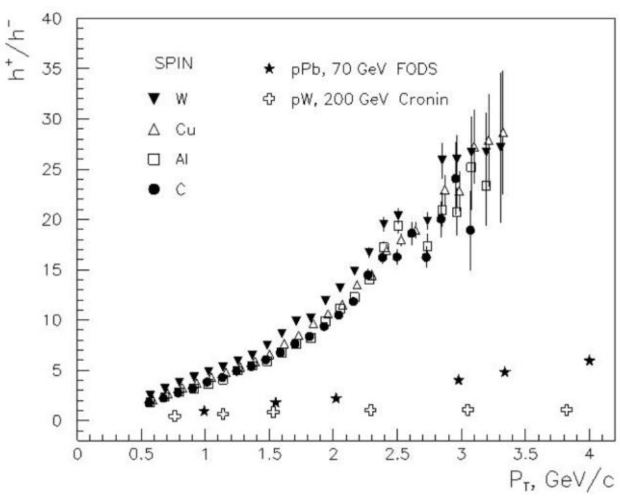


Fig.3 The ratio of the positive and negative particle yields, h^+/h^-, on different targets as a function of the transverse momentum. For comparison, data are presented on the ratio of, p/π^-, for pPb at 70 GeV [B] and for pW at 200 GeV [C]. The measurements of the last two experiments were carried out at a registration angle of 90^0 in the center-of-mass system for collisions of free nucleons.

The measurements in [B, C] were carried out in a close range of the investigated transverse momentums but in the kinematic domain of nucleon-nucleon interactions with higher energies of proton beams. The data [2] obtained demonstrate a significantly higher relative yield which is exactly what was observed in the "classical" studies of cumulative processes.

The analysis of a large set of inclusive data on the particle production in the pre-cumulative and cumulative domains as well as in the processes of subthreshold particle production made it possible [A] using the properties of self-similarity to propose the universal description of the invariant cross sections in the form:

$$f = E\frac{d^3\sigma}{dp^3} = C_1 \cdot A_1^{\frac{1}{3}+\frac{X_I}{3}} \cdot A_2^{\frac{1}{3}+\frac{X_{II}}{3}} \cdot e^{-\frac{\Pi}{C_2}} \qquad (1)$$

here C_1 and C_2 are constants, A_1 and A_2 are the atomic weights of colliding nuclei, $\Pi = \frac{\sqrt{s_{\min}}}{2m_N}$,

s_{min} – is the square of the minimum energy required for the formation of the observed particle, m_N is the nucleon mass. X_1 and X_2 are the masses, in nucleon masses, of the colliding participants in the interaction. Fig. 4 shows that when the constants in the A-dependence 1) are replaced from 1/3 to (2.5) / 3, a brilliant coincidence is observed for negative pions of the cross-section ratios.

Fig. 4 shows that when the constants in the A-dependence are replaced from 1/3 to (2.5)/3 a brilliant coincidence is observed for the cross-section ratios of negative pions.

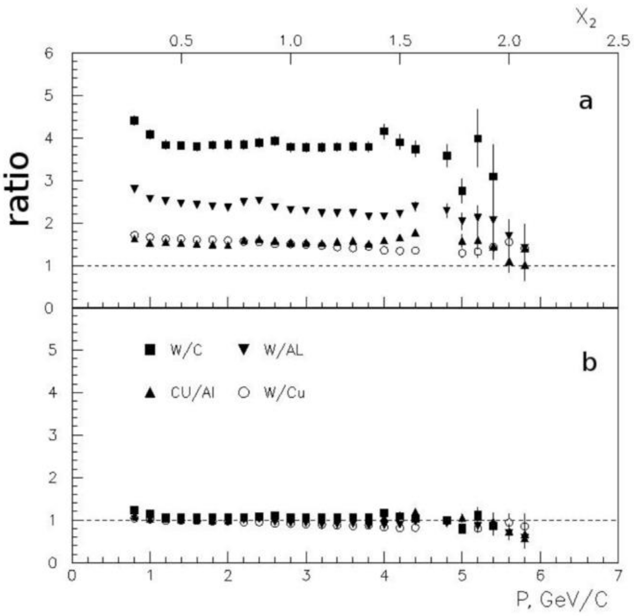


Рис.4 The ratios of the negative pion invariant cross sections for the production of multiplied by the inverse A-dependence. The lower horizontal scale shows the momentum values, the upper - the X_2 values. a) the relationship is obtained when using A-dependence in the form [A] $A^{(1+X2)/3}$, b) A-dependence is taken as $A^{(2.5+X2)/3}$

1.3. In articles [3, 5, 8] the detailed study of the proton, deuteron and triton productions were carried out. The confirmation of direct knocking out processes for of deuterons and tritiums has been obtained.

In article [3] the time of flight for particles particle identification was used. Fig. 5 shows the protons, deuterons and tritium spectra formed on carbon and tungsten targets. A sharp drop in the relative yield of pions relatively to all nuclear fragments is observed. Also, there are an increase in the relative yield of deuterons and tritium relatively to protons. Knowledge of practically all (except for neutrons) hadrons produced in pA collisions makes it possible to determine the average baryon production number <B>. This characteristic makes it possible to assess the contribution of various mechanisms proposed by theoretical models. For example, the mechanism of SRC should lead to an average number of baryons about 1. Hot fluctons will give an average number of baryons less than 1. At the same time, the mechanisms of direct knockout of nuclear fragments in excited and unexcited states will lead to an average number of baryons greater than unity. The average number of baryons produced in pA-collisions is shown in Fig. 6. It demonstrates tendency to an increase <B> with an increase the momentum of the detected particles. The excess of 1 can see already in the pre-cumulative region.

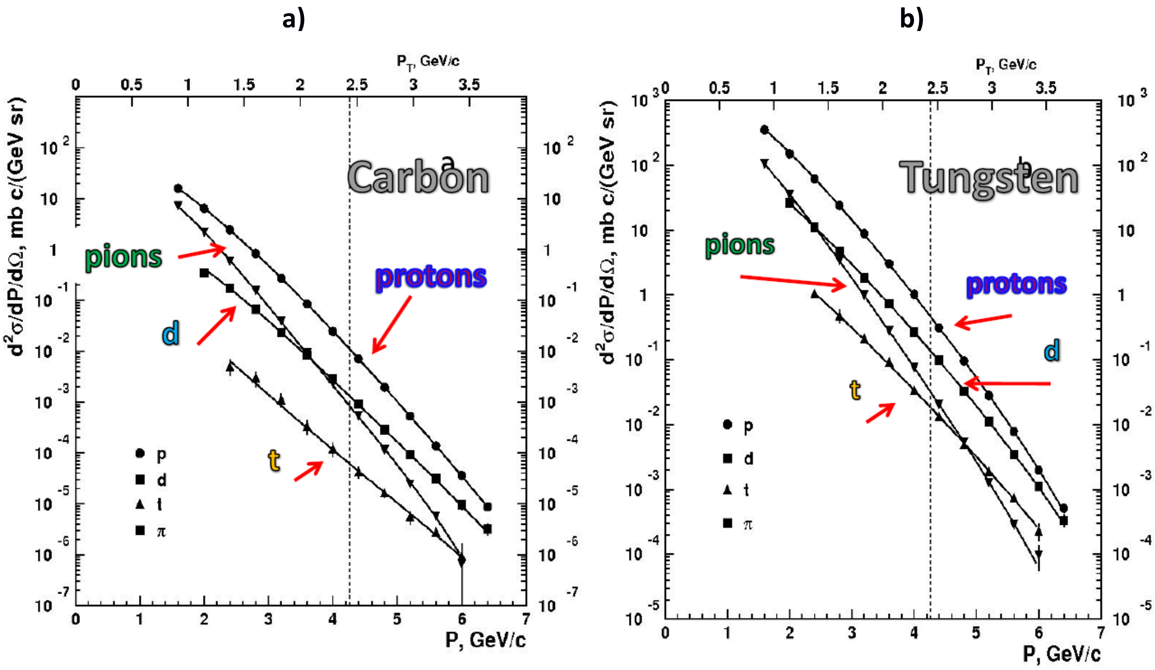


Fig.5 The momentum spectra of positively charged pions, protons, deuterons and tritons for: a) carbon and b) tungsten targets. The upper horizontal scale shows the transverse momentum values. The vertical dashed line corresponds to the limit for elastic nucleon-nucleon scattering.

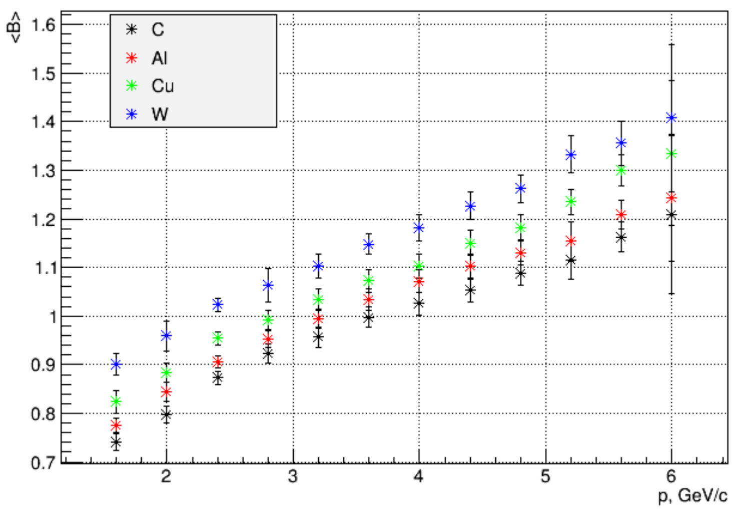


Fig.6 The average number of baryons <B> as a function of the particles detect momentum at the angle 35^0 in pA-interactions with 50 GeV/c proton beam.

This estimate of the average number of baryons <B> is the lower limit since the SPIN magnetic spectrometer registers only one particle with a certain momentum. Neutrons and groups of unbound baryons are not registered. However, the data allow us to conclude that the processes of direct knockout of deuterons and tritium dominate.

The coalescence coefficients were used to determine the region of formation size of nuclear fragments. The results of these studies are presented in [5]. Table 1 shows the average B2 coalescence coefficients B_2 for deuteron production.

Table 1. Mean values B_2 parameter

Target	C	Al	Cu	W
$B_2 \times 10^2$, GeV$^2/c^3$	1.41 ± 0.10	1.56 ± 0.08	1.51 ± 0.07	1.41 ± 0.06

The absence of the A-dependence of B_2 is a direct indication to the local mechanism of deuteron production, i.e. for direct knocking out mechanism.

In article [8] presents the first data on the lightest nuclear fragments production p, d, t with high momenta at the angle of 40^0 (lab. syst.) in the interactions of protons with a momentum of 50 GeV / c and carbon nuclei with a momentum of 20 AGeV/c with different nuclear targets. Fig. 7a shows the spectra of nuclear fragments. The relative yields of deuterons and tritons increase with the momentum in all cases. The yield of deuterons with high p_T values from C + *A* collisions in the cumulative region becomes comparable to the yield of protons.

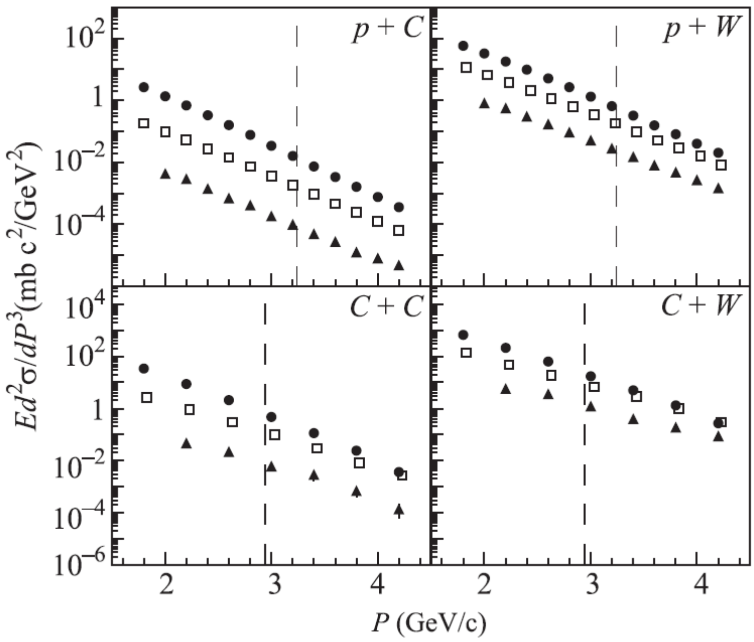


Рис. 7a Spectra of (circles) protons, (rectangles) deuterons, and (triangles) tritons in four different collisions. The vertical dashed straight lines indicate the kinematic limit of elastic nucleon–nucleon scattering at 40°.

According to Eq. (1), the inclusive cross section divided by should give the exponential . Fig. 7b shows distributions of the spectra of *p, d,* and *t* from *pA* and C*A* collisions over the dimensionless quantity

$$g(\Pi) = E\frac{d^3\sigma}{dp^3}\Big/\left(C_1 \cdot A_1^{\alpha(X_1)} \cdot A_2^{\alpha(X_2)}\right).$$

Here, $\alpha(X) = (2.4 + X)/3$ is taken in all cases, $A_1^{\alpha(X_1)}=1$ for *pA* collisions, and constants C_1 specifying the dimension of cross sections were a priori determined when fitting Eq. (1) to experimental data. The dashed lines in all panels of Fig. 7b present the function exp(- Π/C2) with value C2 = 0.172. Fig. 7b demonstrates a similar behavior of for all particles in all collisions. Parameterization (1) is valid only in the absence of secondary rescattering of the products of the quasibinary reaction on nucleons of the nucleus.

The spectra of protons, deuterons and tritons at high transverse momenta p_T in $p + A$ and $C + A$ collisions can be described by Eq. (1) with the same dependence on the masses of nuclei involved in collisions and at similar slopes C_2. Since the parameterization given by Eq. (1) is used to describe the production of particles through hard quasibinary collisions, good agreement of this parameterization with experimental data can be considered as the confirmation of our previous conclusion that deuterons and tritons with high p_T values are directly knocked out from a nucleus in cumulative processes.

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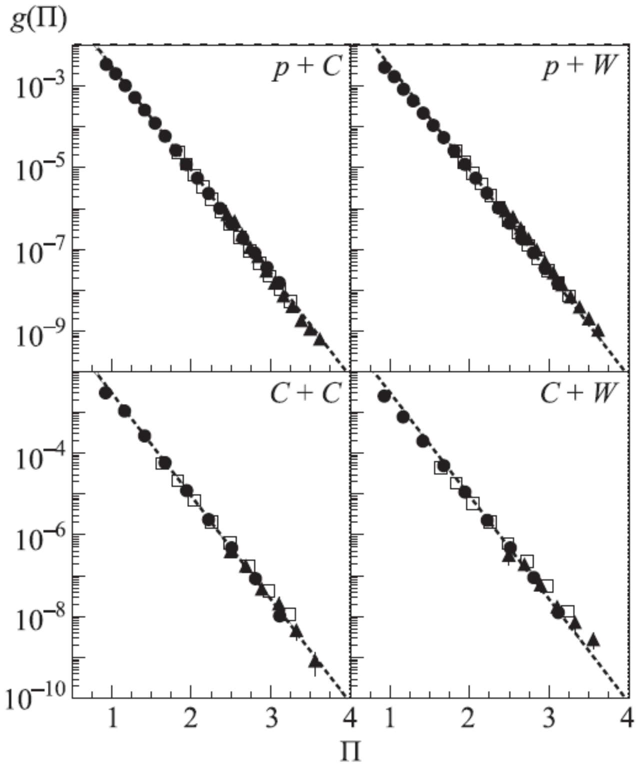

Fig.7б Exponential dependence of the cross sections on Π for (circles) protons, (squares) deuterons, and (triangles) tritons. The dashed lines represent the function exp(−Π/0.172).

3. Preparation of the program for studying the properties of a cold dense baryonic component at the JINR accelerator base [4, 6].

3.1 Deep inelastic fusion of cold dense baryonic matter.

At the end of the 90th of the last century the G.A. Leksin's group of ITEP NRC "Kurchatov Institute" was proposed the mechanism for the cold dense baryonic matter macrosystem formation. Fig.8 provides an illustration of this idea.

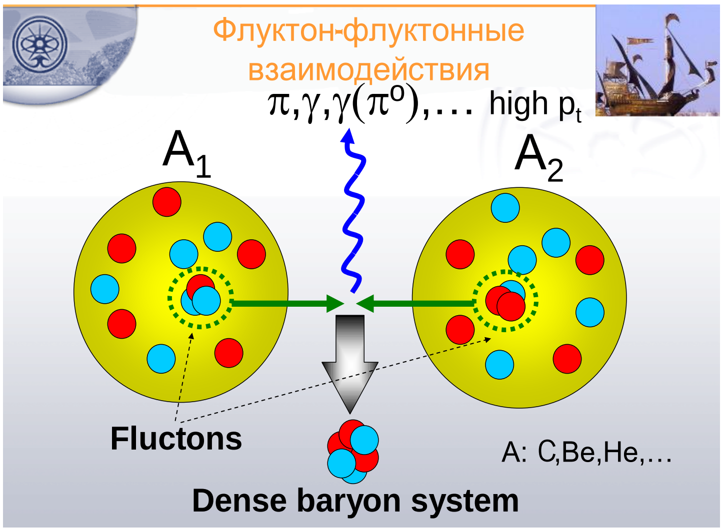

Fig.8 Flucton-flucton deep inelastic fusion of the cold dense baryonic component.

In the NN- and AA- interactions the flucton-flucton collisions are possible. The resulting system will be excited. The system can reset the excitation through the emission of a photon, pions or other hadrons. Then, in the center-of-mass system, it will be possible to observe a close group of baryons flying in one direction, and a photon or meson with energy that compensates for the recoil of the multibaryon (multiquark) system. Such photons and hadrons will be produced in the cumulative kinematic region. The observing cumulative photon production in nucleus-nucleus collisions were carried out [4] at ITEP. The registered photons are corresponding to the formation of systems with more than 4 nucleons in recoil region. Fig. 9 shows the examples of photon spectra observed at ITEP. These data are a direct indication of the possibility to synthesize macrosystems of the cold superdense baryonic component of nuclear matter and studying its properties in correlation experiments at the JINR experimental facilities [6].

The presented series of articles is an important stage in the research of cumulative processes lasting over 50 years which began with A.M. Baldin's article [D]. The hypothesis of D.I. Blokhintseva [E] who predicted the existence in nuclei of nuclei with a lower mass in a compressed state i.e. cold dense baryonic components in nuclear matter. These results force us to take a fresh look at the properties of nuclear interaction as nonperturbative part of QCD and properties the nuclear matter located in the center of massive stars and the star evolution laws.

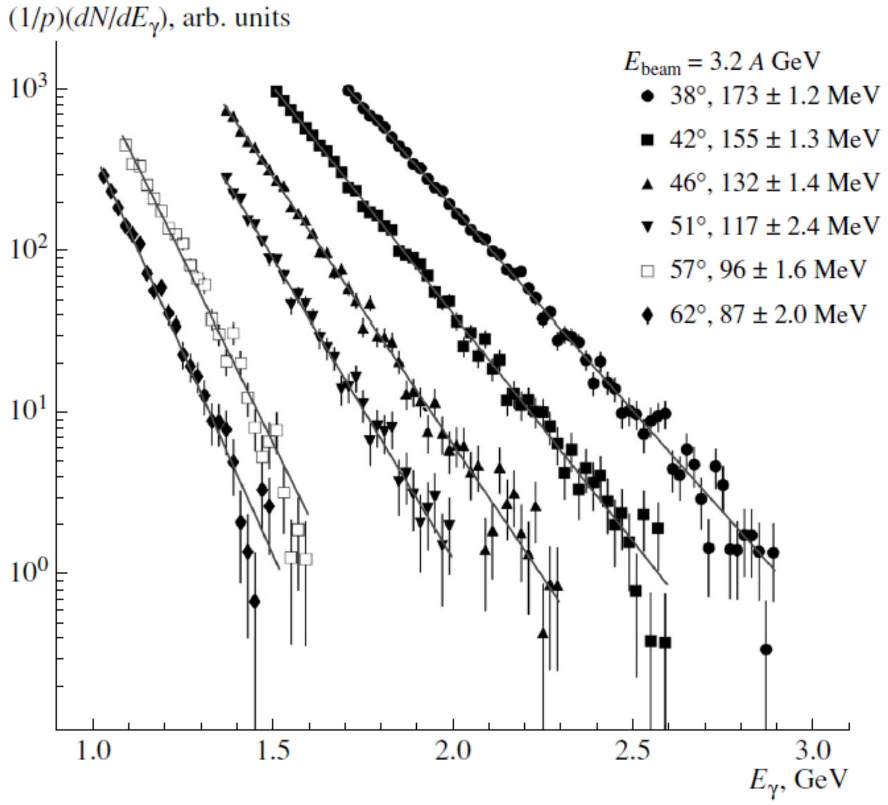

Рис.9 Photon spectra in the reaction C + Be → γ + X at the energy of a carbon beam 3.2 AGeV for different angles of photon emission.

Literature

[A] Балдин А.А., Краткие Сообщения ОИЯИ, № 3-92, 1992, С. 27-37; № 4-96, 1996, С. 185 61-68; № 2-99, 1999, С. 20-29.

[B] Абрамов В.В. и др., ЯФ, 1985, Т. 41, вып.2, С. 357-370.

[C] Cronin J.W. et al., Phys. Rev. V. D11, 1975, P. 3105-3123.

[D] Baldin A.M., "Bulletin of the Lebedev Physics Institute" LPI RAS, N1, p.35, 1971.

[E] Blokhintsev D.I., Sov.Phys.JETP 6 (1958) 5, 995-999,
Zh.Eksp.Teor.Fiz. 33 (1957) 5, 1295-1299.

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