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Physics

Analysis of Characteristics of Particles Produced in Soft and Hard Processes in Nucleus–Nucleus Collisions at Relativistic Energies

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ABSTRACT. **Average Kinematic Characteristics of π^-- mesons and protons in soft and hard processes are analyzed. Soft and hard processes are produced in *(p, d, He, C) Ta* collisions at 4.2*AGeV/c* and 10*GeV/c*. Experimental results in *CTa* - collisions at 4.2*AGeV/c* are compared with predictions of the quark – gluon string model *(QGSM)* and *DCM* - Dubna version of the cascade – evaporation model.The conclusion is made that production of cumulative protons is caused by fluctuations of density of the heavy target nucleus *Ta*, but definite role is played by the mass and energy of the projectile. Characteristics of protons with maximal cumulative number n_c^{max} are studied. It is shown that they do not depend on the atomic number A_i of the projectile, on the atomic number A_t of the target, on the incident energy, but depend only on n_c^{max}.** *© 2017 Bull. Georg. Natl. Acad. Sci.*

Key words: nucleus, quark, cumulative proton, flucton

Analysis of Experimental Data

Separation of Hard - N_{ev}^H and Soft - N_{ev}^S Processes from Inelastic Nucleus-Nucleus Interactions. One of the interesting problems of the relativistic nuclear physics is the separation of soft and hard processes and comparison of characteristics of particles with each other. Experimental data are obtained on the two metre propane bubble chamber *PBC*-500 of the Laboratory of High Energies of the Joint Institute for Nuclear Research (Dubna). The chamber was bombarded by beams of relativistic nuclei *p, d, He, C* in the momentum range (2 – 10*AGeV/c*). Methodic problems of the analysis of data are considered in Refs. [1 – 6].

Actuality of the study of hard and soft processes in nucleus – nucleus collisions is connected with the production of cumulative particles P^{cum} (in this case cumulative protons). Production of cumulative protons is caused by the appearance in the target nucleus the so-called fluctons *FL* [7] – multiquark dense systems in the target, which are produced by the overlap of two or more nucleons in the short time interval. The size of fluctons is less than 1F(10^{-13} cm). Because of the scattering of projectiles on fluctons cumulative protons are produced. Protons are called cumulative if the cumulative number $n_c > 1$ ($n_c = \frac{(E - p_{\|})}{m_N}$), E – is the energy, $p_{\|}$ – the longitudinal momentum in the *Lab*. frame, m_N – is the mass of the nucleon. The event is called hard N_{ev}^{H}, if among the secondaries there is at least one cumulative proton. Events without any cumulative protons are called soft - N_{ev}^{S}. Hard events - N_{ev}^{H} are produced by scattering of projectiles on fluctons, but soft events – by scattering on nucleons or their parts. So, characteristics of particles from hard and soft processes should differ from each other (see *Table 1*).

Fluctons in the target can appear in two different processes. First is caused by the fluctuation of density in the target nucleus and is called "cold"model. Second is caused by the compression of nuclear matter under the influence of the projectile ("hot" model) [7].

Note that in the early interpretations production of cumulative protons was connected with Fermi momentum of nucleons in the target. But calculations indicated that this is not so [8-10].

Average kinematic characteristics of protons, ®= - mesons and cumulative protons from soft_and hard processes are given in Tables.

Among the secondaries besides the cumulative protons P^{cum} $(n_c^p > 1)$ there are noncumulative, surrounding protons $(n_c^p \leq 1)$. This means that the projectile interacts not only with fluctons, but with parts of the nucleons (quarks) and nucleons themselves.

As it was mentioned hard event N_{ev}^{H} is event in which there is at least one cumulative proton P^{cum}. Protons in hard events are denoted by P^{H}. For ®=- - mesons from N_{ev}^{H} introduce the notation *pi*=-*(H)*. For soft processes N_{ev}^{S} introduce the notation P^{S} and *pi*-*(S)* for noncumulative protons and mesons, respectively. If the criterion of separation of inelastic events as N_{ev}^{H} and N_{ev}^{S} is adequate, these processes should have significantly different characteristics (see Tables 1-3). The characteristics of cumulative protons P^{cum} sharply differ from N_{ev}^{H} and leading protons P^{S} from soft collisions:

$$\left.\begin{aligned} &< p_L^{cum} >= (0.578 \pm 0.015) GeV / c;\\ &< \overline{\ }_{L}^{\,cum} >= (105.300 \pm 1.630) \deg r;\\ &< \cos \overline{\ }_{NN}^{\,*,cum} >= (-0.934 \pm 0.021);\\ &< p_L^{S} >= (1.674 \pm 0.009) GeV / c;\\ &< \overline{\ }_{L}^{\,S} >= (25.280 \pm 0.480) \deg r;\\ &< \cos \overline{\ }_{NN}^{\,S} >= (-0.125 \pm 0.006) \end{aligned}\right) \qquad (1)$$

(CTa – collisions. *Table 1).*

It is seen that cumulative protons P^{cum} in the Lab. frame are moving mostly in the backward hemisphere. This is strong influence of the heavy target *Ta*, but for protons from soft processes P^{S} this influence is much weaker:

$$\begin{aligned} &< \cos \overline{\ }_{NN}^{\,*,S} >= (-0.125 \pm 0.006)\ (CTa) \quad (Table\ 1);\\ &< \cos \overline{\ }_{NN}^{\,*,S} >= (-0.552 \pm 0.013)\ (pTa) \quad (Table\ 3). \end{aligned} \qquad (2)$$

Average kinematic characteristics of inclusive protons *p(t)* are in a good agreement with model values *(QGSM* and *DCM)*. The same is valid for ®-- mesons (see Table 1).

It should be noted that significantly differ average kinematic characteristics not only of P^{cum} and P^{S} – protons, but those of P^{S} and P^{ass} - protons (Table 3):

$$\left.\begin{aligned} &< p_L^{S} >= (1.582 \pm 0.036) GeV / c;\\ &< \overline{\ }_{L}^{\,S} > (26.950 \pm 0.400) \deg r;\\ &< \cos \overline{\ }_{NN}^{\,S} >= (-0.552 \pm 0.013);\\ &< p_L^{ass} >= (0.927 \pm 0.020) GeV / c;\\ &< \overline{\ }_{L}^{\,ass} >= (37.080 \pm 0.570) \deg r;\\ &< \cos \overline{\ }_{NN}^{\,ass} >= (-0.829 \pm 0.019). \end{aligned}\right) \qquad (3)$$

Thus, average kinematic characteristics of P^{S} and P^{ass} - protons significantly differ in spite of the fact that in the formation of protons significant role is

Table 1. Characteristics of protons *p* and ®¯- mesons from *CTa* – collisions at *4.2AGeV/c*

particles	$<p_L>$*GeV/c*	$<{}^{-}_{L}>$*degr*	$<Y_L>$	$< \cos^{-*}_{NN} >$
p - protons				
p^H	**0.986ï0.009**	**50.190ï0.510**	**0.436ï0.005**	**-0.616ï0.010**
P^{cum}	**0.578ï0.015**	**105.300ï1.630**	**-0.073ï0.004**	**-0.934ï0.021**
P^S	1.674±0.009	25.280±0.450	0.423±0.002	-0.125±0.006
P^{ass}	**1.098ï0.012**	**35.130ï0.290**	**0.432+0.003**	**-0.529ï0.003**
P(t)(EXP)	**1.144ï0.010**	**46.320ï0.300**	**0.624ï0.0.007**	**-0.500ï0.007**
P(t)(QGSM)	**1.172**	**46.300**	**0.619**	**-0.513**
P(t)(DCM)	**1.127**	**47.600**	**0.610**	**-0.504**
® ¯ *- mesons*				
$p_i^-(H)$	**0.424ï0.011**	**52.270ï1.170**	**0.860ï0/011**	**-0.278ï0.009**
$p_i^-(S)$	**0.570ï0.020**	**39.430ï1.200**	**0.890ï0.012**	**0.001ï0.001**
$p_i^-(EXP)$	**0.458ï0.010**	**50.800ï0.650**	**0.809ï0.010**	**-0.224ï0.007**
$p_i^-(QGSM)$	**0.467**	**53.520**	**0.773**	**-0.245**
$p_i^-(DCM)$	**0.470**	**51.59**	**0.791**	

(Notations: *p*(*t*) and $p_i^-(t)$ - inclusive protons and ®¯ - mesons, respectively.

Table 2. Characteristics of protons and ®¯- mesons from *dTa* –collisions at *4.2AGeV/c*

p - protons				
particles	$<p_L>$*GeV/c*	$<{}^{-}_{L}>$*degr*	$<Y_L>$	$< \cos^{-*}_{NN} >$
p^H	0.763±0.023	58.820±1.500	0.307±0.021	-0.816±0.024
P^{cum}	0.510±0.057	108.400±3. 130	-0.105±0.011	-0.950±0.042
P^S	1.126±0.019	31.780±1.700	0.733±0.021	-0.475±0.011
P^{ass}	0.728±0.011	38.990±0.320	0.484±0.012	-0.758±0.015
P(t)	0.859±0.020	47.941±0.512	0.488±0.021	-0.672±0.015
® ¯ *- mesons*				
$p_i^-(H)$	0.378±0.009	57.150±0.444	0.646±0.055	-0.334±0.022
$p_i^-(S)$	0.486±0.008	47.670±0.776	0.849±0.066	-0.174±0.015
$p_i^-(t)$	0.445±0.005	51.210±0.211	0.773±0.033	-0.234±0.011

played by the nuclear medium in the form of fluctons. Average momentum $< P_L^S >$ of P^S - protons is always larger than the average momentum of P^{ass} - protons. But the average emission angle $< q_L^S >$ is less than $< q_L^{ass} >$. It should be noted that P^S and P^{ass} protons are emitted always in the forward direction in the Lab. frame, in contrast to P^{cum}.

Characteristics of cumulative protons P^{cum} in nucleus – nucleus collisions. Consider cumulative protons P^{cum} in nucleus – nucleus collisions and

Table 3. Characteristics of protons and ®¯- mesons from pTa –collisions at 10 GeV/c

particles	$<p_L>$*GeV/c*	$<^{-}_{L}>$*degr*	$<Y_L>$	$<\cos^{-*}_{NN}>$
p-protons				
p^H	**0.821ï0.016**	**58.120ï1.100**	**0.383ï0.011**	**-0.870ï0.017**
P^{cum}	**0.569ï0.022**	**107.700ï2.580**	**-0.093ï0.041**	**-0.967ï0.031**
P^S	**1.582ï0.0.036**	**26.950ï0.400**	**0.943ï0.022**	**-0.552ï0.013**
P^{ass}	**0.927ï0.020**	**37.080ï0.570**	**0.585ï0.015**	**-0.829ï0.019**
p(t)	**1.071ï0.015**	**47.860ï0.500**	**0.507ï0.014**	**0.766ï0.008**
p_i^- – mesons				
$p_i^-(H)$	**0.526ï0.010**	**50.100ï0.510**	**0.821ï0.021**	**-0.505ï0.005**
$p_i^-(S)$	**0.688ï0.009**	**41.860ï0.330**	**1.079ï0.011**	**-0.317ï0.003**
$p_i^-(t)$	**0.607ï0.004**	**45.980ï0.210**	**0.950ï0.004**	**-0.411ï0.001**

analyze characteristics as a function of atomic number A_i of projectile and incident energy.

It is known that characteristics of secondaries depend on the type of projectile, target and incident energy. But there exist processes which do not depend on A_i and A_t and incident energy – saturation (scaling) takes place. Consider from this point of view production of cumulative protons P^{cum} from A_iA_t – collisions.

Average emission angle of cumulative protons is significantly larger than average emission angle of *p(t)*, p^{ass} and p^S – protons (Table 2).

$$\left.\begin{array}{l} < p_L^{cum} >= (0.510 \pm 0.057) GeV/c; \\ <^{-cum}_{L} > (108.400 \pm 3.130) \deg r; \\ < \cos^{-cum}_{NN} >= (-0.950 \pm 0.042); \\ < p(t) >= (0.859 \pm 0.020) GeV/c; \\ <^{-}_{L} >= (47.941 \pm 0.512) \deg r; \\ < \cos^{-*}_{NN} >= (-0.672 \pm 0.015) \end{array}\right\} \quad (4)$$

Thus, average kinematic characteristics of cumulative protons P^{cum} from *CTa* and *dTa* – collisions at *4.2AGeV/c* and *pTa* collisions are practically identical – they do not depend on the atomic number of projectile and the incident energy. It can be said that the hypothesis of soft decoloration takes place *(Tables 1-4)* [2].

It turnes out that among secondaries leading particles are protons from soft processes P^S (see Tables 1-3).

It can be said that this is in the agreement with the imagination that these particles are produced by spectator quarks of the projectile; but cumulative particles are signals of interaction of other quark of the projectile with flucton [2, 3].

Analysis of characteristics of protons from nucleus – nucleus collisions as a function of n_c^{max}. It is known that from experimental data characteristics of secondaries depend on incident energy, on the target mass, on projectile mass and on cumulative number n_c [4, 5, 11-15].. But there exist quantities, which do not depend on the mass and energy – so called scaling quantities. Consider from this point of view cumulative protons P^{cum} and surrounding protons P^{ass} in hard processes.

Characteristics of P^{cum} and P^{ass} protons significantly differ. Average values of momenta of P^{cum} - protons do not depend on the number of cumulative protons in the event. The same is valid for angular dependence of cumulative protons. The increase of the degree of cumulativity is not observed, i. e. the increase of the number of nucleons in the interaction

Table 4. Characteristics of cumulative protons P^{cum} from *CTa* , *dTa* (*4.2AGeV/c*) and *pTa* (*10GeV/c*) collisions

A_iA_t-collisions	$<p_L>$GeV/c	$<\bar{\ }_L>$degr	$<Y_L>$	$<\cos\bar{\ }^*_{NN}>$
CTa(4.2AGeV/c)	**0.578ï0.015**	**105.300ï1.630**	**-0.073ï0.004**	**-0.934ï0.021**
dTa(4.2AGeV/c)	**0.510ï0.033**	**108.400ï3.910**	**-0.105ï0.011**	**-0.950ï0.049**
pTa(10GeV/c)	**0.569ï0.022**	**107.700ï2.580**	**-0.093ï0.041**	**-0.967ï0.031**

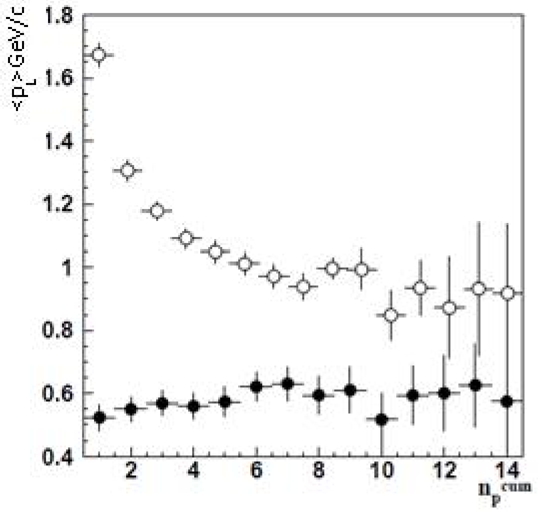

Fig. 1. *CTa*-collisions at *4.2AGeV/c*. Dependence of average momenta of protons on the number of cumulative protons n_p^{cum} in the event. • -P^{cum}, o-P^{ass}.

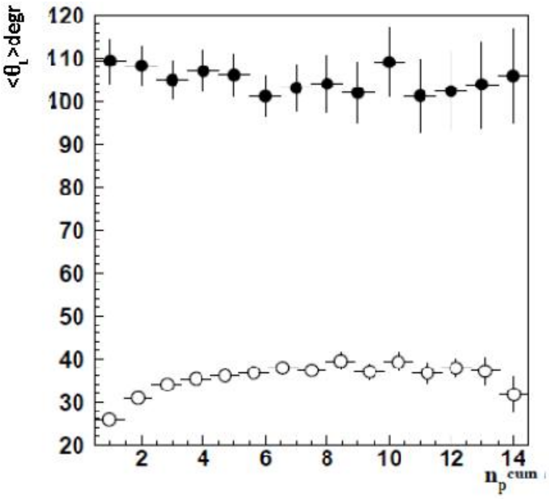

Fig. 2. *CTa*-collisions at *4.2AGeV/c*. Dependence of average emission angle of protons on the number of cumulative protons n_p^{cum} in the event. • -P^{cum}, o -P^{ass}.

does not influence characteristics of protons. It turns out that for the production of cumulative particles there exists the source with similar particles, which do not depend from number of interacting nucleons properties [2] (Figs. 1, 2).

The number of P^{cum} is rather large – it reaches 14 fluctons, i. e. in the heavy *Ta* - tantalum target can appear 14 fluctons. With the increase of the number of cumulative protons in event n_p^{cum} average momentum of surrounding protons decreases sharply, then at $n_p^{cum}>8$ reaches the plateau.

All P^{ass} protons are moving in the forvard direction in the Lab. frame (Fig. 2).

It is interesting to study the dependence of particle characteristics on the maximal cumulative number n_c^{max}, or to study the dependence of average momenta $<P_L(n_c^{max})>$ and emission angle $<q_L(n_c^{max})>$ on n_c^{max}. With the increase of maximal cumulative number n_c^{max} sharply decreases average values of the momentum of proton $<P_L^{max}(n_c^{max})>$ with maximum cumulative number. Sharp decrease of $<P_L^{max}>$ is ended $n_c^{max} \sim 1$ (Fig. 3).

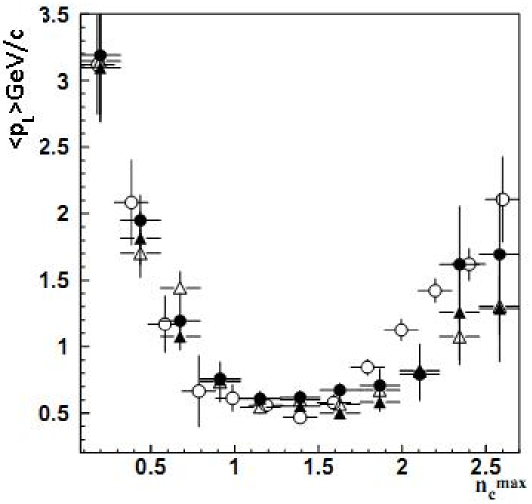

Fig. 3. Dependence of average momenta of protons $< p_L(n_c^{\max}) >$ on the value of $n_c^{\max}$.
• - *CTa(4.2AGeV/c)*, △ - *pTa-(10GeV/c)*;
▲-CC- *(4.2AGeV/c)*; o - *pC(10GeV/c)*

After that the curve reaches the plateau, but at $n_c^{max} \approx 1.5$ and higher (scattering on fluctons) sharp increase of $<P_L^{max}>$ is observed – multiparticle interaction – cumulative effect.

Concerning the behavior of the function $<q_p(n_c^{max})>$, first the sharp increase, then it reaches the plateau (in the interval 1.5 Jn_c^{max}J2.0), then weak decrease is observed [15].

Similar behavior of functions $<P_L^{max}(n_c^{max})>$ and $<q_L^{max}(n_c^{max})>$ is observed for **- mesons in ***C* – interactions at *40 GeV/c* [2, 7, 8].

It should be noted that the behavior of functions $<P_L^{max}(n_c^{max})>$ and $<q_L^{max}(n_c^{max})>$ on the atomic number of target and projectile and incident energy - hypothesis of soft decoloration [16]. Behavior of these functions depends only on n_c^{max}.

Conclusion

1. Hard processes are mostly determined by the atomic number of heavy target *Ta* - tantalum (in *CTa* – collisions at *4.2AGeV/c* near *54%* of events are hard). But there is definite dependence on the incident energy (in *pTa* – collisions at *10 GeV/c* near *42%* of events are hard).

2. (p, d, He, C)Ta central collisions are mostly hard (all central *CTa* – collisions are practically hard).

3. Characteristics of cumulative protons P^{cum} practically do not depend on the atomic number of projectile and the incident energy.

4. Characteristics of protons P^{max} with maximal cumulative number n_c^{max} depend only on n_c^{max}. Results 3 and 4 allow one to conclude that Hypothesis of soft decoloration takes place.

ფიზიკა

რელატივისტურ ბირთვ-ბირთვულ დაჯახებებში ხისტ და რბილ პროცესებში წარმოქმნილი ნაწილაკების მახასიათებლების ანალიზი

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(წარმოდგენილია აკადემიის წევრის ა. ხელაშვილის მიერ)

ნაშრომში განხილულია ხისტ და რბილ პროცესებში მონაწილე ®⁻–მეზონების და პროტონების მახასიათებლები. ხისტი და რბილი პროცესები წარმოიქმნება (p,d,He,C)Ta დაჯახებებში 4,2AGeV/c და 10GeV/c პირველადი იმპულსების დროს.

CTa - ნახშირბად-ტანტალის დაჯახებებში (4,2AGeV/c) წარმოქმნილი ხისტი და რბილი პროცესების სკმ – საშუალო კინემატიკური მახასიათებლები შედარებულია QGSM - კვარკ-

გლუონური სიმური და DCM - დუბნის კასკადურ – აორთქლებადი მოდელების შედეგებთან. მოდელები დამაკმაყოფილებლად აღწერენ ექსპერიმენტს.

ნაჩვენებია, რომ ბირთვ-ბირთვულ დაჯახებებში წარმოქმნილი P_{cum} -კუმულატიური პროტონების მახასიათებლები არ არის დამოკიდებული არც A_i - დამცემი, არც A_t – სამიზნე ბირთვების მასებსა და არც პირველად ენერგიაზე. ექსპერიმენტული მონაცემების ანალიზი გვიჩვენებს, რომ ხისტი პროცესების წარმოქმნა ძირითადად განპირობებულია სამიზნე ბირთვის ნუკლონების სიმკვრივის ფლუქტუაციით – „ცივი“ მოდელი. გარკვეულ როლს თამაშობს დამცემი ბირთვის მასა და პირველადი ენერგია. ის რომ კუმულატიური პროტონების სკმ არ არის დამოკიდებული არც A_i-ზე, არც A_t-სა და არც პირველად ენერგიაზე, შეიძლება მიუთითებს იმაზე, რომ ადგილი აქვს კვარკების ან გლუონების ადრონიზაციის ერთიანი მექანიზმის გამოვლენას – „რბილი“ გაუფერულების ჰიპოთეზა – hypothesis of soft decoloration.

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