ISSN 1063-7788, Physics of Atomic Nuclei, 2010, Vol. 73, No. 12, pp. 2110–2115. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © R.R. Kattabekov, K.Z. Mamatkulov, D.A. Artemenkov, V. Bradnova, S. Vokal, D.M. Zhomurodov, P.I. Zarubin, I.G. Zarubina, Z.A. Igamkulov, N.V. Kondrat'eva, N.K. Kornegrutsa, D.O. Krivenkov, A.I. Malakhov, G.I. Orlova, N.G. Peresad'ko, N.G. Polukhina, P.A. Pukoyatkin, V.V. Rusakova, R. Stanoeva, M. Haiduc, S.P. Kharlamov, 2010, published in Yadernaya Fizika, 2010, Vol. 73, No. 12, pp. 2166–2171.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Exposure of Nuclear Track Emulsion to a Mixed Beam of ^{12}N, ^{10}C, and ^{7}Be Relativistic Nuclei

R. R. Kattabekov[1),2)], K. Z. Mamatkulov[1),3)], D. A. Artemenkov[1)], V. Bradnova[1)], S. Vokal[4)], D. M. Zhomurodov[1),3)], P. I. Zarubin[1)*], I. G. Zarubina[1)], Z. A. Igamkulov[1),3)], N. V. Kondrat'eva[1)], N. K. Kornegrutsa[1)], D. O. Krivenkov[1)], A. I. Malakhov[1)], G. I. Orlova[5)], N. G. Peresad'ko[5)], N. G. Polukhina[5)], P. A. Pukoyatkin[1)], V. V. Rusakova[1)], R. Stanoeva[1),6)], M. Haiduc[7)], and S. P. Kharlamov[5)]

Received February 10, 2010; in final form, June 23, 2010

Abstract—A nuclear track emulsion was exposed to a mixed beam of ^{12}N, ^{10}C, and ^{7}Be relativistic nuclei having a momentum of 2 GeV/c per nucleon. The beam was formed upon charge exchange processes involving ^{12}C primary nuclei and their fragmentation. An analysis indicates that ^{10}C nuclei are dominant in the beam and that ^{12}N nuclei are present in it. The charge topology of relativistic fragments in the coherent dissociation of these nuclei is presented.

DOI: 10.1134/S1063778810120161

INTRODUCTION

The use of accelerated nuclei, including radioactive ones, makes it possible to extend qualitatively the spectroscopy of cluster systems and to render it more versatile. A configuration overlap of the ground state of an accelerated nucleus with final cluster states manifests itself most strongly in the case of dissociation occurring at the periphery of the target nucleus and involving excitation transfer in the vicinity of cluster-binding thresholds. Owing to the collimation of projectile fragments, a determination of interactions as peripheral ones becomes easier as one moves toward energies in excess of 1 GeV per nucleon. The thresholds for their detection disappear, and the energy lost by fragments in a detector material is minimal. Thus, qualitatively new possibilities for studying cluster systems arise in the relativistic region in relation to the region of low energies. The method of nuclear track emulsions ensures the possibility of observing in minute detail and with a record spatial resolution multiparticle systems of relativistic fragments formed as dissociation products.

Events of a coherent dissociation of nuclei, which proceeds without the formation of target fragments and mesons, into narrow jets of light and extremely light nuclei whose total charge is close to the charge of the primary nucleus constitute a moderately small fraction of observed interactions. The most peripheral of them are not accompanied by the formation of target fragments [1] (so-called white stars). The distributions of probabilities for cluster configurations manifest themselves in coherent-dissociation processes, and these distributions are peculiar to each individual nucleus involved.

A series of runs of irradiation of a nuclear track emulsion according to the BECQUEREL Project [2] at the nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna) with beams of a family of cluster nuclei ^{7,9}Be, ^{8,10,11}B, ^{9,10}C, and ^{12,14}N [1, 3–9] continued runs of irradiation at the JINR synchrophasotron, which were initially performed by using the cluster nuclei ^{12}C [10] and ^{6}Li [11]. This created preconditions for analyzing various ensembles of light and extremely light nuclei detected under identical observation conditions. Knowledge of the distributions of the charge topology of white stars in a nuclear track emulsion turned out to be of

1)Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia.
2)Institute for Physics and Technology, Uzbek Academy of Sciences, ul. Timiryazeva 2b, Tashkent, 700084, Republic of Uzbekastan.
3)Dzhizak State Pedagogical Institute, ul. S. Rashidova 4, Dzhizak, 130114, Republic of Uzbekistan.
4)University of P.J. Šafárik, Jesenná 5, SK041 54Košice, Slovak Republic.
5)Lebedev Institute of Physics, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 117924 Russia.
6)South-West University "Neofit Rilski," 66 Ivan Mihailov Street, 2700 Blagoevgrad, Bulgaria.
7)Institute for Space Sciences, P.O.Box MG-23, Ro 077125, Bucharest-Magurele, Romania.
*E-mail: zarubin@lhe.jinr.ru

practical importance in estimating the composition of secondary beams of nuclei and made it possible, for example, to prove the dominance of ^{8}B [5] and ^{9}C [7] nuclei. Investigations of coherent dissociation of neutron-deficient nuclei are advantageous since they ensure most comprehensive observation. In the present study, the approach developed and tested in the aforementioned investigations is used to explore the cluster features of the ^{12}N and ^{10}C nuclei. The ^{10}C nucleus is the only example of a system that possesses super-Borromean properties, since the removal from it of one of the four clusters in the $2\alpha + 2p$ structure (threshold of 3.8 MeV) leads to an unbound state. A feature peculiar to the ^{12}N nucleus is that the proton separation energy is small in it (600 keV). For white stars produced by ^{12}N, it would therefore be natural to expect the leading role of the $^{11}\mathrm{C} + p$ channel. The $\alpha+^{8}$B (threshold of 8 MeV) and $p+^{7}$ Be $+\, \alpha$ coherent-dissociation channels, as well as more complicated configurations leading to the cluster dissociation of cores in the form of the ^{8}B and ^{7}Be nuclei, are also possible.

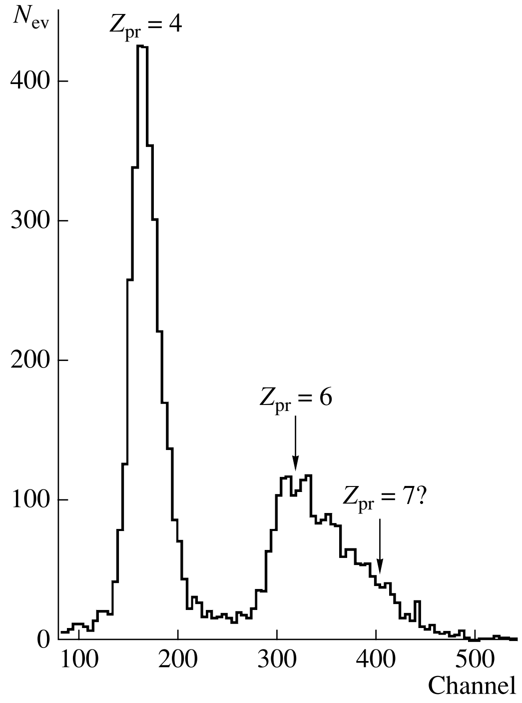

Fig. 1. Amplitude spectrum from a scintillation counter arranged at the locus of irradiation of the track-emulsion stack used, the beam-transportation channel being tuned to the separation of ^{12}N nuclei; the peak positions are indicated for nuclei of charge $Z_{\rm pr} = 4$, 6, and 7.

DESCRIPTION OF THE EXPERIMENT

The production of ^{12}N and ^{10}C nuclei is possible in charge-exchange reactions involving accelerated nuclei of ^{12}C and in their fragmentation. For the ^{10}C and ^{12}N nuclei, the ratios of the charges to the weights, $Z_{\rm pr}/A_{\rm pr}$, differ only by 3%, and the momentum acceptance of the separating nuclotron channel is 2 to 3% [8]. In view of this, the separation of these nuclei is impossible, so that ^{10}C and ^{12}N nuclei are present in the beam, forming a so-called beam cocktail. The contribution of ^{12}N nuclei is much smaller than the contribution of ^{10}C nuclei according to the ratio of the charge-exchange and fragmentation cross sections. The beam also contains ^{7}Be nuclei, which differ from ^{12}N in $Z_{\rm pr}/A_{\rm pr}$ by a value as small as 2%. Because of the momentum spread, ^{3}He nuclei may penetrate into the channel. For the neighboring nuclei ^{8}B, ^{9}C and ^{11}C, the difference from ^{12}N in $Z_{\rm pr}/A_{\rm pr}$ is about 10%. Owing to this, they are suppressed in the irradiation of the track emulsion. The identification of ^{12}N and ^{7}Be nuclei in the irradiated track emulsion can be performed on the basis of beam-nucleus charges as determined by counting δ electrons along beam tracks. In the case of ^{10}C, it is necessary to verify on the basis of the charge topology of white stars whether the contribution of neighboring isotopes is small. These were arguments behind the proposal to expose a stack of nuclear track emulsion to a mixed beam of ^{12}N, ^{10}C, and ^{7}Be nuclei.

A beam of ^{12}C nuclei with a momentum of 2 GeV/c per nucleon was accelerated at the JINR nuclotron and was extracted and directed to a generating target. Through a beam-transportation channel, including four deflecting magnets over a base 70 m long, a secondary beam characterized by a magnetic rigidity optimal for selecting ^{12}N nuclei and by the same momentum per nucleon as ^{12}C nuclei was delivered to the locus of irradiation of the track-emulsion stack used [8]. The amplitude spectrum from the scintillation counter arranged at this locus is indicative of the dominance of the isotopes ^{3}He and ^{7}Be and isotopes of C, the presence of an admixture of ^{12}N nuclei, and an almost complete absence of ^{8}B nuclei (Fig. 1). A stack of 15 layers of BR-2 nuclear track emulsion was exposed to a secondary beam of this composition.

The initial step of scanning the track-emulsion layers consisted in visual searches for beam tracks of charge $Z_{\rm pr} = 1$, 2, and $Z_{\rm pr} > 2$. The ratio of the numbers of $Z_{\rm pr} = 1$, 2, and $Z_{\rm pr} > 2$ beam tracks was about 1 : 3 : 18. For the sake of comparison, we indicate that, in the case of irradiation with ^{9}C nuclei, this ratio was about 1 : 10 : 1. Thus, the contribution of ^{3}He nuclei in this run was much smaller, which

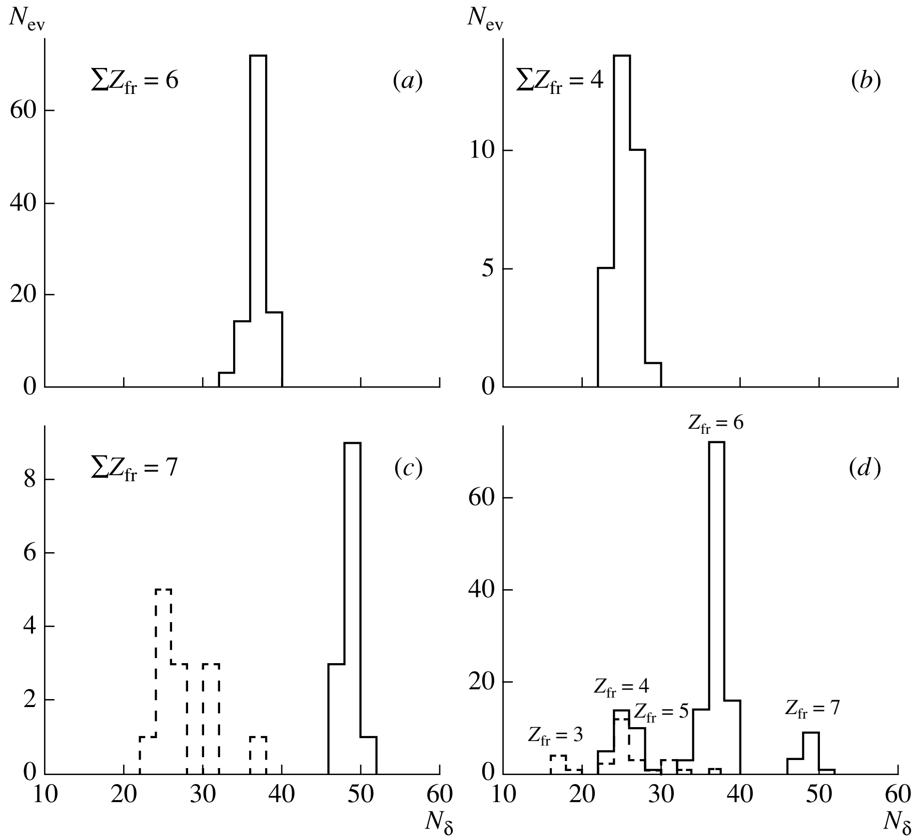

Fig. 2. Distribution of the number N_{tr} of tracks of beam particles and secondary fragments (dashed-line histogram) with respect to the mean number of δ electrons ,N_δ, over 1 mm of the track length in (*a*) 2He + 2H and (*b*) 2He and He + 2H white stars and in events featuring (*c*) $Z_{fr} > 2$ fragments along with (*d*) the distribution of N_{tr} with respect to N_δ for all measured events.

improved radically the efficiency of irradiation and the rate of event searches.

CHARGE TOPOLOGY OF WHITE STARS

Interactions in track-emulsion layers were sought on the basis of $Z_{pr} > 2$ primary tracks without selections. The search for white stars and charge measurements for them were performed in eight layers. The scanning along the total length of primary tracks that was equal to 462.6 m revealed 3258 inelastic interactions, including 330 white stars that involve only He and H relativistic fragments and 27 white stars that involved $Z_{fr} > 2$ fragments. The angular

Table 1. Distribution of the number of white stars N_{ws} over dissociation channels for which the total charge of fragments is $\sum Z_{fr} = 6$

Channel	N_{ws}
2He + 2H	91
He + 4H	14
^{8}B + H	1
^{7}Be + He	5
^{7}Be + 2H	3

Table 2. Distribution of the number of white stars, N_{ws}, over dissociation channels for which the total charge of fragments is $\sum Z_{fr} = 7$, with the measured charge of the beam track is $Z_{pr} = 7$

Channel	N_{ws}
^{7}Be + 3H	4
^{8}B + 2H	3
C + H	1
2He + 3H	6
He + 5H	3
3He + H	2
^{7}Be + He + H	2

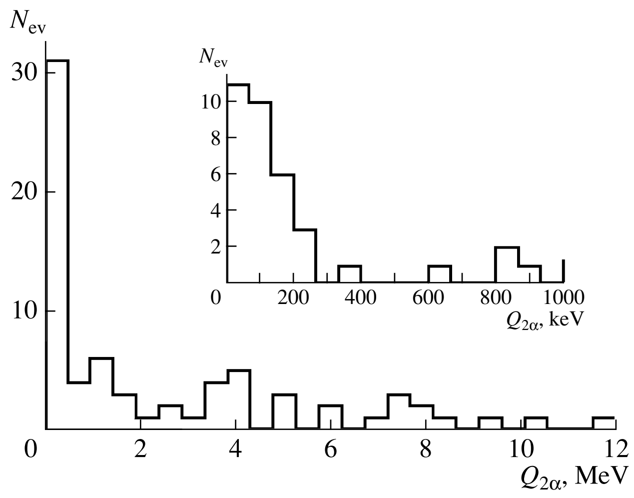

Fig. 3. Distribution of the number of white stars, N_{ws}, having the 2He + 2H topology with respect to the excitation energy $Q_{2\alpha}$ of alpha-particle pairs. The inset shows the distribution $Q_{2\alpha}$ on an enlarged scale.

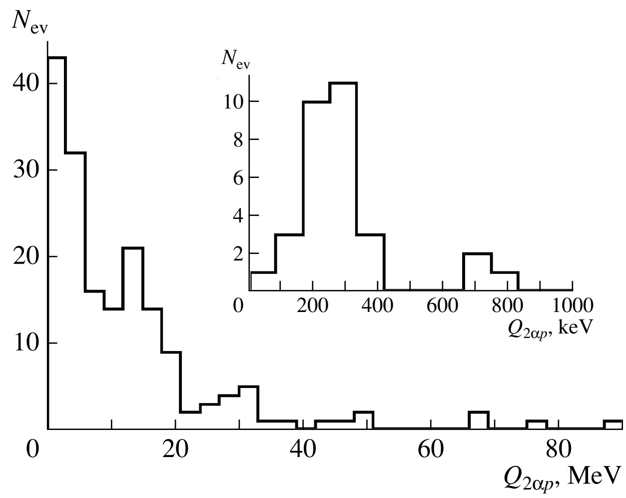

Fig. 4. Distribution of the number of white stars, N_{ws}, having the 2He + 2H topology with respect to the excitation energy $Q_{2\alpha p}$ of the $2\alpha + p$ three-particle system. The inset shows the distribution $Q_{2\alpha p}$ on an enlarged scale.

fragmentation cone was specified by the soft condition $\theta_{fr} < 8°$.

Because of the presence of $Z_{fr} > 2$ fragments, it was necessary to perform a charge identification of beam (Z_{pr}) and secondary (Z_{fr}) tracks. In order to calibrate this procedure, we have measured the mean density of δ electrons, N_δ, over 1 mm of length along the tracks of beam nuclei producing 2He + 2H, 2He, and He + 2H white stars, as well as in stars featuring $Z_{fr} > 2$ fragments as candidates for ^{12}N (see Fig. 2). We observed a correlation of the charge topology $\sum Z_{fr}$ and N_δ, and this enabled us to determine Z_{pr} for each beam track. In this way, we performed a calibration that made it possible to determine the charges of $Z_{fr} > 2$ fragments by the same method. The summed distribution for those measurements is presented in Fig. 2*d*. This spectrum is indicative of the presence of ^{12}N nuclei in the composition of the beam.

For white stars for which the conditions $Z_{pr} = \sum Z_{fr}$ and $\sum Z_{fr} = 6$ hold, Table 1 shows the distribution of their number N_{ws} over dissociation channels. For the case of $\sum Z_{fr} = 6$, this condition was tested only within two layers in performing calibration, since there was no need for a complete test in view of the dominance of carbon nuclei. As might have been expected for the isotope ^{10}C, the most probable channel was represented by 91 2He + 2H events. The He + 4H channel proved to be suppressed. Indeed, a peripheral dissociation of ^{10}C requires overcoming a high threshold for the breakup of the alpha-particle cluster.

For 20 events found here that are characterized by $Z_{pr} = 7$ and $\sum Z_{fr} = 7$ and which are associated with the dissociation of ^{12}N nuclei, the distribution with respect to the charge topology is presented in Table 2. About half of the events features a $Z_{fr} > 2$ fragment, and this is markedly different from what we have for the case of the ^{14}N [9] and ^{10}C nuclei.

PRODUCTION OF UNSTABLE NUCLEI ^{8}Be AND ^{9}B

The unstable nucleus ^{8}Be plays the role of a core in the structure of the ^{10}C nucleus, and this must manifest itself in the dissociation process $^{10}\text{C} \to {}^8\text{Be}$. The relativistic-nucleus decays $^8\text{Be} \to 2\alpha$ through the 0^+ ground state are identified by the appearance of alpha-particle pairs in the characteristic region of smallest divergence angles $\Theta_{2\alpha}$, which, at the momentum of 2 GeV/c per nucleon, is bounded by the condition $\Theta_{2\alpha} < 10.5$ mrad [4]. The excitation energy of an alpha-particle pair, $Q_{2\alpha} = M^*_{2\alpha} - M_{2\alpha}$, where $M^*_{2\alpha}$ is the invariant mass of the system of fragments, $M^{*2} = (\sum P_j)^2 = \sum(P_i \cdot P_k)$, $P_{i,k}$ stand for the fragment-i and fragment-k 4-momenta as determined in the approximation of conservation of the primary momentum per nucleon, and $\mathrm{M}_{2\alpha}$ is the doubled alpha-particle mass, has a physical meaning.

The excitation-energy ($Q_{2\alpha}$) distribution of alpha-particle pairs from 91 2He + 2H white stars is shown in Fig. 3. Among them, 30 events are those in which $Q_{2\alpha}$ does not exceed 500 keV (see inset in Fig. 3). The average value $\langle Q_{2\alpha} \rangle$ is 110 ± 20 keV, and the root-mean-square scatter is $\sigma \approx 40$ keV; this corresponds to the decays of the ground state of the ^{8}Be nucleus [4]. The branching fraction of these decays corresponds to the cases of neighboring cluster nuclei.

The unstable nucleus ^{9}B must be yet another product of the coherent dissociation of the ^{10}C nucleus. Figure 4 shows the distribution of 2He + 2H white stars with respect to the excitation energy $Q_{2\alpha p}$ determined from the difference of the invariant mass of the $2\alpha + p$ three-fragment system and the sum of the proton mass and the doubled alpha-particle mass. In 27 events, the value of $Q_{2\alpha p}$ for one of the two combinatorially possible three-particle systems $\alpha + \alpha + p$ does not exceed 500 keV either (see inset in Fig. 4). The average value $\langle Q_{2\alpha p}\rangle$ is 250 ± 15 keV, and the root-mean-square scatter is $\sigma = 74$ keV. These values correspond to the decay of the ground state of the ^{9}B nucleus through the $p+^8$Be (0^+) channel with the energy and width values known to be, respectively, 185 keV and 0.54 ± 0.21 keV [12]. In the distributions of $Q_{2\alpha} < 1$ MeV and $Q_{2\alpha p} < 1$ MeV, there is a clear-cut correlation in the production of ^{8}Be and ^{9}B in the ground states. The appearance of one $2\alpha + 2p$ event for the $Q_{2\alpha p}$ values of 0.23 and 0.15 keV is noteworthy—that is, the two three-particle systems simultaneously correspond to the decay of the ^{9}B nucleus. In all of the remaining cases of the production of a ^{9}B nucleus, the second of the two possible values of $Q_{2\alpha p}$ is in excess of 500 keV.

In addition, we have studied excitations of the $\alpha + 2p$ system by using the statistical sample of 2He + 2H white stars that remains after the elimination of the decays of the ^{9}B nucleus. In the spectrum of $Q_{\alpha 2p}$, there is no explicit signal from the decays of the ground and first excited states of the unstable nucleus ^{6}Be [12]—an estimate of its contribution does not exceed 20%. This aspect deserves a further analysis with allowance for angular correlations of protons.

CONCLUSIONS

By and large, it seems that the charge topology of the dissociation of the nuclei explored in the present study is not contradictory and that the track-emulsion irradiation performed in our experiment is promising both for enlarging the statistical sample of ^{12}N and ^{10}C white stars and for analyzing them in detail. Even at the present stage of analysis, one can also draw some physical conclusions about clustering features of the ^{12}N and ^{10}C nuclei.

In practical aspects, our analysis of angular correlations supports the conclusion that ^{10}C nuclei are dominant in the beam. The production of ^{8}Be in the dissociation of ^{10}C nuclei has a cascade character: $^{10}\mathrm{C} \to ^9\mathrm{B} \to ^8\mathrm{Be}$. There is no sizable contribution from the decay $^8\mathrm{Be} \to 2\alpha$ through the first excited state (2^+), and this distinguishes qualitatively the ^{10}C nucleus from ^{9}Be. In the case of the ^{9}Be nucleus [4], the contributions of the 0^+ and 2^+ states of the ^{8}Be nucleus to the $^9\mathrm{Be} \to ^8\mathrm{Be}$ transition proved to be close and corresponded to the weights adopted for these states in the calculation of the magnetic moment of the ^{9}Be nucleus on the basis of the $n-^8$Be two-body model [13, 14].

One can assume that the 2^+ state of the ^{8}Be nucleus does not contribute to the ground state of the ^{10}C nucleus and that only the 0^+ extended state forms its basis [15]. Paired protons may play the role of a covalent pair in the ^{10}C molecule-like system controlled by the $\alpha + 2p + \alpha$ two-center potential. Such assumptions will be verified by analyzing correlations in $2p$, 2α, and αp pairs and, later on, in more complex configurations for the $p + ^9$B, $2p + ^8$Be, and $\alpha + ^6$Be unstable nuclei.

In order to investigate nucleon clustering in the ^{12}N nucleus, it is necessary to enlarge the statistical sample used and to identify H and He isotopes by the method of multiple scattering. The ^{11}C nucleus does not manifest itself as the core of the ^{12}N nucleus. The absence of ^{8}B + He events (the respective threshold is 8 MeV) seems unexpected. It is conceivable that a ^{7}Be or a ^{8}B nucleus appears as the core of the ^{12}N nucleus and that the remaining nucleons do not form an alpha-particle cluster.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 96-1596423, 02-02-164-12a, 03-02-16134, 03-02-17079, 04-02-17151, 04-02-16593, and 09-02-9126-ST-a) and by the Agency for Science at the Ministry for Education of Slovak Republic and Slovak Academy of Sciences (grants VEGA nos. 1/2007/05 and 1/0080/08), as well as by grants from the Plenipotentiaries of Bulgaria, Slovak Republic, Czech Republic, and Romania at the Joint Institute for Nuclear Research (JINR, Dubna) in 2002–2009.

We are grateful to U.S. SalikhbaeV, member of Uzbek Academy of Sciences, as well as to Professor R.N. Bekmirzaev (Dzhizak State Pedagogical Institute, Dzhizak) and doctor of physics and mathematics K. Olimov (Institute for Physics and Technology, Tashkent).

REFERENCES

1. N. P. Andreeva et al., Yad. Fiz. **68**, 484 (2005) [Phys. At. Nucl. **68**, 455 (2005)]; nucl-ex/0605015.
2. The BECQUEREL Project, http://becquerel.jinr.ru/

3. N. G. Peresad'ko et al., Yad. Fiz. **70**, 1266 (2007) [Phys. At. Nucl. **70**, 1226 (2007)]; nucl-ex/0605014.
4. D. A. Artemenkov et al., Yad. Fiz. **70**, 1261 (2007) [Phys. At. Nucl. **70**, 1222 (2007)]; nucl-ex/0605018.
5. R. Stanoeva et al., Yad. Fiz. **72**, 731 (2009) [Phys. At. Nucl. **72**, 690 (2009)]; arXiv: 0906.4220 [nucl-ex].
6. M. Karabova et al., Yad. Fiz. **72**, 329 (2009) [Phys. At. Nucl. **72**, 300 (2009)]; D. A. Artemenkov, nucl-ex/0610023.
7. D. O Krivenkov et al., AIP Conf. Proc. **1224**, 224 (2010).
8. P. A. Rukoyatkin, L. N. Komolov, R. I. Kukushkina, et al., Eur. Phys. J. ST **162**, 267 (2008).
9. T. V. Shchedrina et al., Yad. Fiz. **70**, 1271 (2007) [Phys. At. Nucl. **70**, 1230 (2007)]; nucl-ex/0605022.
10. V. V. Belaga et al., Yad. Fiz. **58**, 2014 (1995) [Phys. At. Nucl. **58**, 1905 (1995)].
11. M. I. Adamovich et al., Yad. Fiz. **62**, 1461 (1999) [Phys. At. Nucl. **62**, 1378 (1999)].
12. The Nuclear Data Evaluation Project on Energy Levels of Light Nuclei, $A = 5$–20, http://www.tunl.duke.edu/NuclData/.
13. Y. L. Parfenova and Ch. Leclercq-Willain, Phys. Rev. C **72**, 054304 (2005).
14. Y. L. Parfenova and Ch. Leclercq-Willain, Phys. Rev. C **72**, 024312 (2005).
15. R. B. Wiringa, S. C. Pieper, J. Carlson, and V. R. Pandharipande, Phys. Rev. C **62**, 014001 (2000).

Translated by A. Isaakyan