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Formation of multibaryon clusters in collisions of high energy hadrons and nuclei with carbon and neon nuclei

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Formation of multibaryon clusters in ^{4}He$+^{12}$C and ^{12}C$+^{12}$C collisions at 4.2A GeV/c, and in $\pi^- + ^{12}$C and $p + ^{20}$Ne collisions at 40 and 300 GeV/c, respectively, is studied using universal binary B algorithm of separation of clusters in 4-velocity space. The masses and widths of multibaryon clusters increase linearly with an increase in the number of protons (n_p) in a cluster. The dependences of width of clusters on n_p in $\pi^- + ^{12}$C and $p + ^{20}$Ne collisions differ noticeably from the corresponding dependences in ^{4}He $+ ^{12}$C and ^{12}C $+ ^{12}$C collisions. In nucleus–nucleus collisions, the widths of clusters are significantly larger and grow more rapidly, as the number of protons in a cluster increases, as compared to hadron–nucleus collisions. This result is in line with the fact that, in case of identical target nuclei, the degree of "destruction" of a target nucleus is greater in case of nucleus–nucleus collisions as compared to hadron–nucleus collisions. The lifetimes of multibaryon clusters are of the same order of magnitude with those of strongly decaying baryon resonances. The lifetime of clusters decreases with an increase in n_p.

Keywords: Relativistic nuclear collisions; 4-velocities of hadrons; baryon clusters.

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1. Introduction

In Ref. 1, a universal regularity expressed by independence of the energy spectra of protons (excluding the so called "evaporated" (spectator) protons) on the primary energy, the mass number of fragmenting nucleus, and the projectile–hadron type in hadron–nucleus collisions at incident energy range 3–300 GeV, was found. It is of interest to check the validity of such scaling behavior for the kinematical characteristics of multinucleon systems (clusters) formed in high energy hadron–nucleus and nucleus–nucleus collisions. At the same time, it is interesting also to study the phenomenon of clustering in nuclei itself.

In Refs. 2–4, a relativistically invariant method enabling to determine quantitatively the regions of change of experimentally measurable quantities, where the color degrees of freedom manifest themselves, was proposed. The method is based on representing the cross-sections of multiparticle-production as functions of the relativistic invariants $b_{ik} = -(u_i - u_k)^2$, where $u_i = \frac{P_i}{m_i}, u_k = \frac{P_k}{m_k}, u_i$ and u_k are 4-velocities, and P_i and P_k are 4-momenta of particles i and k, and m_i, m_k — their masses. The quantity b_{ik} means a distance between particles i and k in 4-velocity space. Such a representation of cross-sections made it possible to classify multiparticle processes on the basis of principles of weakening of correlations[5,6] and second kind self-similarity,[7] which reflect the general property of hadron processes: As the distance b_{ik} between any points u_i and u_k in 4-velocity space increases, the interaction between particles i and k weakens monotonically and quite rapidly. At $b_{ik} \gg 1$, the interaction of hadrons i and k falls down to the quark–gluon level. The introduction of concept of distances in 4-velocity space made it possible to define four dimensional clusters and discover them in this space.[3,8] By clusters, we mean a group of particles for which the distance b_{ik} between their 4-velocities u_i is much smaller than the average distance between the particles over the entire phase space of the reaction. An algorithm for extracting clusters and finding the cluster center V, around which the particles belonging to the cluster are grouped, is given in Refs. 5–11. The distance between the point u_k and the cluster center, $b_k = -(V - u_k)^2$, in the rest frame of cluster ($V = 0$) is $b_k = \frac{2T_k}{m_k}$, where T_k is the kinetic energy of a particle in this frame. The average values $\langle b_k \rangle$ proved to be identical in various reactions. In Refs. 8–10, the two types of baryon clusters, for which $\langle b_k \rangle_1 = 0.140$ and $\langle b_k \rangle_2 = 0.280$, were singled out using the above relativistically invariant method of analysis of hadron–nucleus and nucleus–nucleus collisions in terms of b_{ik} variables. The first type of clusters characterized by $\langle b_k \rangle_1 = 0.140$ was shown to possess universal properties in the analyzed interactions at incident momenta range 4–40 GeV/c. This indicated that the process of cluster formation characterized the fundamental properties of hadron matter. If clusters are considered as products of decay of quasistationary states, then the average kinetic energy of particles belonging to a cluster, $\langle T_k \rangle = \frac{m_k \langle b_k \rangle}{2}$, characterizes the cluster temperature. For pion clusters the temperature $\langle T_k \rangle = 150$ MeV,[12] and for baryon clusters the temperatures $\langle T_k \rangle_1 = 70$ MeV and $\langle T_k \rangle_2 = 130$ MeV[9,10] were extracted.

The aim of the present work is to search and study the formation of multibaryon proton clusters in $^4\mathrm{He} + {}^{12}\mathrm{C}$ and $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions at 4.2A GeV/c, and in $\pi^- + {}^{12}\mathrm{C}$ and $p + {}^{20}\mathrm{Ne}$ collisions at 40 and 300 GeV/c, respectively. This paper is a continuation of our previous analysis[13] performed for hadron–nucleus collisions. Proton clusters were extracted using universal binary B algorithm[14] based on the relativistically invariant approach in the space of relative 4-velocities. Criteria for isolating clusters were given in Ref. 14 based on an analysis of production of pion clusters in $\pi^- + p$ and $\pi^- + {}^{12}\mathrm{C}$ collisions at an incident momentum of 40 GeV/c. It was shown[14] that, in case of production of two clusters (jets), the value of cut-off parameter b_{cut} (the largest distance in the space of 4-velocities between two particles which could be combined into a single cluster) should be such that the number of three cluster events (N_3) does not exceed the statistically expected background for the number of two cluster events (N_2), i.e., $N_3 \leq \sqrt{N_2}$.

2. Experimental Data and Analysis

Experimental data on minimum bias $p + {}^{20}\mathrm{Ne}$ collisions (4990 collision events) were obtained using 30-inch neon bubble chamber exposed to a diffractive beam of protons accelerated to a momentum of 300 GeV/c at Fermi National Accelerator Laboratory (FNAL, Batavia, USA). In this experiment, the secondary protons were identified reliably in a momentum range $0.13 \leq p \leq 1.2$ GeV/c. Data on minimum bias $\pi^- + {}^{12}\mathrm{C}$ interactions (16657 collision events) were obtained using 2 m propane (C_3H_8) bubble chamber of the Laboratory of High Energies (LHE) at the Joint Institute for Nuclear Research (JINR, Dubna, Russia) exposed to a beam of negatively charged pions accelerated at the Protvino accelerator (Institute for High Energy Physics) to the momenta 40.00 ± 0.24 GeV/c. Experimental data on minimum bias $^4\mathrm{He} + {}^{12}\mathrm{C}$ and $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions (11974 and 20528 collision events, respectively) were also obtained using 2 m propane bubble chamber of LHE at the

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JINR exposed to the beams of α-particles and ^{12}C nuclei accelerated to a momentum of 4.2 GeV/c per nucleon at the Dubna synchrophasotron. Protons could be reliably identified in a momentum range $0.14 \leq p \leq 0.75$ GeV/c in 2 m propane bubble chamber of LHE. While constructing the proton clusters, the "evaporated" protons (spectators of target nuclei) with momenta $p < 0.175$ GeV/c for collisions with ^{12}C nuclei and protons with $p < 0.2$ GeV/c for proton–neon collisions were excluded from an analysis.

To study the possibility of formation of quasistationary multinucleon states in nuclear interactions, the spectra of invariant masses of proton clusters with different proton multiplicity n_p were analyzed in ^{4}He+^{12}C, ^{12}C+^{12}C, $\pi^- + ^{12}$C, and $p+^{20}$Ne collisions based on the above mentioned B algorithm,[14] which is a modification of algorithm of JADE collaboration.[15–18] It is important to clarify in advance that, due to existence of neutrons in colliding nuclei, the multibaryon clusters cannot consist of protons only. Therefore, multiproton clusters, analyzed in the present work, should be considered as parts of the larger multibaryon clusters, containing also neutrons, which were not detected and measured experimentally. The essence of a binary B algorithm is in replacement of a square of 4-momenta of a pair of particles by a square of difference of their four-velocities, b_{ik}

$$b_{ik} = -\left(\frac{P_i}{m_i} - \frac{P_k}{m_k}\right)^2 = \frac{m_{ik}^2 - (m_i + m_k)^2}{m_i m_k}, \tag{1}$$

where P_i and P_k are 4-momenta, m_i and m_k are masses of particles i and k, and m_{ik} is invariant mass of the particles i and k. For a system of three pre-clusters i, j and k, the following statement holds: If a distance between pre-clusters i, j and k, j is less than b_0 in 4-velocity space ($b_{ij} < b_0$ and $b_{kj} < b_0$), then the distance between the combined pre-cluster (ik) and pre-cluster j cannot exceed the value b_0 since

$$b_{(ikj)} = -\left(\frac{P_i + P_k}{m_{ik}} - \frac{P_j}{m_j}\right)^2 = \frac{m_i b_{ij}}{m_{ik}} + \frac{m_k b_{kj}}{m_{ik}} + 2\left(\frac{m_i + m_k}{m_{ik}} - 1\right) < b_0. \tag{2}$$

So the binary B algorithm is obtained by making substitutions $m_{ik}^2 \to b_{ik}$ and $m_{\text{cut}}^2 \to b_{\text{cut}}$ in JADE algorithm. The detailed analysis[14] showed the possibility of a better separation of clusters both in four-velocity and phase space using binary B algorithm, as compared to JADE algorithm.

Since we deal with the target proton fragments, the expected number of clusters in a collision event is equal to one. The maximal values of b_{ik} observed in experiment for proton pairs proved to be 2.0 for $\pi^- + ^{12}$C, ^{4}He + ^{12}C, and ^{12}C + ^{12}C collisions and 3.2 for $p + ^{20}$Ne collisions. Naturally, the value of b_{cut} should be significantly smaller than these maximal b_{ik} values. To find the optimal b_{cut} value, we constructed distributions on the number of clusters in an event for the values of b_{cut} in ranges 0.1–2.0 and 0.1–3.2 with a step of 0.1 for $\pi^- + ^{12}$C, ^{4}He + ^{12}C, and ^{12}C + ^{12}C collisions and $p + ^{20}$Ne collisions, respectively. We observed a rapid growth of one cluster events and a slow decrease of two cluster events as the value of b_{cut} increased.

As the optimal value of $b_{\rm cut}$, we selected such a value of cut-off parameter for which the number of two cluster events (N_2) did not exceed the statistically expected background for the number of one cluster events (N_1), i.e., $N_2 \leq \sqrt{N_1}$, in accordance with the corresponding criterion introduced in Ref. 14.

The so obtained optimal values of $b_{\rm cut}$ were close to each other for all the four analyzed reactions and proved to be 0.6 ± 0.1 for $p + {}^{20}\mathrm{Ne}$ collisions and 0.5 ± 0.1 for $\pi^- + {}^{12}\mathrm{C}$, ${}^4\mathrm{He} + {}^{12}\mathrm{C}$, and ${}^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions. It should be mentioned that the average values of masses of clusters with the different number of protons increase, for all the four collision types, by about 3% on the average as parameter $b_{\rm cut}$ increases from 0.1 to 0.6. In region $b_{\rm cut} \geq 0.6$, the average values of the masses of proton clusters remain the same within the uncertainties.

The spectra of invariant masses of clusters containing $n_p = 2 - 5$ protons for all the analyzed reactions are presented in Figs. 1(a)–1(d). As seen from Figs. 1(a)–1(d), the invariant mass spectra of proton clusters represent a spectrum of separate

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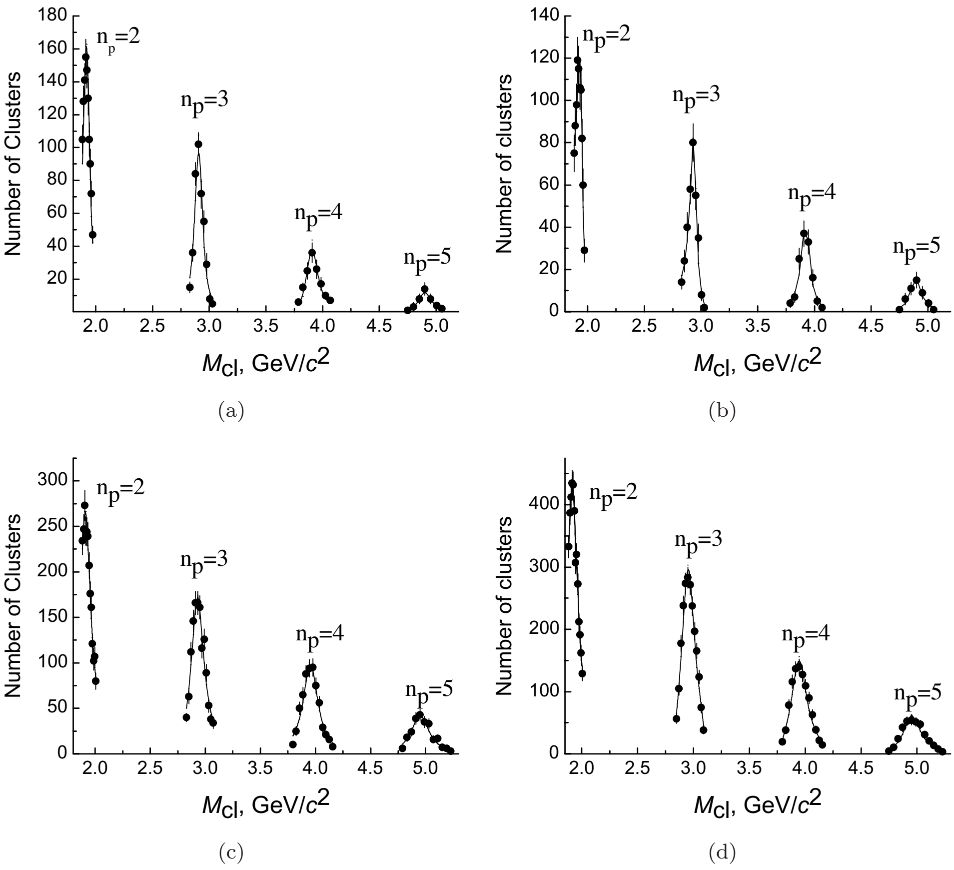

Fig. 1. Invariant mass (M_{cl}) distribution of proton clusters containing the different number of protons (n_p) in $\pi^- + {}^{12}\mathrm{C}$ (a), $p + {}^{20}\mathrm{Ne}$ (b), ${}^4\mathrm{He} + {}^{12}\mathrm{C}$ (c), and ${}^{12}\mathrm{C} + {}^{12}\mathrm{C}$ (d) collisions at $4.2A$ GeV/c. The solid curves represent approximation by the function in (3).

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nonoverlapping single mode distributions. We can see that the spectra of clusters with $n_p = 2$ protons in $^4\mathrm{He} + {}^{12}\mathrm{C}$, $^{12}\mathrm{C} + {}^{12}\mathrm{C}$, $\pi^- + {}^{12}\mathrm{C}$, and $p + {}^{20}\mathrm{Ne}$ collisions have an interesting feature expressed by their asymmetry: the first points in all figures demonstrate enhanced probability of formation of two proton states, which highlights a manifestation of final state interaction of two protons.[19,20] Interest to this effect is caused by the expected suppressed statistical probability of formation of two proton states due to Pauli Exclusion Principle. However, our experimental results show that the dynamics of final state interaction violates these statistics. This agrees with the conclusions of Refs. 17 and 18, where the expression for amplification coefficient of the final proton–proton state, the ratio of probabilities of observing the two proton state in dependence on their relative momentum (relative energy ΔE) in the presence and absence of interaction, was obtained. The maximum value of this coefficient proved to be ≈ 9 at $\Delta E = 0.5\,\mathrm{MeV}$, which could explain, at least qualitatively, the observed behavior of the spectra of invariant masses of two protons at $M_{cl} \approx 1.88\,\mathrm{GeV}/c^2$ in Figs. 1(a)–1(d). The extracted distributions were fitted by an expression representing a sum of Breit–Wigner function, describing a resonance production, a background term taking into account the multiparticle production at the close to resonance energies, and a function which describes the interference between these two contributions. Analytically the approximating function is given by[21]

$$F(M) = \frac{\alpha^2}{(M - M_0)^2 + \Gamma^2/4} + \frac{2\alpha\beta(M - M_0)}{(M - M_0)^2 + \Gamma^2/4} + \beta^2, \qquad (3)$$

where the first term is a Breit-Wigner function, the second term is a function describing the interference between resonance and nonresonance particle production, and the last third term stands for the background, M_0 and Γ are the mass and width of a resonance. The results of approximation are shown as solid curves in Fig. 1. The extracted values of M_0 and Γ are given in Table 1.

It is important to study the influence of experimental uncertainties (proton momentum measurement errors) on the results given in Table 1. Therefore, we estimated the average uncertainties in the extracted masses and widths of proton clusters with the different n_p in the analyzed collisions taking into account the errors of experimental measurements. The values of $\langle \Delta M \rangle$ and $\langle \Delta\Gamma \rangle$ in dependence on the number of protons in a cluster are presented in Table 2. As seen from Table 2, the average experimental uncertainties increase with an increase in the number of protons in a cluster. However, Table 2 shows that the contribution of the experimental measurement errors to the extracted widths of proton clusters, presented in Table 1, does not exceed 10–14% on the average.

It follows from $\chi^2/n.d.f.$ values presented in Table 1 that, for all n_p values, the experimental distributions are described quite well by the function in (3). The dependences of the values of M_0 and Γ on n_p for the assumed multinucleon quasistationary states are presented in Figs. 2 and 3, respectively. As seen from Fig. 2 and Table 1, the extracted masses M_0 of proton clusters at all n_p values coincided

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Table 1. The values of M_0 and Γ extracted from approximation of spectra of invariant masses of proton clusters by the dependence in (3) for clusters with the different number of protons (n_p).

Type of interaction	Projectile momentum	The number of protons in cluster (n_p)	M_0, GeV/c^2	Γ, MeV/c^2	$\chi^2/n.d.f.$
$p + {}^{20}$Ne	300 GeV/c	2	1.94 ± 0.01	65 ± 2	0.46
		3	2.93 ± 0.01	70 ± 7	0.69
		4	3.93 ± 0.01	87 ± 15	0.67
		5	4.89 ± 0.02	103 ± 26	0.80
$\pi^- + {}^{12}$C	40 GeV/c	2	1.92 ± 0.01	72 ± 9	0.54
		3	2.92 ± 0.01	72 ± 7	0.95
		4	3.91 ± 0.01	95 ± 14	0.79
		5	4.89 ± 0.02	104 ± 31	0.27
^{4}He + ^{12}C	4.2A GeV/c	2	1.91 ± 0.01	118 ± 7	0.32
		3	2.93 ± 0.01	138 ± 8	0.54
		4	3.95 ± 0.01	153 ± 12	0.62
		5	4.95 ± 0.01	179 ± 23	0.44
^{12}C + ^{12}C	4.2A GeV/c	2	1.91 ± 0.01	117 ± 12	0.37
		3	2.93 ± 0.01	135 ± 6	0.54
		4	3.94 ± 0.01	155 ± 9	0.55
		5	4.95 ± 0.01	179 ± 16	0.54

Table 2. The average errors in the extracted masses and widths of proton clusters estimated taking into account the uncertainties of the experimental measurements.

Type of interaction	Projectile momentum	The number of protons in clusters (n_p)	$\langle \Delta M \rangle$, MeV/c^2	$\langle \Delta\Gamma \rangle$, (MeV/$c^2$)
$p + {}^{20}$Ne	300 GeV/c	2	6.6 ± 0.1	7.8 ± 0.1
		3	11.2 ± 0.4	10.0 ± 0.3
		4	15.3 ± 1.1	12.0 ± 1.0
		5	19.1 ± 1.5	14.1 ± 1.4
$\pi^- + {}^{12}$C	40 GeV/c	2	4.5 ± 0.1	4.5 ± 0.1
		3	7.6 ± 0.3	6.2 ± 0.3
		4	10.1 ± 1.0	7.1 ± 0.8
		5	12.9 ± 1.5	8.3 ± 1.2
^{4}He + ^{12}C	4.2A GeV/c	2	5.4 ± 0.1	5.3 ± 0.1
		3	9.3 ± 0.1	7.1 ± 0.1
		4	12.5 ± 0.2	8.0 ± 0.1
		5	15.6 ± 0.5	9.0 ± 0.3
^{12}C + ^{12}C	4.2A GeV/c	2	5.4 ± 0.1	5.3 ± 0.1
		3	9.2 ± 0.1	7.0 ± 0.1
		4	12.3 ± 0.1	8.0 ± 0.1
		5	15.7 ± 0.3	9.1 ± 0.2

within statistical uncertainties for ^{4}He+^{12}C and ^{12}C+^{12}C collisions at 4.2A GeV/c, and $p + {}^{20}$Ne and $\pi^- + {}^{12}$C collisions at 300 and 40 GeV/c respectively, showing no dependence on the type of projectile hadron or nucleus, its energy, or the mass of the fragmenting nucleus. As seen from Figs. 2 and 3, the values of M_0 and Γ increase

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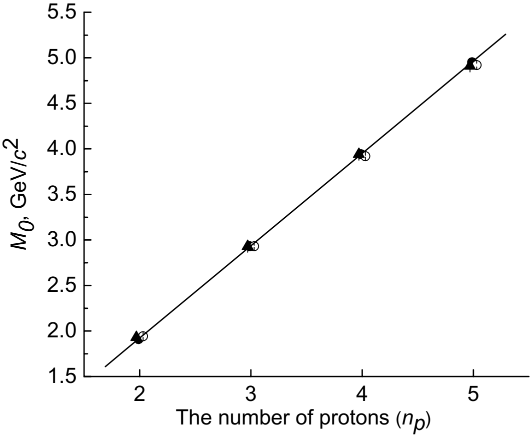

Fig. 2. Dependence of the extracted masses of clusters on the number of protons (n_p). The solid line is approximation of data by the dependence in (4); (○) — $\pi^- + {}^{12}$C collisions at 40 GeV/c, (▲) — $p + {}^{20}$Ne collisions at 300 GeV/c.

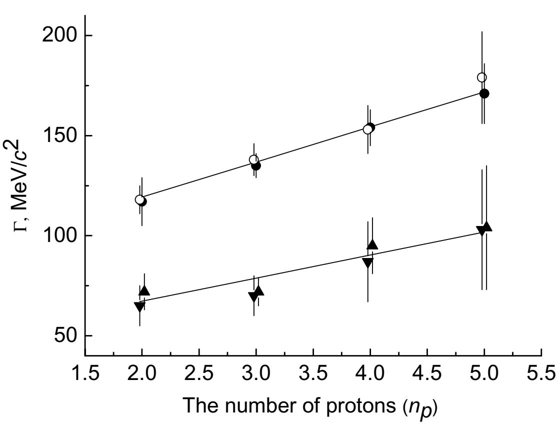

Fig. 3. Dependence of the extracted widths of clusters on the number of protons (n_p). The solid lines are approximations of data by the dependences in (5) and (6); (○) — ^{4}He + ^{12}C and (●) — ^{12}C + ^{12}C collisions at 4.2A GeV/c, (▼) — $\pi^- + {}^{12}$C collisions at 40 GeV/c, (▲) — $p + {}^{20}$Ne collisions at 300 GeV/c.

linearly within the uncertainties as the number of protons n_p in a cluster increases. It is interesting to mention that, for all the four collisions types, the lifetimes of clusters, deduced from the cluster widths presented in Table 1, proved to be of the same order ($\sim 10^{-23}$s) with the lifetimes of baryon resonances decaying via strong force. Increase of a width of clusters with increasing the number of protons in a cluster is equivalent to decrease of a lifetime of clusters. Hence, our results show that the stability of multibaryon clusters decreases as n_p increases.

The dependences of mass M_0 and width Γ of clusters on the number of protons n_p in a cluster are fitted well by a linear function $y = a + bx$ and can be represented as

$$M_0(n_p) = (-0.046 \pm 0.010) + (1.0 \pm 0.03) * n_p[\mathrm{GeV}/c^2]$$
$$\text{for all the four reactions } (\chi^2/n.d.f. = 0.12), \tag{4}$$
$$\Gamma(n_p) = (44.1 \pm 8.3) + (11.5 \pm 2.9) * n_p[\mathrm{MeV}/c^2]$$
$$\text{for } \pi^- + {}^{12}\mathrm{C} \text{ and } p + {}^{20}\mathrm{Ne} \text{ collision } (\chi^2/n.d.f. = 0.36) \text{ and} \tag{5}$$
$$\Gamma(n_p) = (80.4 \pm 5.1) + (18.3 \pm 1.2) * n_p[\mathrm{MeV}/c^2]$$
$$\text{for } {}^4\mathrm{He} + {}^{12}\mathrm{C} \text{ and } {}^{12}\mathrm{C} + {}^{12}\mathrm{C} \text{ collision } (\chi^2/n.d.f. = 0.23). \tag{6}$$

As can be seen from Fig. 3, Table 1, and relations in (5) and (6), the dependences of width of multibaryon clusters on n_p in $p + {}^{20}\mathrm{Ne}$ and $\pi^- + {}^{12}\mathrm{C}$ collisions differ noticeably from those in ${}^4\mathrm{He} + {}^{12}\mathrm{C}$ and ${}^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions: the slope parameter b for nucleus–nucleus collisions proved to be (1.6 ± 0.4) times greater than the respective slope for hadron–nucleus collisions.

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3. Summary and Conclusion

In conclusion, we summarize the main results of the present work. We analyzed the formation of multibaryon proton clusters in ${}^4\mathrm{He} + {}^{12}\mathrm{C}$ and ${}^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions at $4.2A$ GeV/c, and in $\pi^- + {}^{12}\mathrm{C}$ and $p + {}^{20}\mathrm{Ne}$ collisions at 40 and 300 GeV/c, respectively, using the binary B algorithm. It was found that the masses M_0 of multibaryon clusters increase linearly with an increase in the number of protons (n_p) for all the four analyzed reactions, and they (M_0) do not depend on the type of projectile (hadron or nucleus), its energy, or the mass of fragmenting nucleus. The widths Γ of clusters also increased linearly with an increase in n_p. This showed that the stability of multibaryon clusters decreased with an increase in the number of protons in a cluster. However, the dependences of width of clusters on n_p in $\pi^- + {}^{12}\mathrm{C}$ and $p + {}^{20}\mathrm{Ne}$ collisions differed noticeably from those in ${}^4\mathrm{He} + {}^{12}\mathrm{C}$ and ${}^{12}\mathrm{C} + {}^{12}\mathrm{C}$ collisions. In nucleus–nucleus collisions, the width of multibaryon proton clusters was significantly larger and grew more rapidly, with an increase in the number of protons in a cluster, as compared to hadron–nucleus collisions. For all the four reactions, the lifetimes of multibaryon clusters were of the same order of magnitude with those of baryon resonances. The smaller lifetime of multibaryon clusters formed in nucleus–nucleus collisions as compared to hadron–nucleus collisions could be understood from a simple physical reasoning. In nucleus–nucleus collisions, the final state interactions of a relatively large projectile nucleus (or its remnants) with a cluster formed in a target nucleus will cause the faster decay of the cluster, as compared to hadron–nucleus collisions with a relatively small projectile hadron. This is in agreement with the fact that in case of identical target nuclei the degree of "destruction" of a target nucleus is greater in case of nucleus–nucleus collisions as compared to hadron–nucleus collisions.

The analysis performed in the present work does show the possibility of study of quasistationary states of strongly excited nuclear matter by analyzing the formation of clusters in 4-velocity space. However, it is necessary to study the aspect of clustering in nuclei more comprehensively and in more detail in the future works. It is also necessary to understand the nature of mixing of various states in one cluster. Due to the existence of neutrons and the isotopic spin, mixed states cannot consist entirely of protons. The problem of mixing of states with the different baryon charges remains also unclear. Besides it, the hypothesis of multibaryon resonance states implies that the other decay channels, for example, those containing pions as decay products in addition to baryons, should also exist.

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