

# CUMULATIVE PROCESSES

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## Abstract

In this report we talk about nowadays situation with the cumulative effect studies. The experimental program for the nuclotron and other facilities is proposed.

## 1. Introduction

The simple picture that nuclei are consisted of nucleons have only limit range of validity. We know some number of intrigue phenomenons which have no adequate understanding in frame of the naive nucleon model of nuclei. These phenomenons are connected with states of the nuclear matter when nucleons must be overlapped inside the nuclei and the baryon matter converts to the quark-gluon phase of nuclear matter. Through quantum nature the short distances mean the high transfer momentum processes or states under the very high pressure(as we can wait in some stages of the star evolution). Long time investigations of high transfer momentum processes with nuclei give us to say about some unified explanations for their nature. Nowadays we saw great growing interest to the astrophysics problems. We could not know stars evolution laws without understanding of the short distance nucleon-nucleon interaction. Cumulative phenomenons shows that we can wait formation of very exotic star states which haven't investigate before this time(for examples, baryon stars or bosoning stars).

Historically the first of these phenomenons were deep subthreshold particle production processes. Second ones were processes of direct knock out of deuterons in pA-interactions with the very high probability. The birth day of the cumulative processes was 1971 when it had been predicted by A.M. Baldin [1] and short time later was discovered by team of V.S. Stavinsky [2]. In 1993 A. A. Baldin showed [3] that using scaling variables proposed by V. S. Stavinsky [4] there is possibility to describe data on cumulative and subthreshold particle production processes in a same way. This means that the whole set of phenomenons on nuclei in the kinematical region far from the kinematical threshold for free nucleon processes can be considered as processes with the same nature. We can propose to name all these phenomenons as cumulative processes. Because this name(from my point of view) can more adequate reflects their common collective nature.

We will try to show that to isolate the production mechanisms of cumulative processes will need to measure additional observables such as associated multiplicities and polarization characteristics. And the most important that these investigation must to be carry out in the region of high transverse momentum with the half-exclusive(and exclusive) setting of experiments. Moreover the energy region for these studies may be limited by maximal energies 20-30 Gev for proton beams.

Nuclotron is the accelerator of relativistic nuclei which works and continues to be improved in the V.I. Veksler and A.M. Baldina Laboratory of high energies. The accelerator uses the magnets with superconducting coils developed in LHE and has been cre-

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ated to work with proton beams up to energy 12 GeV and nuclei up to 6 GeV/nucleon. Energies of nuclotron beams temporarily exceed energies of the synchrotron but the main characteristics of the new accelerator beams are considerably better and make it possible to plan experiments which could not be carried out earlier. There are some unique nuclotron properties: the possibility to work with internal beams and have the extracted beam duration up to 10 seconds. Another special feature of the accelerating complex lies in the fact that from the middle 1980s it began the acceleration of polarized deuteron beams. From the middle 1990s it was mounted and has been working with a polarized target. Polarization studies are the basic and most important part of the physical program for nuclotron. The unique cryogenic targets created by L.B. Golovanov's team are used in LHE. At present, the possibility to accelerate polarized proton beams [10] and beams of the polarized  $^3\text{He}$  nuclei on nuclotron is investigated. In the next 5–7 years nuclotron will not be a competition.

## 2. Cumulative processes

The bulk of experimental data of cumulative processes was obtained by the inclusive setups in fragmentation regions of beams or targets. Theoretical models have described inclusive spectra of cumulative particles with different level of agreement but fail describing all set of the experimental data. Polarization studies of cumulative processes carried out at LHE [5] resulted in thorough revision of models, because the data on polarization characteristics deviated noticeably from first model predictions. It is still too early to speak about clear understanding of the nature of cumulative processes. That is why new ideas how to resolve the puzzle of these phenomena are so important.

The cumulative data have very nice phenomenological description using variables introduced by V.S. Stavinsky [4]. In Figure.1 graphically presented definitions Stavinsky's variables. They are very close to Bjorken's quark-parton model variables.

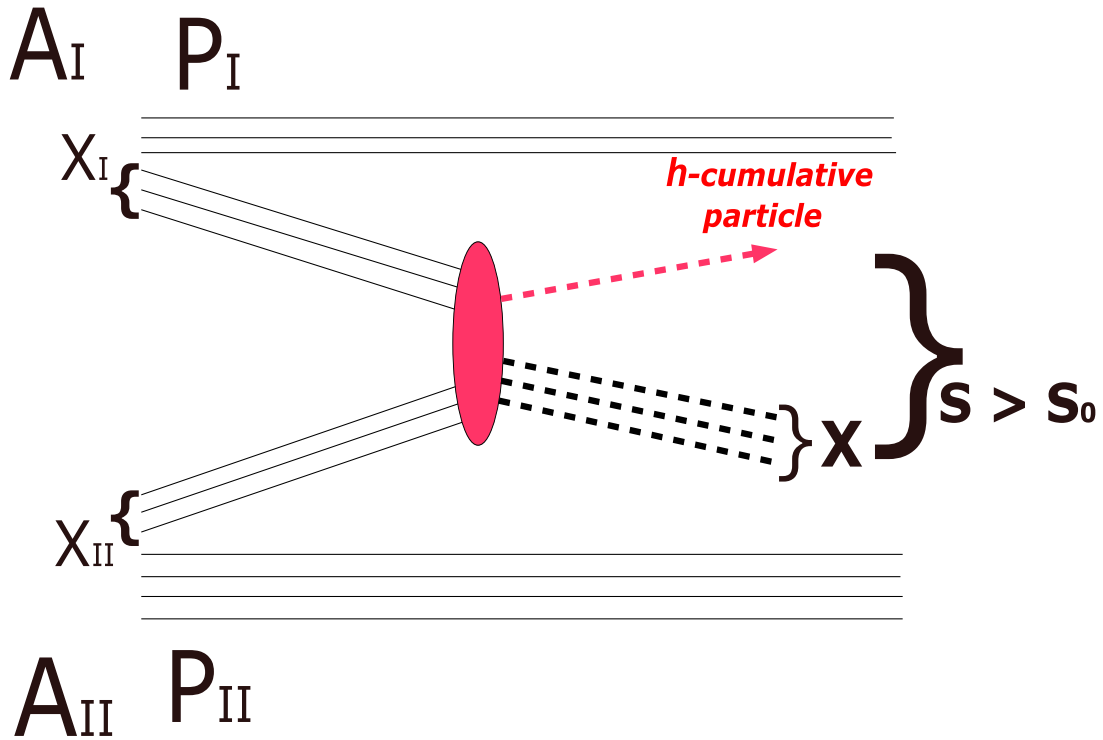


Figure.1 Stavinsky's variables  $X_I$  and  $X_{II}$

In common case Stavinsky's variables describe nuclear-nuclear collisions of nuclei with atomic weights  $A_I$  and  $A_{II}$ . Four-momentums for these nuclei are  $P_I$  and  $P_{II}$ . For cumulative processes we can subtract subprocesses which characterized by the invariant value  $s_{cumulat}$  which defines as

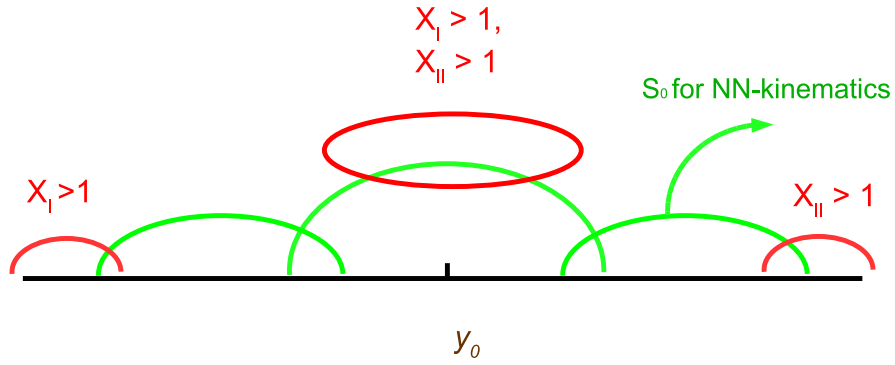
$$s_{cumulat} = \left( X_I \cdot \frac{P_I}{A_I} + X_{II} \cdot \frac{P_{II}}{A_{II}} \right)^2.$$

The  $s_{cumulat}$  need to compare with the invariant value  $s_0$  defines as

$$s_0 = \left( \frac{P_I}{A_I} + \frac{P_{II}}{A_{II}} \right)^2$$

which characterized free nucleon-nucleon interactions. Processes with  $s_{cumulat} > s_0$  are forbidding for free nucleon-nucleon interactions.

The kinematical regions for cumulative processes you can see on Figure.2.



Cumulative processes:

1)  $X_I = 1$  and  $X_{II} > 1$  | Fragmentation  
or  $X_{II} = 1$  and  $X_I > 1$  | regions

2)  $X_I > 1$  and  $X_{II} > 1$  | Central region

Figure.2 Cumulative regions Stavinsky's variables  $X_I$  and  $X_{II}$

$y_0$  is a rapidity for the central mass system of nucleon-nucleon interactions.

Stavinsky's variables have differs compare with  $x$  variables for the quark-parton model. In the quark-parton model  $x$  did not fix and we need to integrate over the full range of  $x$ . The additional condition which fix variables have been introduced by Stavinsky. We need to take  $X_I$  and  $X_{II}$  only which give us the minimal value  $\min(s_{cumulat}^{1/2})$ . Combination with the four-momentum conservation laws give us possibility for unique determination of variables. Thus defined  $X_I$ ,  $X_{II}$  and  $\min(s_{cumulat}^{1/2})$  can use for uniform description of cumulative and subthreshold processes[3] by phenomenological equation

$$E \cdot \frac{d^3\sigma}{dp^3} = C_1 \cdot A_I^{\frac{1}{3} + \frac{X_I}{3}} \cdot A_{II}^{\frac{1}{3} + \frac{X_{II}}{3}} \cdot \exp\left(-\frac{\Pi}{C_2}\right),$$

where  $C_1$  and  $C_2$  are constants and

$$\Pi = \frac{1}{2 \cdot m_{nucleon}} \cdot \min(s_{cumulat}^{1/2}),$$

where  $m_{nucleon}$  is the nucleon mass.

The nuclei characteristics are well described when nucleons can be considered as points and locating in the distances greater than the sizes of nucleons. Complexities in description of nuclei lie at the region of small internucleon distances when nucleons in the nuclei are overlapped and begin to be manifested through quark-gluon degrees of freedom. It is mean that the nucleon momentum of Fermi motion must be greater then  $\sim 0.3\text{GeV}/c$ . Exactly this is a region of the nonperturbative QCD.

The discovery of the cumulative effect stimulated development of theoretical models [6] describing reactions with nuclei in a state in which nucleons strongly overlapped

and loose their personality. The quark-parton model underlies these approaches, since description of processes with large momentum transfers is required. All models we can split on two groups. The first ones say about nucleons with a very high momentum inside nuclei they are short-range correlation(SRC) models. It is a some development of the Fermi motion picture. Main features of SRC are protons with very high momentums( $\bar{k}$ ) inside nuclei and nucleon-nucleon interaction vertexes (see Figure.3).

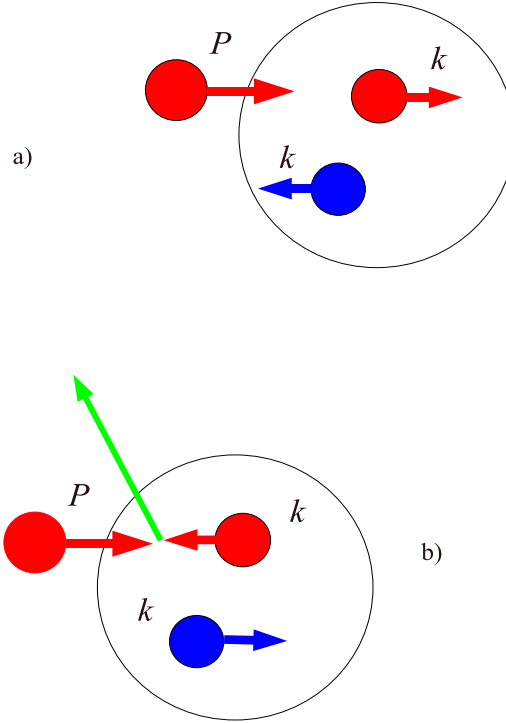


Figure.3 SRC pictures of the backward cumulative particle production: a)nuclear fragments production; b)mesons and antiparticles production

The sketch (a) shows  $pA \rightarrow p, n, \dots + X$  reactions. The cross sections for these processes will be

$$\sigma \sim n(\bar{k}) \cdot \sigma_0,$$

where  $n(\bar{k})$  is a probability to find the nuclear fragment with three-momentum  $\bar{k}$  inside the nucleus. The sketch (b) shows  $pA \rightarrow \pi, K, \bar{p} \dots + X$  reactions. The cross sections for these processes will be

$$\sigma \sim n(\bar{k}) \cdot \sigma(NN \rightarrow \pi, K, \bar{p} \dots + X),$$

where  $n(\bar{k})$  is a probability to find nucleon with three-momentum  $\bar{k}$  inside the nucleus.

The second group of models based on possibility of few nucleons to form a small size hard object named as a flucton. Figure.4 shows how will produce cumulative particles in the backward direction in  $pA$ -collisions.

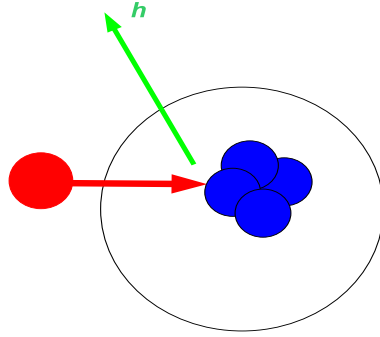


Figure.4 The flucton picture of the backward cumulative particle production

In these models the cross section for  $pA \rightarrow h + X$  reactions will describe by

$$\sigma \sim P_K \cdot G_{h/K}(K),$$

where  $P_K$  is a probability to find the flucton consisting of  $K$  nucleons inside the nucleus. The  $G_{h/K}(K)$  gives probability to produce hadron  $h$  by this flucton. Main features of these models are existence of fluctons and some universal function which describe fragmentation these fluctons into hadrons.

Studies of the inclusive cumulative particle production in fragmentation regions of the target or the beam not allow to separate these two type models. The experiments in low  $p_T$  region have huge experimental problems to detect recoil objects which accompany cumulative particles.

A principally new step in investigation of cumulative phenomena was made in the experiment E850/EVA [7]. In this experiment for the first time the effect was studied in a new set up: semi-exclusive measurements in the maximal  $p_T$  region. It is realised the kinematic presented in Figure.5 (a). In this experiment two protons (kinematic of the quasielastic pp-scattering at the angle  $90^\circ$  in the center-of-mass system) and correlated neutron were detected. It was shown that the neutron with momentum more then Fermi momentum come mainly from n-p SRC.

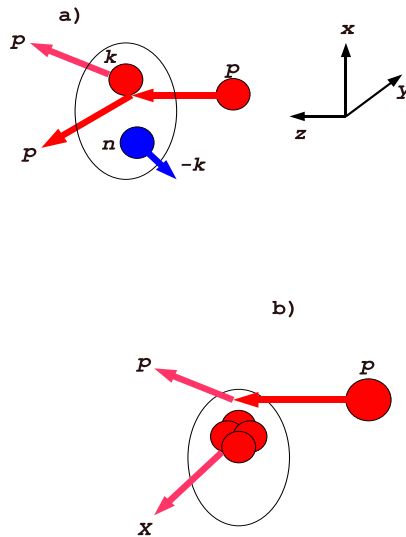


Figure.5 The high  $p_T$  cumulative experiments to find SRC (a) or flucton (b) phenomenons

But there is no possibility to compare this measurement with other predictions which we can see in Figure.5 (b) as the flucton mechanism. That is why only [7] data didn't give us answer about main mechanism for cumulative processes. But it is the first step which have open for us new way to resolve the cumulative puzzle. We need more complete investigation in the range of maximal  $p_T$  in semi-exclusive (and exclusive) experiment set up for comprehension of the nature of cumulative processes. It will need to investigate:

- average number of baryons accompanied high  $p_T$  cumulative particle production and its  $s_{cumulat}$  dependance;

- average multiplicity accompanied high  $p_T$  cumulative particle production and its  $s_{cumulat}$  dependance;

- $s_{cumulat}$  dependence of polarization characteristics (analyse power, asymmetry and so on), for SRC mechanism will be scaling repeating effects for free nucleon-nucleon interactions;

- coincidence cross sections of high  $p_T$  cumulative particle production with prediction of the "quark counting rules" [9] when using Stavinsky's variables.

These investigations will give us new important information to define real mechanisms which respond the processes with  $x > 1$ . We could receive proof about SRC or flucton structures inside nuclei (in the last case we will investigate the some features of fluctons too). We must stress that up to now we haven't quantitative predictions for these exclusive(quasi-exclusive) cumulative characteristics with high  $p_T$  from the theoretical side.

### 3. High $p_T$ phenomenons

It is symbolically that the new data on cumulative processes [7] were obtained as a by-product of studies of other nuclear puzzle named as color transparency of nuclei [8]. It is mean that the same set up will give us possibility to investigate and may be resolve a lot of physical problems in the high  $p_T$  region. Cross sections of such processes quickly fall with the energy of beams. The real possibility for these investigations are limited by beam energy 20-30  $GeV$ . That is why in the nearest time only nuclotron (Dubna) and U-70 (Protvino) in Russia will be useful for these studies.

From the point of view of QCD in elastic processes with large transverse momenta nucleons look like objects comprising of three point-like constituents. The direct experimental proof of it is a very nice working of "quark counting rules" [9]. The quark model makes a proposition that these three observed objects are valence quarks. The nucleus, from QCD, in "quasielastic" processes with large transverse momenta looks like a "soft pie" with hard insets of three valence quarks (nucleons). Therefore, with increasing primary beam energy the processes of "quasielastic" hard scattering of hadrons (leptons) on a nuclear target are similar to elastic scattering on a nucleon target, but a larger number of scattering centers (nucleons). From QCD point of view the ratio between cross sections  $pA \rightarrow "pp" + X$  and  $pp \rightarrow pp$  processes must smoothly growing to unit. In experiments at the accelerator AGS(BNL,USA) [8] with proton beams on carbon nuclei anomalous behavior (of a resonance-type) was observed in a momentum range of 9.5  $GeV/c$ . This is a so called nuclear color transparency problem. The na-

ture of this effect is not well understood yet. A whole physical research program was developed and proposed [8] to clarify this mystery.

Situation is aggravated by the anomaly of behavior in the same kinematical region of the elastic proton-proton cross section. It has no explanation of the strong deviation (about two times) in the same kinematic region where the "quark counting rules" (the transverse momentum  $> 1$  GeV/c, the energy of primary beam  $> 6$  GeV) must working very well.

Other item to the portrait of the "crisis" in our understanding of nucleon-nucleon (nucleon-nuclear) interactions in this region, let us add that till now the "spin crisis of the 70-se" has not been solved. There is no understanding of the anomalously strong spin dependence of the elastic-scattering cross section of protons (at the angle  $90^\circ$  in the center-of-mass system) for momenta of protons 8-9 GeV/c. It is real riddle that in many measurements of cross sections we see that "counting rules" are working very well (in the pp elastic scattering with maximal  $p_T$  too). But naive quark predictions disagree drastically with the polarization data. We can propose to investigate reactions

$$pp(\bar{p}) \rightarrow BB(\bar{B}) + MM,$$

where B is a baryon and M is a meson. Baryons must have the large  $p_T$ . These reactions will give possibility for more detail studies not only the nucleon quarks structure in the valence quark dominance region but the spin structure of the interaction.

Still there is no theory which explains large spin effects in inclusive processes of the meson and the hyperon production. These effects do not vanish up to the energies of hundreds of GeV. These all show that in the region of nucleon energies so many fundamental problems have been accumulated that even a small number of an additional data can radically help for their solution.

To carry out all these investigations as cumulative ones in high  $p_T$  region LHE will need to create spacial experimental set up.

#### 4. Summary

In this report we have presented new physical programm which realization should help to resolve fundamental problems as nature of the cumulative effect and huge disagreement polarization phenomenons with predictions naive quark models in high  $p_T$  region.



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