

BARYON NUMBER IN HIGH-ENERGY COLLISIONS*

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Distributions of baryons in high-energy collisions of hadrons and nuclei contain important information on the mechanism underlying multiparticle production processes. In this work, we present a phenomenological study of new, high precision experimental data on non-strange baryon spectra in pp and pC reactions at $\sqrt{s_{NN}} = 17.3$ GeV, made in the framework of the Dual Parton Model. These new experimental data are not subject to limitations imposed to earlier data sets used in such studies. We find that the classical mechanism proposed by Capella and Tran Thanh Van cannot describe the full distribution of final-state baryons in pC reactions in which the proton projectile undergoes multiple collisions with carbon nucleons. This reveals a new class of baryonic final states, characterized by long-distance transfers of baryon number in rapidity space. If confirmed, our observation brings important implications for antiproton reactions with nuclear targets, suggesting the need for a new experimental programme aimed at studies of such processes.

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1. Introduction

Processes of multiparticle production in inelastic scattering of hadrons on nuclei at high energies and small momentum transfers have been studied for many years. Such “soft processes” are very common and contribute a large fraction to inelastic cross sections. Nevertheless, they are still rather poorly understood. A rigorous theoretical description of soft processes is lacking because perturbative QCD is not valid in this case. Only phenomenological models are available at present which offer a quantitative description of rather limited accuracy. These models depend on experimental information

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in a most crucial way and their predictive power is also limited. However, they provide us with some general picture and insight into the mechanism of non-perturbative phenomena.

In this article, we present a brief report on our attempt to describe high precision data on pp [1] and pC [2] inelastic scattering at 158 GeV/ c beam momentum, which corresponds to $\sqrt{s_{NN}} = 17.3$ GeV. The analysis has been performed in the framework of the Dual Parton Model [3]. Our work has revealed a new class of final states in multiple scattering of protons on nuclei. These final states are characterized by long-distance transfers of baryon number in rapidity space. If true, this observation leads to very interesting implications for inelastic scattering of antiprotons on nucleons and nuclei. In processes involving $\bar{p}$ and two or more nucleons in a nucleus, a long-distance transfer of baryon number may result in antiproton annihilation on a few participating nucleons, in contrast with annihilation on a single nucleon.

Our work is a logical continuation of the study started a few decades ago by Kacper Zalewski and one of us (M.J.) [4] and followed later in Refs. [5, 6]. It is largely inspired by the fact that the limitations of the cited analyses related to the scarcity of available experimental data have been at present at least partially lifted.

2. Collisions of hadrons and nuclei in the Dual Parton Model

An attractive feature of the Dual Parton Model (DPM) is that it resembles and closely follows a successful description of “hard” processes in the framework of QCD. Hadrons are described as systems of constituents with longitudinal momentum fractions given by constituent distribution functions. However, there is a clear difference between constituents of DPM and partons of QCD. The number of partons in a hadron is infinite, whereas the number of constituents is always finite. Let us start from hadron–hadron collisions. In single scattering processes, a meson is described as a compound of a colour triplet valence quark q and a colour antitriplet valence antiquark $\bar{q}$, whereas a baryon is composed of a diquark D and a quark q . The diquark is a constituent containing two valence quarks in colour antitriplet state. We will further elaborate on this below.

Of course, before the collision hadrons are colour singlets. Exchanges of an octet or a singlet are only allowed by the $SU(3)$ algebra of colour in interactions of mesons with hadrons and nuclei. It is so because for the two constituents of a meson, which are in colour representations 3 and $\bar{3}$, respectively, only the octet and singlet states can be made out of them. It is plausible that the singlet exchange initiates inelastic diffraction events because it does not affect the colour configuration of all the constituents, which together produce a very energetic secondary particle in the final state. It is assumed that non-diffractive inelastic processes are initiated by colour octet

(gluon) exchange between colliding particles 1 and 2. As a result, the constituents of these particles are in colour octet states. However, it is possible to form two colour singlets by connecting one constituent of particle 1 with a constituent of particle 2. The two remaining constituents form another colour singlet. Baryons are composed of three valence quarks. In the product of three fundamental representations of $SU(3)$, $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus \bar{8} \oplus 10$, only three irreducible representations appear: singlet, octet and decuplet. However, soft collisions of mesons and baryons are initiated by octet or singlet exchanges only. The decuplet exchange is not allowed between two baryons which are initially both in colour singlet states. It is so, because after the decuplet being exchanged, one of these protons would become an antidecuplet which is impossible for an object composed of three quark constituents. Due to this limitation, in all hadron-hadron processes, baryons can be treated as composed of two constituents: a quark q and a diquark D .

Let us now consider a meson-meson collision. A fundamental building block is a high mass colour singlet system $q_1\bar{q}_2$ which fragments into hadrons in the same way as a virtual photon or a W boson of the same mass. In our notation, q_1 denotes the quark in particle 1 and $\bar{q}_2$ the antiquark in particle 2, and $\bar{q}_1q_2$ is the other colour singlet. A colour singlet system of two constituents spanned by a colour field tube (a string) is called a *chain*. For meson-meson processes, two chains are formed: $q-\bar{q}$ and $\bar{q}-q$. With elapsing time, the strings break via quark-antiquark pair creation in a strong colour field and each of the chains fragments (dominantly) into mesons. This mechanism of chain fragmentation implies that the electric charge of a constituent is transferred into a particle whose rapidity is not much different from the rapidity of this constituent. This means that the net electric charge of leading (*i.e.* most energetic) particles which are created in the fragmentation process depends on the electric charge of the corresponding constituent. In other words, this electric charge is deposited locally, *i.e.* within a limited distance in rapidity. However, the same mechanism of string fragmentation leads to a very different result for the baryon number: for a chain of $3-\bar{3}$ type, the baryon number $B = \frac{1}{3}$ is transferred from a colour triplet constituent at one end to $\bar{3}$ at the other end of the chain. *We observe that a long-distance transfer of the baryon number in rapidity space is a very common phenomenon and it always goes in the direction given by the underlying colour configuration: from 3 to $\bar{3}$.* Of course, it does not mean that these long-distance transfers are always manifest. On the contrary, in processes which are initiated by octet exchange two chains are formed, one of $3-\bar{3}$ and the other of $\bar{3}-3$ type, and the corresponding transfers of baryon number cancel out.

For those meson–baryon inelastic collisions which are initiated by colour octet exchange, two chains are formed. One of them is a $\bar{q}$ – q chain, which has been already discussed, and the other is q – D , a new type of 3 – $\bar{3}$ chain. A long-distance transfer of baryon number for a q – D chain results in production of a baryon whose momentum is a large fraction of the constituent diquark. We note that the same conclusion can be obtained by studying the fragmentation of the q – D chain in the diquark rest frame: it is evident that this process should be dominated by fragmentation into a slow baryon and a q – $\bar{q}$ chain. In principle, the fragmentation function for the q – D chain can be obtained from a good quality experimental input. This has been attempted in the past in Ref. [6] and will again be performed, with better accuracy, in Sec. 4 below.

For proton–proton collisions and octet exchange, two chains are produced: q – D and D – q . In our convention, the first constituent defining the chain originates from the proton moving to the right and the second one is coming from the proton moving to the left in the center-of-mass frame. In the fragmentation of the q – D chain, a fast baryon is produced which in most cases moves to the left, *i.e.* it is slow in the rest frame of the diquark D . In the process of the D – q chain fragmentation, another baryon appears moving to the right. Apparently in the spectrum of the produced particles, no long-distance transfer of baryon number is present in accordance with our earlier remark. However, for protons scattered on more than one nucleon in a nucleus, a decuplet exchange is not forbidden by the rules of colour algebra. If the time evolution starts from the three constituents of the incident proton in the colour decuplet state, which is colour symmetric, it is not possible to describe these constituents as a quark + diquark system. Evidently, if such a situation happens and the diquark is disintegrated by subsequent collisions with participating nucleons, then the framework of DPM becomes too restrictive and has to be extended. As an example, let us consider a decuplet exchange in interaction with three participants in the nucleus and assume that after the colour exchange, each participant in the nucleus is a normal DPM colour octet qD system composed of two constituents, whereas the proton is qqq in colour 10 representation. It is not forbidden by the rules of colour algebra that three chains of q – D type are produced, where all the quarks come from the proton. Long-distance transfers of baryon number due to fragmentation of the q – D chains do not cancel out. It is just opposite: they add and result in a transfer of $B = 1$ from the proton hemisphere to the hemisphere of the nucleus. It is necessary to study the fate of three “orphans” — the quark constituents of the nucleons — participants. Being a colour singlet they may form a new object whose fragmentation leads to production of a baryon in the nucleus hemisphere. A similar construction with a long transfer of baryon number can be made for any number of participating target nucleons larger than one.

As the last and presumably the most interesting case, we consider $\bar{p}p$ and $\bar{p}$ -nucleus inelastic collisions. For $\bar{p}p$ and octet exchange, two chains are produced: $\bar{q}-q$ and $\bar{D}-D$. The latter is a new type of a chain and its fragmentation is dominated by production of a fast antibaryon moving in the direction of $\bar{p}$ and a fast baryon moving in the direction of p [6]. There is, however, another option: $\bar{D}-D$ can fragment into mesons only, which may be related to a contribution to $\bar{p}p$ annihilation, decreasing with energy.

An exciting possibility is that the decuplet exchange is not very much suppressed for $\bar{p}p$. Such a process is not forbidden by the rules of colour addition. In contrast to pp , the antiproton can be an antidecuplet in the process of decuplet exchange. It is up to the experiment to measure the corresponding cross section and to decide whether it can be neglected. As the fragmentation of three $\bar{q}-q$ chains is dominated by final states with no baryons, this would be another contribution to the annihilation. One may even speculate that the cross section of such a contribution does not decrease with energy. If the decuplet exchange is found to be strongly suppressed in $\bar{p}p$ processes, such an observation can be understood as a consequence of a single octet exchange as a dominating mechanism initiating hadron-hadron inelastic collisions. Even if the cross section for the annihilation of $\bar{p}p$ into three $\bar{q}-q$ chains is found to be very small, it is still possible that a novel mechanism of annihilation on a few nucleons in nuclei exists and is *not* small. This result follows from a reasoning in a close analogy to that presented above and leading to long-distance transfers of baryon number in the case of proton-nucleus collisions.

3. Experimental progress

A significant limitation for the earlier studies was the lack of complete, precise experimental data on baryon emission in (at least) the full projectile hemisphere of hadron-hadron and hadron-nucleus reactions. We note that even nowadays, high precision data in these processes usually suffer from limited coverage as it is the case, for instance, for measurements performed at the Large Hadron Collider. Hermeticity still remains on the experimental to-do list even at much lower energies of the order of $\sqrt{s_{NN}} = 20$ GeV.

However, an improvement of this situation is to be noted at CERN SPS energies where high precision and extended coverage data on pp and pC collisions have been released in 2005–2013 [1, 2, 7–9]. Specifically, new measurements include not only proton but also neutron spectra and extend up to the kinematic limit at $x_F = 1$ with no lower cut-off on transverse momentum p_T . This brings us several advantages with respect to the earlier studies [4–6]:

- The necessity of very doubtful basing of the phenomenological analysis on protons as a proxy for the total baryon number disappears. Specifically, no assumptions on the “isospin flip” in the course of the constituent fragmentation process has to be made as the latter becomes in fact a measured quantity.
- The inclusion of essentially *all* emitted protons into the measurements [1, 2] allows for the delimitation of processes without colour exchange (diffractive) which is important for the normalization of our model predictions.
- The fact that both pp and pC data sets were provided by the same experiment (NA49 at the CERN SPS [10]) allows for the isolation of baryon distributions in the final state of *multiple* proton–nucleon collisions, as it will be discussed in Sec. 5.

In the following two sections, we briefly summarize our study of the cited data; a fully detailed description will be provided in a separate paper.

4. Diquark fragmentation in proton–proton collisions

As a first part of our analysis, we study pp collisions [1] in the framework of the diquark–quark (D – q) chain fragmentation scenario formulated by Capella and Tran Thanh Van [3]. Our approach is identical to that applied in Ref. [6] but our fragmentation function parametrizes the fragmentation of the chain into all non-strange baryons. In Fig. 1, we present the net non-strange baryon rapidity distribution which we obtained from net proton and neutron spectra [1]:

$$\frac{dn}{dy} (pp \rightarrow (B - \bar{B}) X) = \frac{dn}{dy} (pp \rightarrow (p - \bar{p}) X) + \frac{dn}{dy} (pp \rightarrow (n - \bar{n}) X) . \quad (1)$$

We note that in Eq. (1) above, in order to subtract the contribution from baryon–antibaryon pair creation, we took the assumption $\bar{n} = \bar{p}$ for simplicity (see Ref. [1] for comparison). We also derived the neutron rapidity distribution from the published dn/dx_F spectrum assuming the similarity of p_T distributions for protons and neutrons. As it is evident from the figure, a properly defined fragmentation function allows for a detailed description of the net baryon spectrum up to 2.5 units in c.m.s. rapidity. This description does evidently not include the proton diffractive peak at high rapidity which is generally believed to originate from processes with no colour exchange.

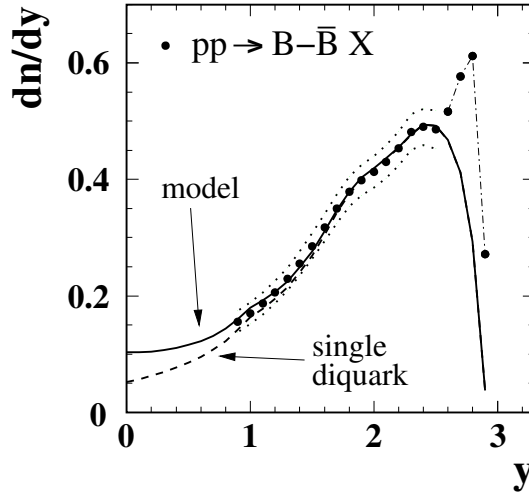


Fig. 1. Distribution of net non-strange baryons measured in pp collisions at $\sqrt{s_{NN}} = 17.3$ GeV (data points), put together with the result of our model calculation (solid line). The dotted lines in the region of matching the model to the data represent our tentative estimate of the uncertainty of the data points, evaluated from systematic errors provided in Ref. [1]. The contribution from the projectile diquark is indicated with a dashed line.

5. Collision of a proton with more than one nucleon

As the second step of this analysis, we turn towards inclusive inelastic pC reactions where experimental data on non-strange baryons of quality comparable to pp collisions are available [2]. We obtain the net non-strange baryon rapidity distribution $\frac{dn}{dy}(pC \rightarrow (B - \bar{B})X)$ in the way identical to pp reactions discussed above. Subsequently, we note that the inclusive sample of inelastic proton-carbon collisions is in fact dominated by single proton-nucleon interactions, which will be similar to pp collisions once proper isospin effects are taken into account. We make use of the fact that the two data sets [1] and [2] originate from the same experiment which results in similar data coverage, binning, and systematic errors. Consequently, we extract the net baryon distribution in the sub-inclusive sample of pC reactions in which the projectile proton undergoes only *multiple* collisions with nucleons from the carbon target¹. This distribution we obtain as

¹ We take this term from Ref. [11], where a similar extraction was performed for pion spectra.

$$\frac{dn}{dy} (pC_{\text{multiple collisions}} \rightarrow (B - \bar{B}) X) = \frac{1}{1-P(1)} \left(\frac{dn}{dy} (pC \rightarrow (B - \bar{B}) X) - P(1) \frac{dn}{dy} (pp \rightarrow (B - \bar{B}) X) \right), \quad (2)$$

where $P(1)$ is the probability of the proton projectile to hit a single nucleon from carbon which we take from a Glauber Monte Carlo dedicated to the data sample [2] which one of us (A.R.) published elsewhere [11]. The result is presented in Fig. 2 as data points. Account taken that the multiple collision pC sample is dominated by events where the proton collides with $n = 2$ carbon nucleons, it becomes evident that the latter are characterized by significantly “softer” final-state baryons with respect to pp collisions shown in Fig. 1.

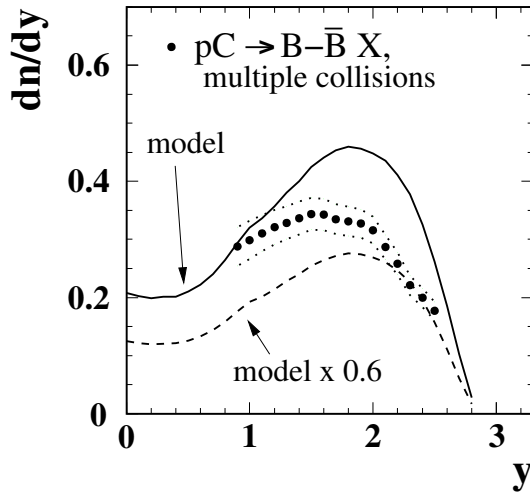


Fig. 2. Distribution of net non-strange baryons in pC reactions at $\sqrt{s_{NN}} = 17.3$ GeV in which the projectile proton undergoes only multiple collisions with target nucleons (data points), put together with the result of our model calculation (solid line). The dotted lines represent our tentative estimate of the uncertainty of the data points, evaluated from systematic errors provided in Refs. [1, 2]. The dashed line illustrates the result of our model calculation (solid line) scaled by 0.6.

Subsequently, we perform the analysis of this sub-inclusive multiple collision component of pC reactions in the framework of the Dual Parton Model. In the “standard” DPM scenario formulated by Capella and Tran Thanh Van [3], a proton undergoing the process of collision with n target nucleons is composed of $2n$ constituents, out of which $2n - 2$ are sea quarks and antiquarks, while the remaining are the valence quark and diquark whose

momentum distribution is modified as a function of n following the formulae specified in Ref. [6]. Our present work follows strictly the prescriptions given therein, but our Monte Carlo code includes also the formation of q - D chains between valence and sea quarks from the projectile proton and the diquarks from the carbon target, which contribute to the target baryon number feed-over into the projectile hemisphere at positive c.m.s. rapidity. We use the chain fragmentation function obtained from pp collisions in Sec. 4, and take for granted that all processes where the proton collides with multiple nucleons are attributable to colour exchange rather than to diffractive phenomena².

The result of our analysis is presented in Fig. 2 as the solid line. Evidently, the standard scenario of softening the projectile diquark D - q chain fragmenting into baryons significantly underpredicts the nuclear stopping power³ in the situation of a collision with $n > 1$ nucleons. In this way, an old controversy [13] is fixed in favour of Ref. [12]. The failure of the model is quite spectacular account taken of its success at $n = 1$, see Fig. 1 for comparison. *In the collision of the projectile proton with multiple carbon target nucleons, the fragmentation of the D - q chain cannot be considered as the only mechanism responsible for bringing the initial baryon number into the final state.*

6. Transport of baryon number in more than one collision

The precision of the experimental data allows us to establish the upper limit for the contribution of the standard D - q fragmentation mechanism for $n > 1$ collisions. As shown in Fig. 2, we estimate this upper limit to about 60% (this number has some uncertainty imposed by the accuracy of the data points also presented in the figure). The remaining $\sim 40\%$ must be attributed to another mechanism, the importance of which should increase for baryons found at lower rapidities. We remind the reader that this mechanism cannot be the standard fragmentation of q - D chains connected to target diquarks because the latter is already included in our calculation (Fig. 2, solid line) and, in fact, gives a significant contribution to the baryon spectrum at $y \approx 0$, see Fig. 1 for comparison.

Our conclusion from our study is that the projectile diquark can remain intact in the course of not more than about 60% of multiple collision processes. In our view, the most evident alternative is its *disintegration* into separate valence quarks. This scenario clearly opens new configurations for colour string (chain) formation, including in particular the appearance of multiple chains connecting the target diquark to projectile valence quark,

² A justification based on experimental data [1, 2] will be presented in a separate paper. The conclusions formulated in Secs. 6–8 depend very little on this statement.

³ Term taken from Ref. [12].

far more efficient in bringing the net baryon number towards low or negative rapidities than the standard scenario proposed by Capella and Tran Thanh Van [3], see discussion made in Sec. 2.

Of course, the above may result in quite a complicated picture as it is difficult to believe that the contribution from this new mechanism will remain constant for $n = 2, 3, 4, \dots$ or more collisions. On the contrary, it seems more plausible to suppose an n -dependence for the probability of diquark disintegration. We will further elaborate on this issue in a separate paper. However, it seems clear to us that already the modern experimental data [1, 2] offer deeper insight into the mechanism of transport of baryon number to the final state with respect to what was available to earlier studies [4–6, 14]. This has important consequences which we will address below.

7. Need for measurements with antiprotonic beams

It is generally not disputable that the transport of baryon number from the initial to the final state of the high-energy collision offers one of the best chances to obtain a reliable insight into the fate of quarks in non-perturbative strong processes. The transfer of initial collision energy into final-state baryons has a fundamental importance for the totality of nowadays heavy-ion physics, including most of all the energy density necessary for quark–gluon plasma formation [15], and this issue is not exempt of spectacular controversies [16]. Having this in mind, the state-of-the-art knowledge on this process must be stated as surprisingly limited. This is even more so as our main present source of information on strong interactions at high energy — the LHC experimental programme — suffers from stringent limitations as far as new measurements of identified baryons in large continued ranges of x_F of the type discussed here are concerned. This is trivially imposed by the characteristic ranges of $\sqrt{s_{NN}}$ of the order of tens of TeV.

On the other hand, our study described here makes it apparent to us that with the advent of new experimental data like [1, 2], quite fundamental elements of this process — such as the survival or disintegration of diquarks in the course of the collision⁴ — can be elucidated with far better certitude than in the earlier studies which built the present state-of-the-art knowledge on the energy deposition in collisions of hadrons and nuclei [5, 6, 12, 15]. The corresponding key factors seem to us to be the completeness, coverage and precision of new measurements, as well as their isospin-independence obtained by means of neutron data of unprecedented reliability.

Consequently, we feel obliged to point out the two possible ways for a feasible improvement of the present phenomenological situation.

⁴ We note in passing the connection between the discussion made here and the numerous phenomenological issues raised by the studies made in the framework of the wounded constituent (quark–diquark) model [17–19].

The first, more obvious option is of course the need for new experimental data — fulfilling the reasonably rigorous requirements specified above — on meson-induced and proton-induced reactions on protons and heavier nuclei. It is evident that a phenomenological analysis of such reactions would allow for studies of processes such as diquark disintegration in multiple scattering processes more in-depth with respect to what we presented above. We admit that at the present moment, we are not aware of such data of quality comparable to [1, 2] at least for $\sqrt{s_{NN}} > 15$ GeV, although various preliminary and final data are available from, *e.g.* NA49 and NA61/SHINE collaborations [20–25]. However, obtaining such new data seems to constitute a manpower/financial effort close to negligible with respect to the overall working effort of the heavy-ion field.

The second, less obvious but possibly more rewarding option is a new experimental programme aimed at new data on antiproton-induced reactions. It has been known since the early works [4–6] that the usage of a projectile with negative baryon number offers new possibilities of studying the properties of the non-perturbative strong process by the presence of its annihilation, see Sec. 2 for comparison. In our view, the results of the introductory study reported in Secs. 4–5 entitle us to the statement that a comparative analysis of identified net antibaryon (net baryon) spectra in antiproton (proton) induced reactions as a function of the number of interacting target nucleons offers the unique (best ever) opportunity for a detailed disentanglement of the different elements of the process of baryon number transport up to, *e.g. the annihilation of baryon number from the disintegrated anti-diquark over multiple nucleons*. It seems evident that such an experimental programme, followed by proper phenomenological analyses not constrained by the limitations characteristic to the old data sets, would constitute a relatively easy way to improve and concretize the presently still unclear “map” of the process of baryon transport in its relation to energy loss, quark-gluon plasma formation and particle production.

8. Summary

As a logical continuation of the work started by Kacper Zalewski and one of us in 1979, we performed a phenomenological analysis of new high precision data on pp and pC reactions at $\sqrt{s_{NN}} = 17.3$ GeV in the framework of the Dual Parton Model. This analysis was not subject to the limitations imposed by older data sets including in particular data coverage and isospin flip uncertainties. Our study revealed a new class of baryonic final states, characterized by long transfers of baryon number in rapidity space. Specifically, the corresponding distances are, on the average, significantly longer than these predicted by the original mechanism [3]. If confirmed, our observation leads to very interesting implications for antiproton collisions with

nucleons and nuclear targets, including antiproton annihilation on multiple scattered nucleons rather than one nucleon. In our view, a new experimental programme aimed to study such reactions as a function of the number of participating target nucleons and collision energy is to be considered as a realistic option to improve the presently limited state-of-the-art knowledge on the fate of quarks in the non-perturbative baryon number transport process and its relation to the characteristics of the system created in heavy-ion collisions, including quark–gluon plasma formation.

We warmly congratulate Professor Kacper Zalewski for His 85th birthday, and gratefully acknowledge His many years long collaboration with one of us, as well as his teaching and advice brought to the two of us. We wish Him all the very best for many years of fruitful scientific work. We also acknowledge the work of Hans Gerhard Fischer on the release of the experimental data [1, 2] which made this study possible. This work was supported by the National Science Centre, Poland (NCN) under grant No. 2014/14/E/ ST2/00018.

REFERENCES

- [1] NA49 Collaboration (T. Anticic *et al.*), *Eur. Phys. J. C* **65**, 9 (2010).
- [2] NA49 Collaboration (B. Baatar *et al.*), *Eur. Phys. J. C* **73**, 2364 (2013).
- [3] A. Capella, J. Tran Thanh Van, *Phys. Lett. B* **93**, 146 (1980).
- [4] M. Jeżabek, K. Zalewski, *Acta Phys. Pol. B* **11**, 425 (1980).
- [5] R. Bailey *et al.*, *Z. Phys. C* **29**, 1 (1985).
- [6] M. Jeżabek, J. Karczmarszuk, M. Różańska, *Z. Phys. C* **29**, 55 (1985).
- [7] NA49 Collaboration (C. Alt *et al.*), *Eur. Phys. J. C* **45**, 343 (2006).
- [8] NA49 Collaboration (C. Alt *et al.*), *Eur. Phys. J. C* **49**, 897 (2007).
- [9] NA49 Collaboration (T. Anticic *et al.*), *Eur. Phys. J. C* **68**, 1 (2010).
- [10] NA49 Collaboration (S. Afanasiev *et al.*), *Nucl. Instrum. Methods Phys. Res. A* **430**, 210 (1999).
- [11] G. Barr *et al.*, *Eur. Phys. J. C* **49**, 919 (2007).
- [12] W. Busza, A.S. Goldhaber, *Phys. Lett. B* **139**, 235 (1984).
- [13] M. Jeżabek, M. Różańska, *Phys. Lett. B* **175**, 206 (1986).
- [14] A. Brenner *et al.*, *Phys. Rev. D* **26**, 1497 (1982).
- [15] W. Busza, R. Ledoux, *Annu. Rev. Nucl. Part. Sci.* **38**, 119 (1988).
- [16] A. Białas, A. Bzdak, V. Koch, *Acta Phys. Pol. B* **49**, 103 (2018).
- [17] A. Białas, A. Bzdak, *Phys. Lett. B* **649**, 263 (2007).
- [18] A. Białas, A. Bzdak, *Phys. Rev. C* **77**, 034908 (2008).

- [19] M. Barej, A. Bzdak, P. Gutowski, *Phys. Rev. C* **100**, 064902 (2019).
- [20] H.G. Fischer, *Nucl. Phys. A* **715**, 118c (2003).
- [21] NA49 Collaboration (A. Rybicki), *Acta Phys. Pol. B* **33**, 1483 (2002).
- [22] D. Varga, *Eur. Phys. J. C* **33**, S515 (2004).
- [23] NA61/SHINE Collaboration (N. Abgrall *et al.*), *Eur. Phys. J. C* **76**, 84 (2016).
- [24] NA61/SHINE Collaboration (A. Aduszkiewicz *et al.*), *Eur. Phys. J. C* **77**, 671 (2017).
- [25] NA61/SHINE Collaboration (A. Aduszkiewicz *et al.*), *Phys. Rev. D* **100**, 112004 (2019).