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On the performance of Zero Degree Calorimeters in detecting multinucleon events

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ABSTRACT

The facilities designed to study collisions of relativistic nuclei, such as the MPD at NICA (JINR), STAR at RHIC (BNL), ALICE, ATLAS and CMS at the LHC (CERN), are equipped with pairs of hadronic Zero Degree Calorimeters (ZDC) to detect forward nucleons at the both sides of the interaction point and estimate the collision centrality. The energy deposited in a ZDC fluctuates from one event to another, but on average it is proportional to the number of absorbed nucleons. Forward nucleons are also emitted in electromagnetic dissociation (EMD) of nuclei in ultraperipheral collisions, and they are used to monitor the luminosity. As known, ZDC energy spectra are specific to each facility, because they are affected by the ZDC acceptance, and the ZDC energy resolution depends on the beam energy. In this work a simple probabilistic model leading to handy formulas has been proposed to connect the numbers of emitted and detected forward nucleons taking into account a limited ZDC acceptance. The ZDC energy spectra from the EMD with the emission of one, two, three and four forward neutrons and protons have been modeled for the collision energies of NICA and the LHC. The case of a rather small ZDC acceptance has been investigated and a possibility to measure the inclusive nucleon emission cross section has been demonstrated.

1. Introduction

There exists a relationship between the impact parameter as an important initial condition of a nucleus–nucleus collision event and the number of spectator nucleons beyond the overlap zone which continue to propagate in the forward direction after the collision. This motivates the use of forward hadronic calorimeters in studies of interactions of relativistic nuclei. In particular, the experiments at heavy-ion colliders like the MPD at NICA (JINR) [1,2], STAR at RHIC (BNL) [3], ALICE [4–6], ATLAS [7] and CMS [8] at the LHC (CERN) are equipped with pairs of hadronic Zero Degree Calorimeters (ZDC) for detecting forward nucleons at the both sides of the interaction point. One of the most reliable methods to sort collision events into centrality classes is based on detecting spectator neutrons in the ALICE ZDC [9]. The electromagnetic dissociation (EMD) of nuclei in ultraperipheral collisions is another source of forward nucleons. This process is used to monitor the collider luminosity [10,11] on the basis of the EMD cross sections which were reliably calculated [11,12] and accurately measured [13].

It is quite common to calculate the distributions of energy absorbed in a ZDC (ZDC energy spectra) by Monte Carlo modeling specifically for each facility. The simulations account for the actual beam energy, the geometric acceptance of ZDC and the efficiency of nucleon registration, which vary from one set-up to another. Therefore, ZDC energy spectra calculated for different facilities differ from each other, but nevertheless one can point out common characteristics of the spectra and study their dependence on the beam energy and ZDC acceptance. ZDC are designed for counting forward nucleons resulting from nucleus–nucleus collisions on the basis of energy deposited by these nucleons in ZDC. However, the performance of ZDC deteriorates when some of nucleons emitted in a multinucleon event do not hit ZDC. Since spectator nucleons are emitted close to the directions of the colliding beams in heavy ion colliders [3,4,14], the space available for placing a ZDC is rather limited. A ZDC installed in a close proximity of beam pipes can be also partially obscured by collimators, vacuum chambers or other collider components [14]. Forward protons hit the LHC beam pipes before they reach the ALICE proton ZDC [4,14] and some protons are scattered by

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the walls of the pipes at large angles. In the present work a simple probabilistic model leading to handy formulas is proposed to relate the numbers of emitted and detected forward nucleons taking into account a limited ZDC acceptance.

2. ZDC response to forward nucleons

A ZDC is typically build in such a way that its dimensions are sufficient for the absorption of a primary forward nucleon as well as most of secondary particles created by this nucleon in electromagnetic processes and nuclear reactions inside the calorimeter [5]. Therefore, the average energy deposited in the ZDC by a single spectator nucleon corresponds to its energy which, in its turn, amounts to the beam energy. The energy deposited in the ZDC fluctuates from one multinucleon event to another, but on average it is proportional to the number of absorbed nucleons. It is quite common to characterize the distribution of energy in the ZDC for one-nucleon events by means of a Gaussian with the mean μ_1 equal to the beam energy E_0 and the dispersion σ_1 also depending on E_0. Two functions are usually considered to approximate the dependence of energy resolution σ_1/μ_1 on E_0. For example, in Refs. [1,4] the energy resolution has been evaluated as:

$$\frac{\sigma_1}{\mu_1} = \sqrt{\frac{a^2}{E_0} + b^2}, \tag{1}$$

while in Refs. [5,15] a bit different approximation has been adopted:

$$\frac{\sigma_1}{\mu_1} = \frac{c}{\sqrt{E_0}} + d. \tag{2}$$

Naturally, the functions (1) and (2) are nearly equivalent to each other in the case of $a \approx c$ and the smallness of the second terms in comparison to the first ones at low beam energy. The higher the beam energy, the better the ZDC energy resolution is. For example, σ_1/μ_1 calculated at $E_0 = 2510$ GeV with Eq. (1) for the ALICE neutron ZDC with the parameters $a = 256.6\%\ \mathrm{GeV}^{1/2}$ and $b = 10.3\%$ amounts to 11.5% [4].

The numbers of forward nucleons are obtained in ALICE [5,13] and other experiments [7,8] by fitting the measured distributions of energy E deposited in calorimeters in multinucleon events. In particular, the fitting functions $F(E)$ are constructed as the sum of four Gaussians corresponding to $i = 1, 2, \ldots, 4$ nucleons emitted in EMD events [13]:

$$F(E) = \sum_{i=1}^{4} f_i(E) = \sum_{i=1}^{4} \frac{\mathsf{N}_i}{\sqrt{2\pi}\sigma_i} e^{-\frac{(E-\mu_i)^2}{2\sigma_i^2}} . \tag{3}$$

Each Gaussian $f_i(E)$ representing an ith peak is characterized by its mean value μ_i, its dispersion σ_i and the normalization constant N_i which is proportional to the numbers of events with i nucleons. Here $\mu_1 = E_0$, $\mu_i = i\mu_1$ and $\sigma_i = \sqrt{i}\sigma_1$. In addition, a correction for the pedestal in the ZDC signal has been introduced in Ref. [13], which affects σ_i. However, for the sake of simplicity the function (3) without a pedestal correction is used in the present work to represent the ZDC energy spectra in NICA/MPD and ALICE experiments.

3. Correction for ZDC acceptance to the measured yields

As discussed above in Section 2, the numbers of events with different multiplicities of forward nucleons N_i can be reliably measured by fitting the ZDC energy distribution by the sum of Gaussians providing that all such nucleons are intercepted by the ZDC. However, the determination of N_i is not straightforward in the case when some of forward nucleons are lost due to a limited ZDC acceptance. These nucleons either do not hit the calorimeter at all or deposit a reduced energy due to their peripheral impact on the ZDC and shower leakage. In particular, in some of three-nucleon events either one or two nucleons can be lost. As a result, such three-nucleon events are misidentified, respectively, as two-nucleon or one-nucleon events. In general, n_i as numbers of *detected* events of each nucleon multiplicity i have to be used in Eq. (3) instead of *true* numbers N_i.

The corrections for the ZDC acceptance and efficiency to the yields of one-, two- and three-neutron events measured in the EMD of 158A GeV indium nuclei in collisions with Al, Cu, Sn and Pb targets has been introduced in Ref. [16]. Such corrections were specific to the experiment of Ref. [16], but one can think of a more general approach to account for the ZDC acceptance. In the present work a simple probabilistic (combinatorial) model is formulated to account for a limited ZDC acceptance and to study the impact of this limitation on measured ZDC energy spectra. In this model the numbers n_i of *detected* events of nucleon multiplicity i are related with the numbers of *true* events N_i. In particular, this model can be applied to forward nucleons emitted in the EMD, where one-nucleon and two-nucleon channels dominate [12]. Due to this dominance it is sufficient to consider only the emission of one, two, three and four nucleons to find the connection between n_1, n_2, n_3, n_4 and N_1, N_2, N_3, N_4. These numbers are connected by means of a triangular transformation matrix P:

$$\begin{pmatrix} \mathsf{n}_1 \\ \mathsf{n}_2 \\ \mathsf{n}_3 \\ \mathsf{n}_4 \end{pmatrix} = \begin{pmatrix} \mathsf{p}_{11} & \mathsf{p}_{12} & \mathsf{p}_{13} & \mathsf{p}_{14} \\ 0 & \mathsf{p}_{22} & \mathsf{p}_{23} & \mathsf{p}_{24} \\ 0 & 0 & \mathsf{p}_{33} & \mathsf{p}_{34} \\ 0 & 0 & 0 & \mathsf{p}_{44} \end{pmatrix} \begin{pmatrix} \mathsf{N}_1 \\ \mathsf{N}_2 \\ \mathsf{N}_3 \\ \mathsf{N}_4 \end{pmatrix} = \mathsf{P} \begin{pmatrix} \mathsf{N}_1 \\ \mathsf{N}_2 \\ \mathsf{N}_3 \\ \mathsf{N}_4 \end{pmatrix}. \tag{4}$$

The diagonal elements of P represent the probabilities $\mathsf{p}_{11}, \ldots, \mathsf{p}_{44}$ to detect exactly the same numbers of forward nucleons as were emitted in events with respective multiplicity $i = 1, \ldots, 4$. The off-diagonal elements p_{kn}, $k < n$ represent the probability to detect k nucleons out of n emitted. In ZDC energy spectra low-multiplicity peaks are filled by high-multiplicity events as some of nucleons are lost.

The most reliable way to obtain p_{kn} consists in Monte Carlo modeling of the respective experimental setup. However, one can assume that the probability p to detect a forward nucleon remains the same in low and high multiplicity events. This condition holds when the transverse momentum distribution of forward nucleons has a weak dependence on the event multiplicity. This assumption leads to the binomial distribution of the probabilities with its parameter p:

$$\mathsf{p}_{kn} = \binom{n}{k} \mathsf{p}^k (1-\mathsf{p})^{n-k} . \tag{5}$$

Here the binomial coefficient is defined as $\binom{n}{k} = n!/(n-k)!k!$. Following this assumption, the transformation matrix is written as:

$$\mathsf{P} = \begin{pmatrix} \mathsf{p} & 2\mathsf{p}(1-\mathsf{p}) & 3\mathsf{p}(1-\mathsf{p})^2 & 4\mathsf{p}(1-\mathsf{p})^3 \\ 0 & \mathsf{p}^2 & 3\mathsf{p}^2(1-\mathsf{p}) & 6\mathsf{p}^2(1-\mathsf{p})^2 \\ 0 & 0 & \mathsf{p}^3 & 4\mathsf{p}^3(1-\mathsf{p}) \\ 0 & 0 & 0 & \mathsf{p}^4 \end{pmatrix} \tag{6}$$

Due to a limited ZDC acceptance the detection of multinucleon events is suppressed, while the relative contribution of detected single-nucleon events is enhanced. In order to obtain *true* numbers N_i of events of each multiplicity, an inverse transformation can be applied to the numbers n_i of *detected* events:

$$\begin{pmatrix} \mathsf{N}_1 \\ \mathsf{N}_2 \\ \mathsf{N}_3 \\ \mathsf{N}_4 \end{pmatrix} = \mathsf{P}^{-1} \begin{pmatrix} \mathsf{n}_1 \\ \mathsf{n}_2 \\ \mathsf{n}_3 \\ \mathsf{n}_4 \end{pmatrix}, \tag{7}$$

with the following explicit result:

$$\begin{cases} \mathsf{N}_1 = \dfrac{1}{\mathsf{p}}\left(\mathsf{n}_1 - \dfrac{2(1-\mathsf{p})}{\mathsf{p}}\mathsf{n}_2 + \dfrac{3(1-\mathsf{p})^2}{\mathsf{p}^2}\mathsf{n}_3 - \dfrac{4(1-\mathsf{p})^3}{\mathsf{p}^3}\mathsf{n}_4\right) \\ \mathsf{N}_2 = \dfrac{1}{\mathsf{p}^2}\left(\mathsf{n}_2 - \dfrac{3(1-\mathsf{p})}{\mathsf{p}}\mathsf{n}_3 + \dfrac{6(1-\mathsf{p})^2}{\mathsf{p}^2}\mathsf{n}_4\right) \\ \mathsf{N}_3 = \dfrac{1}{\mathsf{p}^3}\left(\mathsf{n}_3 - \dfrac{4(1-\mathsf{p})}{\mathsf{p}}\mathsf{n}_4\right) \\ \mathsf{N}_4 = \dfrac{1}{\mathsf{p}^4}\mathsf{n}_4 \end{cases} \tag{8}$$

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