New detector for studies of cumulative processes in hadron collisions in NA61(SHINE) at the CERN SPS

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Abstract. The increase of luminosity of the SPS beams expected after 2020 allows considering the investigation of rather rare processes. In particular, so-called cumulative particle production can be studied in hadron collisions by measurements of secondary particle yields in regions kinematically forbidden for reactions with free nucleons. Such processes could be either a result of hard parton collisions with some large-density multi-quark configuration or of the formation of heavy baryonic resonances. Measurements in the backward hemisphere in fixed target experiment should provide the event-by-event data that could be used, along with those from the forward region, for a correlation analysis, thus resulting in new constraints on models. In this report the preliminary design, ideas, technology and the first GEANT simulations of a proposed new detector are presented and discussed.

1. Introduction
Production of particles from nuclei in a region, kinematically forbidden for reactions with free nucleons is called the cumulative effect.

The first clear experimental confirmation of the cumulative effect was obtained by the group of A.M. Baldin and V.S. Stavinsky in Dubna, where in 1971 the first relativistic deuteron beams were produced [1, 2]. In these experiments the emission of pions with energy higher than half of the energy of the incident deuterons was observed. The classical explanation of this effect is the presence of nuclear fluctons, droplets of cold dense nuclear matter in nuclei, composed of a few nucleons. Nevertheless, one has to keep in mind that some contribution from rescattering processes at large (nuclear) distances on several free nucleons is possible.

From the modern point of view fluctons in nuclei must be interpreted as the presence of multi-quark (6q-, 9q-, 12q- and so on) clusters in nuclear matter, allowing two mechanisms of cumulative fragment production. The first is fragmentation of one fast quark of the flucton into a cumulative hadron [3], and the second proposes cumulative hadron formation due to the coherent coalescence of three fast flucton quarks in the framework of the Coherent Quark Coalescence (CQC) model as formulated in [4]. The latter mechanism is more convenient for the production of cumulative nucleons. The dominant process for the production of light cumulative fragments, e.g. deuterons, is coherent coalescence of weakly virtual nucleons [5]. In contrast to the treatment of fluctons as droplets of cold QGP some theories propose that clusters appear due to the formation and subsequent statistical decay of massive hadron clusters (fireballs)[6–8]. The observed particles, i.e. mesons, nucleons, and light nuclei are emitted from the fireball. This approach allows to successfully describe the momentum spectra of protons and light nuclei...
produced in high-energy particle-nucleus and nucleus-nucleus collisions both in the cumulative and non-cumulative regions [7, 8], but this approach can not explain the cumulative effect in deep inelastic scattering. Along with this hypothesis a variety of other theoretical models were proposed for the explanation of cumulative production, however the physical origin of this effect is still not understood completely.

2. Features of cumulative particle production

The first experiments of A.M. Baldin and V.S. Stavinsky [1, 2] gave rise to a wave of similar experiments, which identified a number of important features of cumulative production, such as the weak dependence of the inclusive cross sections on the energy of the incoming particle. Already at a projectile momentum of a few GeV/c the cross section reaches a plateau. Another feature is the exponential dependence of inclusive cross section on the cumulative particle momentum. The most common way to detect cumulative particles are measurements in the backward hemisphere by fixed target experiments, in regions where only cumulative particles can be produced. Due to the extremely low cross sections, such measurements were done mainly for cumulative particle momentum not exceeding 1.5-2.0 GeV/c (e.g. [9–11]). The latest results, which were obtained for the high $p_T$ region, up to the 3.5 GeV/c, showed the same characteristics as in previous research [12]. The new experimental capabilities at the SPS and the expected high event rate will allow to extend the region of experimental studies of the cumulative effect. One of the new approaches to the experimental study of the cumulative effect is the investigation of correlations between cumulative particles and other fragments. In particular, these studies can be done by the NA61(SHINE) Collaboration at the CERN SPS, which measures hadron production in p+p, p+A, and A+A collisions.

2.1. Estimates of the cumulative particle yield in p-A collisions

The total number of cumulative particles with certain momentum which are emitted into a certain angle is estimated using assumptions on the invariant cross section from the formula [13]:

$$E \cdot \frac{d^3 \sigma}{dp^3} = \frac{E \cdot d^2 \sigma}{p^2 dp d\Omega} = \frac{E}{p^2} \frac{A}{N_A} \cdot \rho \cdot t \cdot \epsilon \cdot \Delta P \cdot \Delta \Omega \cdot \frac{1}{N_{prot}} \cdot N,$$

where:
- $E \cdot \frac{d^2 \sigma}{dp^2}$ – invariant inclusive cross section;
- $E, p$ – cumulative particle energy and momentum;
- $A$ – number of nucleons in the nucleus;
- $N_A$ – Avogadro constant;
- $\rho, t$ – target density and thickness;
- $\Delta P, \Delta \Omega$ – momentum and solid angle coverage;
- $\epsilon$ – detector efficiency (assumed 100%);
- $N_{prot}$ – total number of protons passed through the target;
- $N$ – number of particles registered at the given momentum and solid angle.

In the following the reaction $p + A \rightarrow X + h$ is considered. $N$ is the number of cumulative particles, which we would like to calculate. The inclusive cross section $E \cdot \frac{d^2 \sigma}{dp^2}$ (normalized to the number of nucleons in the nucleus) should be taken from experimental data. The following approximations were made:

- Inclusive cross section depends on momentum as $b \cdot \exp(-p/p_0)$;
- Inclusive cross section normalized to $A$ remains constant at $A > 100$ [14]. This allows us to estimate the particle yield in the future experiment from one particular target based on experimental data obtained for a different target.
• Inclusive cross section depends on angle as \( a \cdot \exp(w \cdot \cos(\theta)) \) \[10\];

• \( b, p_0, a, w \) – use of parameter values obtained from experimental distributions.

The calculations of the particle yield were made for the collision of one proton incident on a 1 mm Pb target and were based on data for the reaction \( p + Ta \rightarrow p + X \) from \[11\].

2.1.1. Estimation of the cumulative proton yield in the momentum range between 1.5 – 4 GeV/c

The total number of cumulative particles, which are produced in a collision of one proton incident on a 1mm Pb target (the second column in table 1), was calculated for several values of polar emission angles (the first column in table 1). For each emission angle, values of particle yields were summed over momentum. For the calculation we assume that the momentum interval \( \Delta P \) is 0.12 MeV/c, and the angle interval where we neglect momentum dependence of the cross section is approximately 8 degrees(corresponding to \( \Delta \Omega \) in formula (1)).

Table 1: Calculation of the cumulative proton yield in the momentum range 1.5 – 4 GeV/c

| Emission angle, degree | Total number of cumulative protons |
|-----------------------|-----------------------------------|
| 70 ± 4                | \((3.2 \pm 0.2) \cdot 10^{-6}\)    |
| 90 ± 4                | \((0.3 \pm 0.02) \cdot 10^{-6}\)   |
| 119 ± 4               | \((3.8 \pm 0.3) \cdot 10^{-8}\)   |
| 137 ± 4               | \((1.21 \pm 0.09) \cdot 10^{-8}\) |
| 160 ± 4               | \((5.3 \pm 0.3) \cdot 10^{-9}\)   |

2.1.2. Estimation of the cumulative proton yield in the polar angular range between 20° and 175°

The total number of cumulative particles, which are produced in a collision of one proton incident on a 1mm Pb target (the second column in the table 2), was calculated for several values of particle momentum (the first column in the table 2). For each momentum, values of the particle yield were summed over angle. For the calculation we assume angular intervals of 0.008 rad, and momentum intervals where we neglect the cross section changes of 0.001 GeV/c. The integration range (detector acceptance) was assumed to extend from 20° to 175°.

Table 2: Calculation of the cumulative proton yield in the polar angular range between 20° and 175°

| Momentum, GeV/c | Total number of cumulative protons |
|-----------------|-----------------------------------|
| 2               | \((1.6 \pm 0.2) \cdot 10^{-6}\)   |
| 3               | \((8.9 \pm 0.1) \cdot 10^{-8}\)   |
| 4               | \((4.87 \pm 0.05) \cdot 10^{-9}\) |

3. Detector requirements

The proposed new detector for cumulative particle production measurements should consist of:

• position sensitive detector for track and vertex reconstruction. Primary vertex reconstruction is necessary for rejecting non cumulative events (rescattering on components of the detector, beam halo, etc.). Estimation of the particle yield above shows that cumulative events are rare, so detectors should have good noise characteristics and fast integration time (for the correlation measurements);

• particle identification for momentum up to 4 GeV/c in the backward region.

Upgrading of the NA61(SHINE) facility after 2020 envisages the installation of a compact backward and side detector. A schematic of the present setup is shown in figure 1. The new detector would be placed inside the first vertex magnet, replacing the time projection chamber VTPC-1, together with the target and the (forward) vertex detector.
4. Conceptual design

4.1. Tracking system

Particle momentum measurement and vertex position can be obtained from the reconstructed tracks. It is proposed to implement in the new NA61(SHINE) detector for cumulative studies the latest ALICE developments of the upgraded Inner tracking system (ITS) [16]. Pixel detectors (e.g. ALPIDE), which are based on MAPS technology, form three tracking layers with a geometry similar to the structural sandwich of the existing prototype of the ALICE Inner Barrel (shown in figure 2). This option is the most attractive for the tasks of the new detector for NA61(SHINE). Additional tracking and identification at low momentum could be provided by silicon strip detectors. As an option it is proposed to use 300 µm double-sided strip detectors. Such detectors provide particle identification in the momentum range up to the 0.5 GeV/c for π - K separation and 0.8 GeV/c for proton separation.

4.2. Particle identification in the momentum range between 1 GeV/c and 4 GeV/c

For identification of particles with momentum up to the 4 GeV/c it is necessary to construct a special detector system which will be able to cover a wide region of production angles to register particles both in the backward and forward hemispheres, in order to enable correlation measurements. The important constraint for the detector is the inner size of the magnet in which the future setup will be placed. The proposed radius of the chamber inside the magnet is 1.8 m and its height is 1 m. One option for a suitable and compact detector for the given momentum range is a Ring Imaging Cherenkov Detector with liquid or aerogel radiator. A RICH detector with liquid radiator is also used in the ALICE experiment (ALICE HMPID [17]) for π, K separation up to the 4 GeV/c and proton separation up to 6 GeV/c. This satisfies the above general requirements for particle identification.

4.3. Geometry simulation

The discussed requirements for particle acceptance lead us to a first preliminary layout of the new detector system. A GEANT4 simulation of this geometry is presented in figure 3. Optimization of the number of layers and their position is in progress.

5. Conclusion

New ideas were presented for cumulative particle production experiments in NA61(SHINE). Upgrading the capabilities of the NA61(SHINE) setup will provide the opportunity for entirely new experiments on the cumulative effect. It seems possible to add a detector with complicated geometry which would cover together with the high granularity VD a wide angular range both in...
Figure 3: GEANT4 simulation of the preliminary layout. 1 - Target; 2 - Three layers of pixel detectors. Mean radii of layers: $R = 2.3, 3.1, 3.9$ cm; 3 - Four layers of silicon strip detectors for particle identification at low momenta and tracking. Radii of layers (the same as at Vertex Detector): $R = 5, 10, 15, 20$ cm; 4 - Vertex Detector; 5, 6 - liquid radiator and photodetector for the Ring Imaging Cherenkov detector. Distance between radiator and photodetector: 80 mm.

the forward and backward region (except the area of the beam). The proposed detector provides the unique possibility to study various correlations between cumulative particles and fragments with high momentum (up to the 4 GeV/c in the backward region), providing experimental information related to the mechanism of cumulative particle production.

Further work on this project will include geometry and event simulations in the SHINE software environment, close to the realistic conditions; further development of methods of track reconstruction for the modified NA61(SHINE) set-up; modifications of the conceptual design according to the track reconstruction and estimates of the noise level.

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