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Physics

The Study of Jet Quenching Effect in Nucleus-Nucleus Collisions

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ABSTRACT. According to modern theoretical concept, hadronization of produced quark can proceed into one or several cumulative particles, which form cumulative jets outside the nucleus. Jet is the set of cumulative particles (in our case protons), which fly in the approximately same direction and have relatively small transverse momenta. Jet can consist of 1, 2, … , n particles. The production of cumulative protons is connected with the existence of the multiquark states (fluctons). In nucleus angular widening of the produced jets and softening of the momentum spectrum can take place. This is called the jet quenching effect. The study of average kinematic characteristics of cumulative jets and surrounding particles in (p, d, He, C) (C, Ta) collisions leads to the conclusion that jet quenching effect takes place.

Key words: nucleus, quark, cumulative proton, flucton

Analysis of Experimental Data

The topicality of the study of hard processes in nucleus-nucleus collisions is connected with the production of cumulative protons p^{cum}. The hard process is the interaction where hadrons are produced which have the kinematic characteristics forbidden in the *NN*- interactions.

The production of cumulative protons is connected with creation in target nucleus of the multiquark configuration (fluctons) [1]. The flucton in the target nucleus is created by fluctuation of nuclear density, when two or more nucleons form the multiquark configuration. The incoming particle (in our case nucleon) interacts with flucton as a composite system. The size of the flucton is less than $1F$=($10^{-13}cm$). As a result of interaction, cumulative protons are produced, which create the cumulative jet. The process is assumed to be hard if among the secondary protons there is at least one proton with cumulative number $n_k>1$,

$$n_k= (E-p_{||})/m_N. \quad (1)$$

Here, E is the energy, $p_{||}$ is the longitudinal component of the momentum in the Lab frame, m_N is the nucleon mass. The event in which there are no cumulative particle is called soft. The jet is the group of particles which fly in the same direction with small relative transverse momentum [1-4].

According to the modern theoretical concepts, the hadronization of produced parton (quark) proceeds into one or several cumulative particles which produce the jet [1]. We will study the average kinematic characteristics of jets and surrounding particles (protons and p^--mesons).

Multiquark systems (fluctons) can be produced by two physical processes. The first is connected with the fluctuation of average density of target nucleus and is called “cold” model. The second -”hot” model assumes that the fluctuation of density of nucleons in target nucleus proceeds under the influence of incoming nucleus (particle) [5-9].

The existence of quarks and gluons is most well seen in jets, which are produced in hard processes. One of the first experiments, in which the existence of cumulative particles and jets was fixed was e^+e^- annihilation into hadrons ($\sqrt{s} = 30GeV$, PETRA – Collaboration). The production of jets occurs via two steps. First, $q\bar{q}$ - pair was produced, then quark hadronization into jets occured. After that the cumulative particles and their characteristics were studied in hA_t, hh and A_tA_t – collisions. It was shown that cumulative particles (and jets) spectra are similar for different target nuclei, incoming particles at different energies [10] – Hypothesis of soft decoloration .

In this connection two important problems are interesting: the first is whether the cumulative particles are produced in the nucleus or outside of it, second – jet quenching problem. Consider this problems in (*p, C*) (*C, Ta*) – collisions for incoming momenta of 4.2A*GeV/c* and 10*GeV/c*.

Average Kinematic Characteristics of Jets and Surrounding Protons and π_- mesons in Nucleus-Nucleus Collisions

It is known from experimental data that average kinematic characteristics of secondary particles depend on the type of incoming and target objects, on the energy and the value of the cumulative number n_k. Besides, there exist characteristics, which do not depend on the energy, on the type of interacting nuclei. Scale invariance (scaling) takes place.

In Tables 1,3 the dependence of average kinematic characteristics of cumulative protons - p^{cum} and surrounding protons - p^{ass} on the number of cumulative protons N_P^{cum} in the event is given. It is known that the values of cumulative number n_k for cumulative protons p^{cum} and surrounding protons p^{ass} considerably differ. Therefore, their average kinematic characteristics considerably differ.

The dependence of average momentum and emission angle of cumulative protons on the number of cumulative protons is almost constant. The number of cumulative protons is rather high (In *CTa* – collisions the maximum number of cumulative protons is 14), 14 fluctons are produced. These fluctons influence only the average momentum of surrounding protons.

The number of cumulative protons produced in jets is 7 in *pTa*-collisions (10*GeV/c*). The important role in the production of cumulative protons is played by the atomic number of projectile.

Let us compare the average kinematic characteristics of cumulative protons p^{cum} and surrounding protons p^{ass} in *pC*-collisions (10*GeV/c*) and *CC*-collisions (4.2*AGeV/c*). In A_tA_t- collisions the increase of the atomic number of the projectile causes the increase of the average momentum and decrease of the emission angle of secondaries, i. e., the increase of the atomic number of projectile causes the collimation of secondaries. This is observed also in our case.

$$\left.\begin{array}{ll} < p_{L,p^{ass}}, CC >= (1.939 \pm 0.016) GeV/c; & < p_{L,p^{ass}}, pC >= 1.701 \pm 0.025) GeV/c; \\ < \theta_{L,p^{cum}}, CC >= (95.55 \pm 1.28) \deg r; & < \theta_{l,p^{cum}}, pC >= (99.38 \pm 1.60) \deg r; \\ < \theta_{L,p^{ass}} (CC) >= (22.26 \pm 0.18) \deg r; & < \theta_{L,p^{ass}} (pC) = (26.99 \pm 0.32) \deg r. \end{array}\right\}. \quad (2)$$

Table 1. ***CTa*-collisions (4.2*AGeV/c*). Average kinematic characteristics of jets and surrounding protons, when in the Lab. protons frame the number of forward and backward moving cumulative protons p^{cum} are equal.** $N_{P^{cum}_{(f)}} = N_{P^{cum}_{(b)}}$. $N_{p^{cum}}(jet)$ **- number of p^{cum} in jet**

$N_{p\ cum}(jet)$	$<p_L(jet,b)>GeV/c$	$<p_L(jet,f)>GeV/c$	$<\theta_L(jet,b)>$degr	$<\theta_L(jet,f)>$degr	$<p_L(p^{ass})>GeV/c$	$<\theta_L(p^{ass})>$degr	$<Y_{L_f}(b)>$	$<Y_{L_f}(f)>$	$<n_k(b)>$	$<n_k(f)>$
1	0.443±0.040	0.797±0.095	121.1±1.22	77.25±2.20	1.238±0.0.040	33.34±1.04	-0.205±0.010	0.148±0.011	1.34	1.12
2	0.471±0.045	0.734±0.100	117.0±1.30	77.86±2.30	0.945±0.060	36.35±1.06	-0.173±0.011	0.1395±0.012	1.28	1.11
3	0.481±0.54	0.890±0.110	121.4±2.10	75.76±2.40	0.998±0.070	36.85±1.10	-0.214±0.012	0.174±0.012	1.38	1.12
4	0.500±0.070	0.859±0.115	113.5±2.50	74.03±2.60	1.005±0.075	37.77±1.20	-0.167±012	0.194±0.013	1.33	1.20
5	0.560±0.100	1.100±0.120	127.1±3.00	73.50±3.00	0.944±0.100	36.80±1.40	-0.305±0.035	0.247±0.010	1.55	1.15
							-0.192±0.011	0.169±0.012		

Table 2. Average kinematic characteristics of forward and backward moving cumulative protons in the Lab. frame in nucleus-nucleus collisions

A_fA_t- collisions	$p_0 GeV/c$	$<p_L> GeV/c$	$<\theta_L>degr$	$<cos\theta^*_{NN}>$	$<T>mev$	$<n_k>$
pC(b)	4.2	0.445±0.036	113.910±3.110	-0.971±0.060	77.000±3.000	1.280±0.030
pC(f)	4.2	0.743±0.051	78.650±2.710	-0.886±0.058	171.000±8.000	1.100±0.040
dC(b)	4.2	0.475±0.045	113.700±6.110	0.971±0.090	87.500±6.000	1.290±0.071
dC(f)	4.2	0.774±0.073	77.860±5.710	-0.873±0.081	150.000±4.000	1.090±0.090
HeC(b)	4.2	0.445±0.025	112.900±2.300	-0.972±0.010	85.000±5.000	1.276±0.020
HeC(f)	4.2	0.799±0.035	77.570±2.200	-0.868±0.062	160.000±5.000	1.110±0.010
CC(b)	4.2	0.445±0.014	112.600±2.110	-0.970±0.027	84.000±2.000	1.280±0.030
CC(f)	4.2	0.833±0.023	77.160±1.470	-0.60±0.024	180.0003.000	1.110±0.030
pC(b)	10	0.446±0.016	113.900±2.560	-0.971±0.029	87.160±1.730	1.290±0.040
pC(f)	10	0.709±0.027	78.950±1.950	-0.387±0.003	160.000±3.800	1.100±0.030
dTa(b)	4.2	0.436±0.025	120.000±3.110	-0.976±0.031	80.000±3.000	1.320±0.040
dTa(f)	4.2	0.706±0.032	77.650±2.120	-0.883±0.002	170.000±3.000	1.090±0.050
CTa(b)	4.2	0.440±0.015	119.600±2.270	-0.975±0.030	73.000±1.300	1.320±0.030
CTa(f)	4.2	0.857±0.019	76.310±1.320	-0.852±0.014	133.000±0.500	1.120±0.040
pTa(b)	10	0.448±0.022	120.420±2.550	-0.967±0.013	75.000±1.400	1.330±0.050
pTa(f)	10	0.867±0.055	76.510±3.360	0.937±0.038	175.000±2.100	1.130±0.040

One can conclude that jets of cumulative protons in *CC*-collisions are more collimated than in *pC*-collisions.

It is known that average kinematic characteristics of cumulative particles do not depend on the target and projectile type and on incoming energy. Since average kinematic characteristics of cumulative protons p^{cum} are almost identical, one can conclude that cumulative particles p^{cum} escape from the nucleus without secondary interaction and jets formation proceeds outside the nucleus.

As is seen from our data (*CTa* (4.2*AGeV/c*)), an average momentum of cumulative protons p^{cum} is (0.578±0.015)*GeV/c*, average emission angle is ($<\theta>$=105.3±1.63) degree. But the average kinematic characteristics of forward and backward emitted (p_f^{cum} *and* p_b^{cum}) cumulative protons considerably differ. In the Lab. frame 70% of cumulative protons are going backward and 30% are going forward (Table 2).

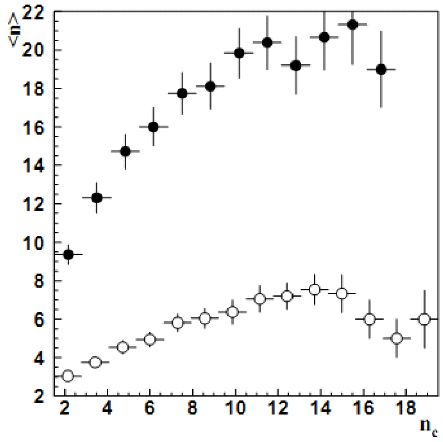

Fig. 1. *CTa*-collisions (4.2*AGeV/c*). The dependence of average multiplicity of surrounding protons p^{ass} (·) and pions p^{ass}(o) on the summing cumulative number n_c.

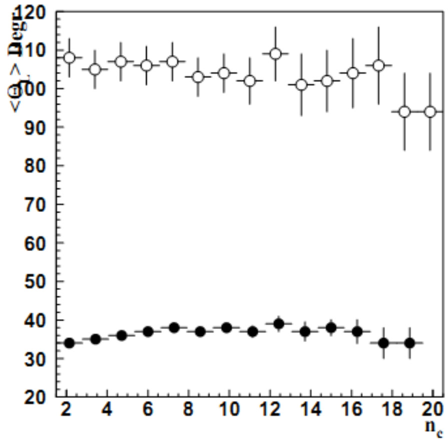

Fig. 2. *CTa*-collisions (4.2*AGeV/c*). The dependence of average emission angle of cumulative protons (o) and surrounding protons (·) on the summing cumulative number.

It is known that the increase of the degree of the cumulativity (i. e. increase of the number of p^{cum}) causes the increase of the number of surrounding particles (protons and pions).

Consider events in which the number of forward and backward moving cumulative protons is equal

$$R_{bf} = \frac{N_{P_b^{cum}}}{N_{P_f^{cum}}} = 1 \quad . \tag{2}$$

Let us see how their average kinematic characteristics change.

Average kinematic characteristics of forward and backward moving cumulative protons p^{cum} considerably differ. For instance, when $N_{P_f^{cum}} = N_{P_b^{cum}} = 3$

$$\begin{aligned} &< p_{L,jet,b} >= (0.481 \pm 0.05) GeV / c \,, \quad < \theta_{L,jet,b} >= (121 \pm 2.1) \deg r \,, \\ &< p_{L,jet,f} >= (0.890 \pm 0.090) GeV / c \,, \quad < \theta_{L,jet,f} >= (75,76 \pm 2.31) \deg r \,, \\ &< Y_{L,jet,f} >= (0.174 \pm 0.010) \qquad < Y_{L,jet,b} >= (-0.214 \pm 0.021) \end{aligned} \tag{3}$$

But average kinematic characteristics of surrounding protons p^{ass} practically do not differ.

Since cumulative number n_k is the additive quantity it is interesting to study the dependence of characteristics of multiple processes on n_c, where

$$n_c = \sum_{i=1}^{n_p^{cum}} n_k \quad . \tag{4}$$

Let us consider the dependence of average kinematic characteristics of cumulative protons p^{cum} and surrounding protons p^{ass} on n_c (Figs. 1-3). One can conclude that momentum and angular characteristics of cumulative protons p^{cum} do not depend on summing cumulative number n_c. As to the surrounding protons p^{ass} momentum distribution, it depends on n_c. When $n_c \geq 10$ momentum curve reaches the plateau (Fig. 3). The increase of n_c causes the sharp increase of the average multiplicity of surrounding protons p^{ass} and pions p^{ass} (Fig. 1). We note that n_c varies in the interval from 2 to 20.

The Study of Jet Quenching Effect

Cumulative protons p^{cum} are produced as a result of interaction of incoming nucleons with fluctons and their cumulative number is bigger than one. Average kinematic characteristics of forward and backward moving

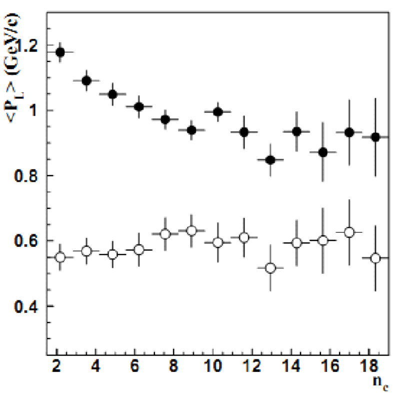

Fig. 3. *CTa*-collisions (4.2*AGeV/c*).The dependence of average momentum of cumulative protons (o) and surrounding protons (·) on the cumulative number n_c.

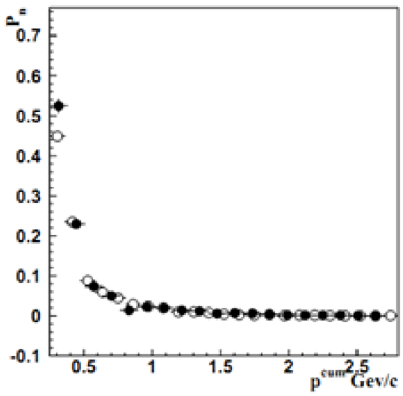

Fig. 4. The spectrum of cumulative protons from *pTa*-collisions (·) and *pC*-collisions (o) (10*GeV/c*).

cumulative protons p^{cum} considerably differ (Table 2), but they do not depend on the atomic numbers of incoming and target nuclei and on the initial energy.

The study of characteristics of cumulative particles and jets in lepton-hadron, hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at various energies shows that cumulative particles have universal properties (so called hypothesis of soft decoloration) [3,10].

Let us compare average kinematic characteristics of cumulative protons p^{cum} (jets) and surrounding protons p^{ass} and pions p^{ass} in *CTa* and *CC* (4.2*AGeV/c*), pC and pTa (10*GeV/c*) – collisions. It is seen that momentum spectra of cumulative protons p^{cum} and surrounding protons p^{ass} in *CTa*-collisions are more soft than in *CC*-collisions.

$$\left.\begin{array}{lcl} <\theta_L(p_L^{ass}(CTa))>\deg r & > & <\theta_L(p_L^{ass}(CC)>\deg r \\ <p_L^{ass}(CTa)>GeV/c & < & <p_L^{ass}(CC)>GeV/c \\ <\theta_L(p^{cum}(CTa))>\deg r & > & <\theta_L(p^{cum}(CC)>\deg r \\ <p_L(p^{cum}(CTa))>GeV/c & < & <p_L(p^{cum}(CC))>GeV/c \end{array}\right\}. \quad (5)$$

It can be said that jet quenching phenomenon takes place. Jets are more pronounced in *CC*-collisions than in *CTa*-collisions. The same is valid for *pTa* and *pC*-collisions. One can conclude that in the production of cumulative protons the atomic number of projectile plays the essential role. In *CTa*-collisions 14 cumulative protons are produced, but in *pTa*-collisions only 7.

According to some model ideas in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions some exited compound system is formed. Instant decay of these systems is forbidden. Some particles are emitted from the compound system independently (without correlation with other particles). Some particles (for instance, resonances) are emitted from the compound system and decay outside it.

In nucleus-nucleus collisions at relativistic energies the process of production of cumulative protons – p^{cum} can be considered as follows: as a result of collision of nucleon (from projectile) with flucton some compound system is formed, which "consists" of flucton and proton. As a result of the decay of the compound system cumulative proton p^{cum} is produced, which is emitted without secondary interaction and the jets are produced outside the nucleus. Otherwise one can not explain independence of characteristics of cumulative protons on the energy, on type of interacting nuclei (objects).

Table 3. ***pTa*-collisions (10*GeV/c*). The dependence of average multiplicity of surrounding protons R^{ass} on the number of cumulative protons -** $N_{p^{cum}}$ **.** $< n_{p^{ass}} >= f(N_{p^{cum}})$

N	$< n_{p^{ass}} >$	$N_{p^{cum}}$
1	2.26±0.07	0
2	3.55±0.17	1
3	4.54±0.31	2
4	5.64±0.43	3
5	5.70±0.61	4
6	6.67±0.80	5

It is possible to consider the decay of the compound system in other terms. The produced cumulative proton p^{cum} sometime is without the field. In this period it can not interact and is emitted from nucleus without interaction.

Conclusions

1. Cumulative protons R^{cum} are emitted from the exited nucleus without secondary interaction.
2. Jets are formed from the cumulative protons outside the nucleus.
3. In *CTa*-collisions the jet quenching phenomenon takes place.
4. The increase of the number of cumulative protons causes the increase of multiplicity of surrounding particles.

ფიზიკა

ჭავლების ჩაქრობის ეფექტის შესწავლა ბირთვ-ბირთვულ დაჯახებებში

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თანამედროვე თეორიული წარმოდგენების თანახმად A_iA_t -ბირთვ-ბირთვული ხისტი დაჯახებების შედეგად წარმოქმნილი q-კვარკის ადრონიზაცია შეიძლება მოხდეს ერთ ან რამდენიმე კუმულაციურ ნაწილაკად, რომლებიც ქმნიან ბირთვის გარეთ jet-კუმულაციურ ჭავლებს. ჭავლი არის კუმულაციური ნაწილაკების (ჩვენ შემთხვევაში პროტონების) ერთობლიობა, რომლებიც მიფრინავენ დაახლოებით ერთი მიმართულებით და ერთმანეთის მიმართ გააჩნიათ მცირე განივი იმპულსი. jet-ჭავლი შეიძლება შედგებოდეს 1,2,3,....,n ჰადრონისაგან (ჩვენ შემთხვევაში პროტონისაგან). კუმულაციური პროტონების წარმოქმნა დაკავშირებულია ბირთვში მრავალკვარკიანი სისტემის - ფლუქტონის წარმოქმნასთან. ბირთვ-ბირთვულ დაჯახებებში შეიძლება ადგილი ჰქონდეს წარმოქმნილი ჭავლების კუთხურ გაფართოებას და იმპულსური სპექტრის შერბილებას - ამ პროცესს ეწოდება ჭავლების ჩაქრობის ეფექტი. შევისწავლეთ რა jet-კუმულაციური ჭავლებისა და მათი თანმხლები ნაწილაკების საშუალო კინემატიკური მახასიათებლები (p,dpHe,C)(C,Ta) დაჯახებებში, ვაკეთებთ დასკვნას, რომ ადგილი აქვს ჭავლების ჩაქრობის ეფექტს.

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