EPJ Web of Conferences 66, 03001 (2014)
DOI: 10.1051/epjconf/20146603001

Cumulative protons in ^{12}C fragmentation at intermediate energy

B.M.Abramov, P.N.Alekseev, Yu.A.Borodin, S.A.Bulychjov, I.A.Dukhovskoi, A.I.Khanov, A.P.Krutenkova [a], V.V. Kulikov, M.A.Martemianov, M.A.Matsuk, and E.N.Turdakina

Institute for Theoretical and Experimental Physics, Moscow, 117218, Russia, B. Cheremushkinskaya, 25

Abstract. In the FRAGM experiment at heavy ion accelerator complex TWAC-ITEP, the proton yields at an angle 3.5° have been measured in fragmentation of carbon ions at T_0 = 0.3, 0.6, 0.95 and 2.0 GeV/nucleon on beryllium target. The data are presented as invariant proton yields on cumulative variable x in the range $0.9 < x < 2.4$. Proton spectra cover six orders of invariant cross section magnitude. They have been analyzed in the framework of quark cluster fragmentation model. Fragmentation functions of quark-gluon string model are used. The probabilities of the existence of multi-quark clusters in carbon nuclei are estimated to be 8–12% for six-quark clusters and 0.2–0.6% for nine-quark clusters.

1 Introduction

The origin of cumulative particles which were discovered in seventies [1, 2] is usually connected with the existence of nuclear matter density fluctuations in nuclei [3]. Modern theoretical approaches (see, e.g., [4, 5]) bound the cumulative effect with contribution from multi-quark states. These states (first of all, six-quark states) are considered for nuclear matter phase transitions at high densities. At intermediate energies the production of multi-quark clusters in cold and hot baryonic matter blurs the boundary between hadronic and quark-gluon phases [6]. Probability of the two-nucleon flucton based on the experimental data on pion cumulative production was for the first time estimated in [7] for ^{12}C. Its value is in qualitative agreement with theoretical expectation for quark cluster in a nucleus, which was obtained later within quark cluster model [8]. Similar model, in which fragmentation functions of quark clusters were calculated within the quark-gluon string model, was successfully used in [4] for the description of K^-, π- and antiproton inclusive spectra in hadron-nucleus interactions.

Ion beams open new possibilities for the cumulative effect study. One of the authors of [4], A.B. Kaidalov, suggested to use the data from our experiment FRAGM [9–11] for the experimental estimation of the probability of multi-quark clusters in nuclei. In this experiment, cumulative protons are measured in inverse kinematics, i.e. in the fragmentation region of projectile nucleus. Such measurement has definite advantages over measurements in the target fragmentation region. First, relativistic boost of forward going protons, increases considerably proton detection solid angle in the rest-frame of fragmented nucleus at fixed acceptance in laboratory frame. Second, in the inverse kinematics there are no problems with a detection of the protons which are at rest in projectile rest frame because they have laboratory momentum close to momentum per nucleon of the projectile. This allows to clearly see nucleon-nucleon component of the projectile that is impossible for target fragmentation.

[a] e-mail: anna.krutenkova@itep.ru

2 Experiment and Data analysis

In the FRAGM experiment [9] at the accelerator complex TWAC (Tera-Watt Accumulator) ITEP, the proton yield was studied in carbon ion fragmentation on beryllium target:

$$^{12}\mathrm{C} + \mathrm{Be} \to \mathrm{p} + \mathrm{X}. \tag{1}$$

The main goal of the experiment is to collect data at high proton momenta. In this paper the proton spectra from the reaction (1), obtained at carbon kinetic energies T_0 = 0.3, 0.6, 0.95 and 2.0 GeV/nucleon are analyzed. Invariant cross sections of proton yield $\sigma_{inv} = (E/p_0)d^2\sigma/dxd(p_t^2)$ as a function of cumulative variable $x = p/p_0$ are shown in Fig. 1. Here p_0 is projectile momentum per nucleon, p is proton momentum in the laboratory frame. The data cover six orders of differential cross section. It is three orders of magnitude more than in the most precise previous experiment [12] at 2 GeV/nucleon. In the region of the maximum ($x \approx 1.0$) the shapes of the spectra are close to gaussians as predicted by statistical models. However, already at $x \geq 1.3$ the spectra become exponentials, which is typical for cumulative processes.

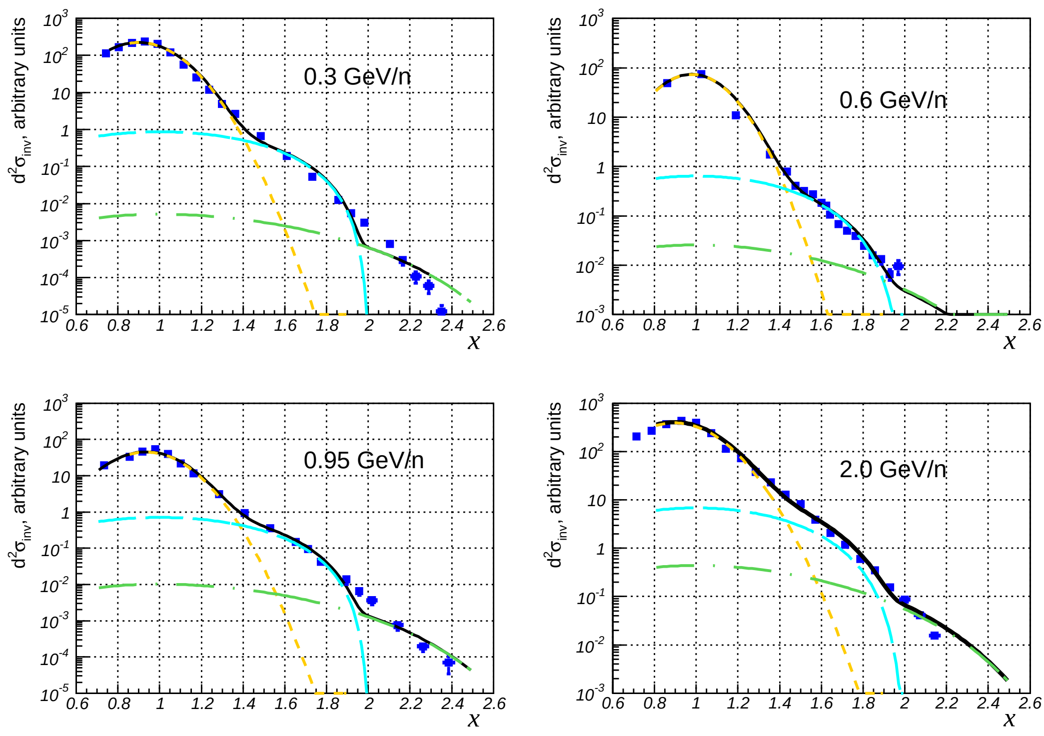

Figure 1. Points are invariant cross section σ_{inv} of proton yield at indicated projectile energies as function of x variable. Solid curve is a fit to the data in quark-cluster model. Contributions from one-, two- and three-nucleon clusters are shown with dashed, dotted and dash-dotted lines, respectively.

The most successful approach to the problem of cumulative particle production is the quark cluster model [4]. This model was used to describe yields of cumulative pions, kaons and antiprotons.

However, for protons such analysis was not performed. Reliable identification of one-nucleon component in inverse kinematics allows to apply this analysis also for protons. In the framework of this model the clusters existing in a nucleus consist of $3k$ (k = 1, 2, 3,...) valence quarks. Conventional nucleon component of the nucleus corresponds to $k = 1$. Let's denote the probability of the existence of such clusters, consisting of A nucleons, as w_k then $\sum_{k=1}^{A-1} w_k = 1$. As cluster contribution into observed processes falls with increasing k, we limit ourselves with k = 1, 2, 3 only and represent the invariant cross section as a sum of three components:

$$\sigma_{inv} \propto G w_1 g(x, p_t^2) + w_2 b_2(x, p_t^2) + w_3 b_3(x, p_t^2), \tag{2}$$

where functions g, b_2 and b_3 are fragmentation functions of quark clusters into protons, g is a conventional gaussian

$$g(x, p_t^2) = \exp(-0.5((1-\Delta)-x)^2/\sigma_x^2)\exp(-0.5p_t^2/\sigma_p^2), \tag{3}$$

b_2 and b_3 are predicted in the framework of the quark-gluon string model:

$$b_2(x, p_t^2) = \begin{cases} B_2(x/2)^3(1-x/2)^3\exp(-\alpha_1 p_t^2), \\ 0, \ x \notin [0,2], \end{cases} \tag{4}$$

$$b_3(x, p_t^2) = \begin{cases} B_3(x/3)^3(1-x/3)^6\exp(-\alpha_2 p_t^2), \\ 0, \ x \notin [0,3]. \end{cases} \tag{5}$$

The values G, B_2 and B_3 are known normalization constants defined by

$$G = (4\sqrt{2\pi}\sigma_x\sigma_p^2)^{-1}, \ \ \sigma_p = \sigma_x m_p p_0/(T_0 + m_p), \tag{6}$$

$$\int_0^\infty\int_0^\infty b_i(x, p_t^2)dxdp_t^2 = i/2, \ i = 2, 3. \tag{7}$$

The values of the cross section slopes on p_t^2, α_1 = 5 GeV$^{-2}c^2$ and α_2 = 3 GeV$^{-2}c^2$, were extracted by us from [12] and extrapolated to the region of our measurements.

3 Discussion

The results of fit of our experimental data with the formula (2) at projectile energies 0.3, 0.6, 0.95 and 2.0 GeV are given in Fig. 1. The fits are shown by solid lines, while contributions of one-nucleon (3q) component, two-nucleon (6q) and three-nucleon (9q) clusters are shown by dashed, dotted and dashed-dotted lines, respectively. The fitted parameters are mean value (1-Δ) and r.m.s. of gaussians (σ_x), and also probabilities w_2 and w_3, bounded to w_1 with the relation $w_1 + w_2 + w_3$ =1. The obtained probabilities w_2 and w_3 of the quark clusters in carbon nucleus are given in the Table 1. Two-nucleon cluster probability, estimated at different projectile energies apart from 0.3 GeV/n, varies within 7.7 - 11.9%, while the three-nucleon one lies within 0.2-0.6%, which is compatible both with given statistical errors of the fit and with expected independence of these probabilities on projectile energy. It should be emphasized that obtained probabilities of existence of quark clusters in carbon nucleus could be considered only as estimates. It is connected with difficulties to take into account systematic uncertainties of the theoretical approach. This concerns first of all the fragmentation functions (4) and

(5), which were justified in the quark-gluon string model only in the boundary regions near x=0, x=2 and x=3. The calculation of fragmentation functions in the whole x range is still unsolved problem of the model and the fragmentation functions (4,5) are the simplest possible (and widely used) functions, satisfying above mentioned boundary conditions. Moreover, in Fig. 1 at $x > 1.3$ one can see wave-like behaviour of the fitting function with respect to exponentially-falled invariant cross section observed experimentally. This can be considered as indication that the model does not take into account some small effects which smear fragmentation functions behaviour. The first small effect is clear. It is internal movement of two- and three-nucleon clusters in a nucleus which is not considered in this approach. One can hope that improvement of multi-quark cluster approach will allow to overcome these difficulties. The important result of the presented analysis is the demonstration of possibility to use data on cumulative proton yields in the inverse kinematics (in projectile fragmentation region) for estimates of these probabilities. Obtained w_2 can be compared as with the value of 6%, obtained in [7] in the data analysis on cumulative pions, as with theoretical predictions of 12.5% given in [8]. However, the value of w_3 is much smaller than predicted 2.6% of [8]. The values w_2 (w_3) can be also compared with probabilities of existence of two-nucleon (three-nucleon) correlations in nuclei, obtained in the experiment of TJNAF on electron scattering on nuclei [13], being (19.3 ± 4.1)% and (0.55 ± 0.17)% for carbon nucleus. Reasonable agreement of the results of this experiment with those obtained in the experiment [13] can be considered as evidence for unique nature of quark clusters and short-range nucleon correlations in nuclei.

The work has been performed with financial support from the RFBR grant No. 12-02-01111-a.

T_0, GeV/n	p_0, GeV/c/n	x_{max}	w_2	w_3
0.3	0.8	2.35	.054(10)	.0004(1)
0.6	1.22	1.95	.077(10)	.004(2)
.95	1.6	2.4	.119(17)	.002(1)
2.0	2.72	2.15	.098(18)	.006(1)

Table 1. Results of the fit. T_0 and p_0 are kinetic energy and momentum of the projectile per nucleon, x_{max} is maximal reached value of x, probabilities w_2 and w_3 for carbon nucleus are defined in the text. In parentheses only statistical errors are given.

References

[1] A. M. Baldin, Sov.J. Nucl.Phys. **18**, 41 (1973).
[2] Yu. D. Bayukov et al., Sov.J. Nucl.Phys. **18**, 639 (1973).
[3] D. I. Blokhintsev, Sov. Phys. JETP **6** (1957).
[4] A. V. Efremov, A. B. Kaidalov, G. I. Lykasov, N. V. Slavin, Phys. At. Nucl. **57**, 874 (1994).
[5] M. I. Krivoruchenko, Phys. Atom. Nucl. **74**, 371 (2011), arXiv:1006.0570v2.
[6] H. J. Pirner and J. P. Vary, Phys. Rev. C **84**, 015201 (2011).
[7] V. V. Burov, V. K. Lukyanov, A. I. Titov, Phys. Lett. B **67**, 46 (1977).
[8] M. Sato, S. A. Coon, H. J. Pirner and J. P. Vary, Phys. Rev. C **33**, 1062 (1986).
[9] B. M. Abramov, et al., JETP Letters, **97**, 439 (2013). See also arXiv:1304.6220v1.
[10] B. M. Abramov, P. N. Alekseev, Yu. A. Borodin et al., J. Phys.: Conf. Ser., **381**, 012037 (2012).
[11] B. M. Abramov et al, Izv. RAN. Ser. fiz. **75**, 536 (2011).
[12] L. Anderson, W. Bruckner, E. Moeller et al., Phys. Rev. C **28** 1224 (1983).
[13] K. S. Egiyan et al., Phys. Rev. Lett. **96**, 082501 (2006).