Physics Letters B 811 (2020) 135851

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Spectra of cosmic ray carbon and oxygen nuclei according to the NUCLEON experiment

D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, A. Panov, D. Podorozhny, A. Turundaevskiy *, O. Vasiliev

Moscow State University, Skobeltsyn Institute of Nuclear Physics (SINP MSU), 1(2), Leninskie gory, GSP-1, Moscow 119991, Russian Federation

A R T I C L E   I N F O

Article history:
Received 12 July 2020
Received in revised form 29 September 2020
Accepted 6 October 2020
Available online 15 October 2020
Editor: W. Haxton

Keywords:
Cosmic ray
Carbon
Oxygen
Rigidity spectra

A B S T R A C T

The aim of the NUCLEON space was to measure spectra of high-energy cosmic rays. The cosmic ray acceleration and propagation processes are determined by the magnetic rigidities of the particles. Thus the magnetic rigidity spectra of cosmic ray carbon and oxygen nuclei obtained by the NUCLEON experiment are analyzed and compared to some other experimental results. The spectral indices calculated for different thresholds with regard to magnetic rigidity are presented. The carbon and oxygen nuclei spectra are steeper than helium nuclei spectra in the 400-10000 GV area. The spectra of carbon and oxygen nuclei are similar to the proton spectrum before the "knee".

1. Introduction

Measurements of cosmic rays spectra are necessary to understand the processes of their acceleration and propagation. Differences from power-law form can be caused by nearby sources. Carbon and oxygen nuclei spectra are measured using a number of different experiments (ATIC [1], TRACER [2], CREAM [3], PAMELA [4], CALET [5]). The spectra hardening was discovered at magnetic rigidities of more than 200-300 GV, but numbers of events were insufficient.

The large statistics was obtained in the AMS-02 experiment [6] but these measurements were performed only at magnetic rigidities less than 3000 GV.

The aim of the NUCLEON space was to measure spectra of cosmic rays in the energy range 2-500 TeV per particle.

The study of the spectra of cosmic ray carbon and oxygen nuclei is part of the research into the energy region preceding the main "knee" in the spectrum [7,8]. This study is based on data obtained by the NUCLEON apparatus [9]. The energy spectra of these components are presented in [8].

Energy measurements were performed by the new KLEM method (Kinematic Lightweight Energy Meter) [9]. This method is based on the registration of the spatial distribution of secondary particles after the first nuclear interaction of a primary particle with a target in the spectrometer. The spatial distribution of secondary particles is registered by silicon microstrip detectors.

The acceptance, calibration dependencies and detection efficiencies were determined by means of Monte-Carlo simulation for different nuclei. The GEANT software package was applied. High energy nuclear interactions were described by the QGSJET generator [8].

The NUCLEON apparatus was installed onboard the Russian satellite "Resurs-P". This satellite was launched on 26 December, 2014, and operated for three years. The obtained databank includes protons and nuclei up to nickel in energy range 2-500 GeV per particle.

2. Data analysis

A universal deconvolution method suitable for all components [8] has been developed. The method allows us to take into account bin to bin migration, essentially due to insufficient energy resolution in individual cases. The measurement region can be divided into bins in terms of both energy and magnetic rigidity. The corrected number of events in a bin i is calculated by the formula $M_i = \sum_{j=1}^{n} a_{ij} N_j$ [10,11]. The matrix elements a_{ij} are determined with the use of a Monte-Carlo simulation.

---

[*] Corresponding author.
E-mail address: turun1966@yandex.ru (A. Turundaevskiy).

https://doi.org/10.1016/j.physletb.2020.135851

The value of the matrix element a_{ij} corresponds to the probability that, according to the Bayes theorem, the particle detected in a magnetic rigidity bin j will have rigidity falling into bin i for an a priori power spectrum

$$a_{ij} = P(R \in i \mid R_{rec} \in j, \frac{dN}{dR} \sim R^{-(\gamma+1)})$$

Initially the spectrum with an integral exponent of 1.6 was simulated. The additional simulation showed that the exponent variation from 1.5 to 1.7 does not significantly change the results. Statistical errors with regard to the deconvoluted spectrum are equal to

$$\sigma(M_i) = \sqrt{\sum_j a_{ij}^2 N_j}$$

The statistical errors are less than without the deconvolution, but these errors are correlated because of the summation of different values N_j.

The systematic uncertainties were evaluated. The effect caused by low energy resolution was investigated with the use of an additional Monte-Carlo simulation. This simulation was performed for all the obtained spectra of registered energies N_j. The primary energy distribution was simulated according to the matrix a_{ij}.

The probability that the particle detected in magnetic rigidity bin j will have rigidity falling into bin i, is equal to

$$P(R \in i) = \frac{a_{ij}}{\sum_k a_{kj}}$$

Thus, we evaluated these errors statistically. Systematic uncertainties caused by low energy resolution include the effect of nuclear interactions inside the detector. These interactions were taken into account by the Monte-Carlo simulation [8].

Systematic errors caused by other effects were also investigated [8].

3. Experimental results

The preliminary results of the NUCLEON space experiment including carbon and oxygen nuclei energy spectra were presented in ICRC2017 [12].

Since the cosmic ray acceleration and propagation processes are determined by the magnetic rigidities of the particles, it is advisable to consider and compare the measured rigidity spectra.

The carbon and oxygen nuclei magnetic rigidity spectra obtained from the NUCLEON experiment are presented in Fig. 1 (a, b) and compared to other experimental results.

Spectra at rigidities more than 300-500 GV are harder than spectra at lower rigidities as measured by different experiments. The sum of the magnetic rigidity spectra of both carbon and oxygen nuclei is also presented in Fig. 1c. The summation of the fluxes of the two components reduces statistical errors.

To calculate the spectral exponent, we applied the formula based on the maximum likelihood method and the power fit of the spectra:

$$\gamma(R > R_t) = 1/ < \ln(R/R_t) >$$

The parameter R_t is the magnetic rigidity threshold. If the error of the rigidity measurements is negligible, the error in the spectrum exponent calculation depends only on the statistics.

$$\Delta\gamma = \frac{\gamma}{\sqrt{N}}$$

The experimental uncertainty of the KLEM method (~60%) [9] is not negligible. We applied the Monte-Carlo simulation to evaluate the error of the reconstructed spectral exponent.

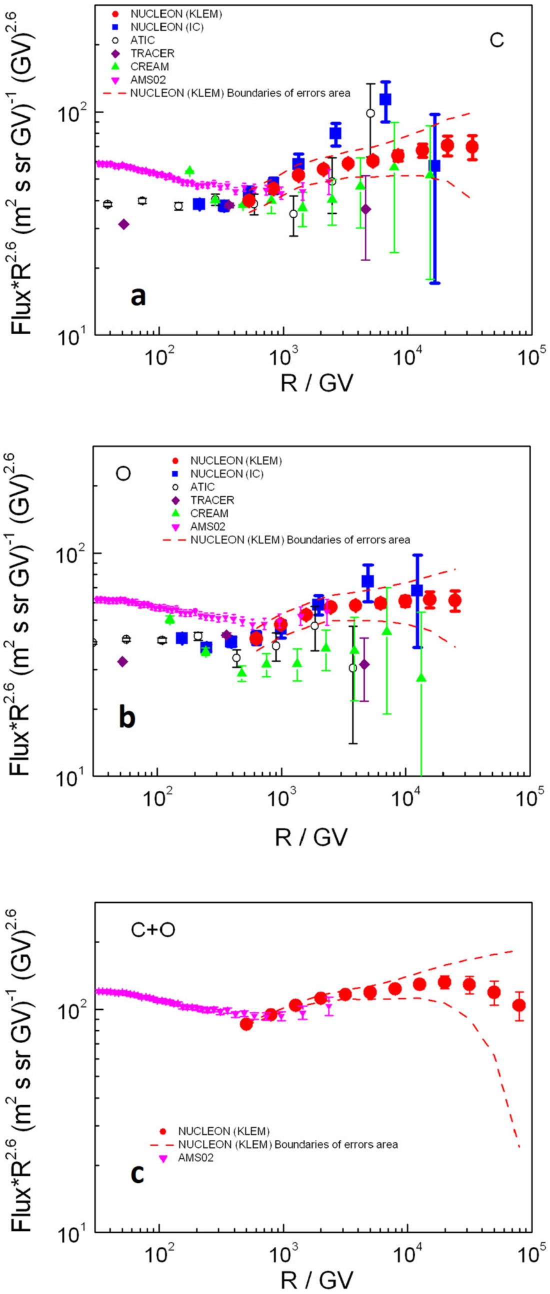

Fig. 1. Carbon (a) and oxygen (b) nuclei magnetic rigidity spectra and the sum of both carbon and oxygen nuclei spectra (c).

For each registered event with a reconstructed magnetic rigidity value of R_{rec}, the probabilities of getting into each true rigidity bin were calculated.

$$P(R \in i) = \frac{a_{ij}}{\sum_k a_{kj}}$$

The deconvolution matrix element a_{ij} is calculated by means of a Monte-Carlo simulation of the device's response function, and its a priori magnetic rigidity spectra [8]. Thus the true magnetic rigidity spectra were simulated for the reconstructed magnetic rigidity spectra by means of calculated probability distributions.

The spectral exponent value was calculated for every simulated true rigidity spectrum according to above-mentioned formula:

$$\gamma(R > R_t) = 1/ < \ln(R/R_t) >$$

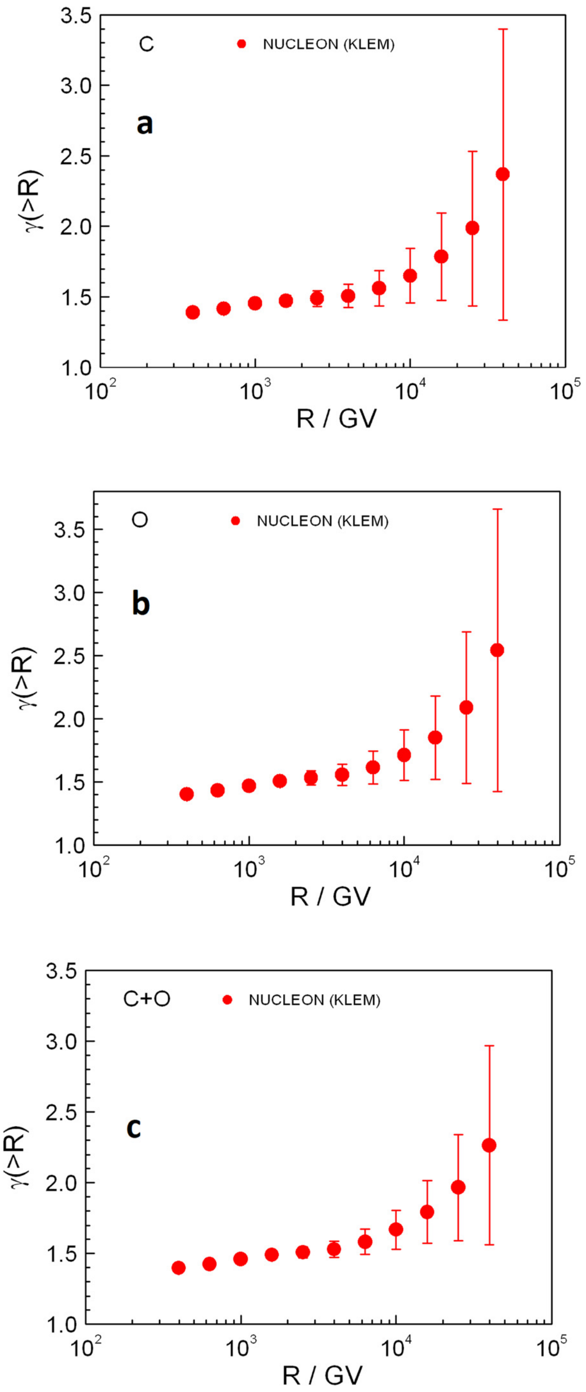

Fig. 2. Spectral index dependences on magnetic rigidity threshold for carbon (a) and oxygen (b) nuclei and the sum of both carbon and oxygen nuclei spectra (c).

Ten thousand true rigidity spectra were simulated. The mean value and root-mean-square deviation were calculated for every spectral bin. This RMS deviation is the systematical error caused by rigidity measurement uncertainty. This error was taken into account by calculation of the boundaries of the errors area for Fig. 1.

The uncertainties of the spectral exponents were calculated. The spectral indices dependencies on magnetic rigidity thresholds are presented in Fig. 2.

At low thresholds (up to 1000 GV) spectra are very hard (with a spectral index near 1.4-1.5). For a pure power-law spectrum, the index does not depend on the selected threshold. However, the experiment showed the presence of such a dependence. As the threshold increases, the spectrum becomes softer. This is due to the presence of a "knee" at high magnetic rigidities. The statistical significance of the existence of a break in the spectra was also estimated by means of a Monte-Carlo simulation. The values of the spectral index were determined by Maximum Likelihood Estimation for every simulated spectrum for two rigidity regions, 400-4000 GV (γ_1) and >4000 GV (γ_2). The probability that γ_2-$\gamma_1 > 0$ is equal to 99.83%. This confirms the results of the new "knee" investigation for different components [7].

The "knee" structure in the proton and helium spectra near 10 TV was found by different experiments such as NUCLEON [7], CREAM [11], CALET [13], DAMPE [14]. The agreement of these results is discussed in [15].

The question arises as to whether or not the spectra of carbon and oxygen nuclei are the same. The ratio of C and O rigidity spectra is presented in Fig. 3a in comparison with the ratio obtained as a result of the AMS-02 experiment [6,16] for lower rigidities. The ratio is constant at the 400-4000 GV area, but its value is slightly (at the statistical error level) higher than in the AMS-02 experiment. There are signs of a small increase at higher magnetic rigidities within the measurement errors.

The carbon and oxygen nuclei spectra can be compared with helium nuclei spectra. The ratio of helium and oxygen nuclei rigidity spectra is presented in Fig. 3b in comparison with data from the AMS-02 experiment [16] for lower rigidities. The significant magnetic rigidity dependence shows that helium spectra are harder than the heavier primary nuclei spectra.

The He/O ratio slope is different for the NUCLEON and AMS-02 experiments. The oxygen nuclei rigidity spectrum is softer than the He spectrum for the NUCLEON results. The NUCLEON data were obtained at higher rigidity than the AMS-02 measurements area.

In order to reduce the influence of measurement errors, the ratio of helium nuclei spectra to total carbon and oxygen nuclei spectra was calculated, taking into account small differences in C and O. This ratio is shown in Fig. 3c.

If this ratio is fitted with a power function, taking into account statistical and systematic errors, its exponent is equal to 0.142 ± 0.40. Thus the carbon and oxygen nuclei spectra are softer than the helium spectra in the area preceding the "knee".

The ratio of proton spectrum to total C and O nuclei rigidity spectrum is presented in Fig. 3d. This ratio is almost constant, the exponent of the power fit is equal to 0.012 ± 0.058. The spectra of carbon and oxygen nuclei are similar to the proton spectrum before the "knee".

The "knee" was found in rigidity spectra of different components [7]. The proton spectrum is softer than helium one before the "knee' [17]. However the ratio of the fluxes of protons and helium nuclei is nearly constant in the "knee" region [17]. The ratio of protons and carbon and oxygen fluxes is nearly constant in this region too (Fig. 3d). These effects can be caused by the universal astrophysical mechanism.

4. Conclusions

The application of the KLEM method to measure cosmic ray spectra has shown that, with high statistics, it is possible to determine significant spectrum parameters despite the low accuracy of energy measurements. However, at high energies, the error of spectra measurements is large due to low statistics

The study of carbon and oxygen nuclei spectra measured by the NUCLEON experiment allows us to identify some important characteristics.

It can be seen that the nuclei spectrum is very hard at a rigidity area between 400 and 10000 GV. The spectral exponent is near 1.4-

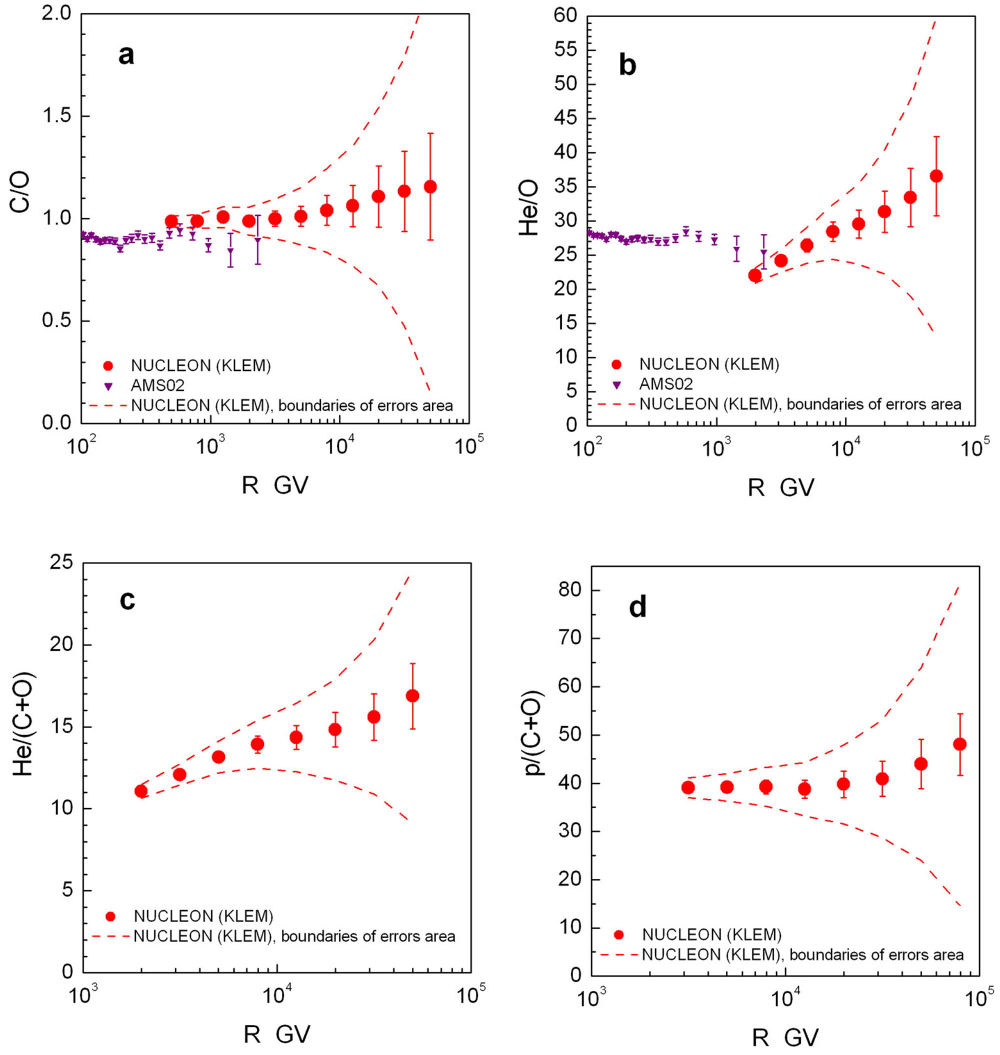

Fig. 3. C/O (a), He/O (b), He/(C+O) (c) and p/(C+O) (d) ratios.

1.5. The NUCLEON statistics are significantly larger than those from previous experiments.

The total carbon and oxygen nuclei spectra are significantly softer than helium spectra. The ratio of helium spectra to total carbon and oxygen nuclei spectra is fitted by a power function with exponent 0.142 ± 0.40. The spectra of carbon and oxygen nuclei are similar to the proton spectrum before the “knee”.

Spectral characteristics depend on cosmic ray acceleration and propagation processes. There are different astrophysical models of these processes [18–24]. The hardening can be caused by the transition from one type of source to another, with different chemical composition or spectral indices. This corresponds to results obtained from the analysis of protons and helium nuclei spectra [17].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Roscosmos State Corporation for Space Activities and the Russian Academy of Sciences.

References

[1] A.D. Panov, J.H. Adams Jr, H.S. Ahn, G.L. Bashinzhagyan, J.W. Watts, J.P. Wefel, J. Wu, O. Ganel, T.G. Guzik, V.I. Zatsepin, I. Isbertd, K.C. Kim, M. Christl, E.N. Kouznetsov, M.I. Panasyuk, E.S. Seo, N.V. Sokolskaya, J. Chang, W.K.H. Schmidt, A.R. Fazely, Energy spectra of abundant nuclei of primary cosmic rays from the data of ATIC-2 experiment: final results, Bull. Russ. Acad. Sci., Phys. 73 (2009) 564–567, https://doi.org/10.3103/S1062873809050098.

[2] A. Obermeier, M. Ave, P. Boyle, Ch. Hoppner, J. Horandel, D. Muller, Energy spectra of primary and secondary cosmic-ray nuclei measured with TRACER, Astrophys. J. 742 (2011) 14, https://doi.org/10.1088/0004-637X/742/1/14.

[3] H.S. Ahn, P. Allison, M.G. Bagliesi, J.J. Beatty, G. Bigongiari, J.T. Childers, N.B. Conklin, S. Coutu, M.A. DuVernois, O. Ganel, J.H. Han, J.A. Jeon, K.C. Kim, M.H. Lee, L. Lutz, P. Maestro, A. Malinin, P.S. Marrocchesi, S. Minnick, S.I. Mognet, J. Nam, S. Nam, S.L. Nutter, I.H. Park, N.H. Park, E.S. Seo, R. Sina, J. Wu, J. Yang, Y.S. Yoon, R. Zei, S.Y. Zinn, Discrepant hardening observed in cosmic-ray elemental spectra, Astrophys. J. Lett. 714 (2010) L89–L93, https://doi.org/10.1088/2041-8205/714/1/L89.

[4] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Boezio, E.A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Borisov, S. Bottai, A. Bruno, F. Cafagna, D. Campana, R. Carbone, P. Carlson, M. Casolino, G. Castellini, L. Consiglio, M.P. De Pascale, C. De Santis, N. De Simone, V. Di Felice, A.M. Galper, W. Gillard, L. Grishantseva, G. Jerse, A.V. Karelin, S.V. Koldashov, S.Y. Krutkov, A.N. Kvashnin, A. Leonov, V. Malakhov, V. Malvezzi, L. Marcelli, A.G. Mayorov, W. Menn, V.V. Mikhailov, E. Mocchiutti, A. Monaco, N. Mori, N. Nikonov, G. Osteria, F. Palma, P. Papini, M. Pearce, P. Picozza, C. Pizzolotto, M. Ricci, S.B. Ricciarini, L. Rossetto, R. Sarkar, M. Simon, R. Sparvoli, P. Spillantini, Y.I. Stozhkov, A. Vacchi, E. Vannuccini, G. Vasilyev, S.A. Voronov, Y.T. Yurkin, J. Wu, G. Zampa, N. Zampa, V.G. Zverev, PAMELA measurements of cosmic-ray proton and helium spectra, Science 332 (2011) 69–72, https://doi.org/10.1126/science.1199172.

[5] P. Maestro, Measurement of cosmic-ray carbon and oxygen energy spectra with CALET, Adv. Space Res. 64 (2019) 2538–2545, https://doi.org/10.1016/j.asr.2019.04.015.

[6] M. Aguilar, D. Aisa, B. Alpat, et al., AMS Collaboration, Precision measurement of the helium flux in primary cosmic rays of rigidities 1.9 GV to 3 TV with the alpha magnetic spectrometer on the international space station, Phys. Rev. Lett. 115 (2015) 211101, https://doi.org/10.1103/PhysRevLett.115.211101.

[7] E. Atkin, V. Bulatov, V. Dorokhov, N. Gorbunov, S. Filippov, V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, M. Merkin, A. Panov, D. Podorozhny, D. Polkov, S. Porokhovoy, V. Shumikhin, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, New universal cosmic-ray knee near a magnetic rigidity of 10 TV with the NUCLEON space observatory, JETP Lett. 108 (2018) 5–12, https://doi.org/10.1134/S0021364018130015.

[8] V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, A. Panov, D. Podorozhny, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, Energy spectra of abundant cosmic-ray nuclei in the NUCLEON experiment, Adv. Space Res. 64 (2019) 2546–2558, https://doi.org/10.1016/j.asr.2019.10.004.

[9] E. Atkin, V. Bulatov, V. Dorokhov, N. Gorbunov, S. Filippov, V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, M. Merkin, A. Pakhomov, D. Podorozhny, D. Polkov, S. Porokhovoy, V. Shumikhin, L. Sveshnikova, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, The NUCLEON space experiment for direct high energy cosmic rays investigation in TeV–PeV energy range, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 770 (2015) 189–196, https://doi.org/10.1016/j.nima.2014.09.079.

[10] Y.S. Yoon, H.S. Ahn, P.S. Allison, M.G. Bagliesi, J.J. Beatty, G. Bigongiari, P.J. Boyle, J.T. Childers, N.B. Conklin, S. Coutu, M.A. DuVernois, O. Ganel, J.H. Han, J.A. Jeon, K.C. Kim, M.H. Lee, L. Lutz, P. Maestro, A. Malinine, P.S. Marrocchesi, S.A. Minnick, S.I. Mognet, S. Nam, S. Nutter, I.H. Park, N.H. Park, E.S. Seo, R. Sina, S. Swordy, S.P. Wakely, J. Wu, J. Yang, R. Zei, S.Y. Zinn, Cosmic-ray proton and helium spectra from the first CREAM flight, Astrophys. J. 728 (2011) 122, https://doi.org/10.1088/0004-637X/728/2/122.

[11] Y.S. Yoon, T. Anderson, A. Barrau, N.B. Conklin, S. Coutu, L. Derome, J.H. Han, J.A. Jeon, K.C. Kim, M.H. Kim, H.Y. Lee, J. Lee, M.H. Lee, S.E. Lee, J.T. Link, A. Menchanca-Rocha, J.W. Mitchell, S.I. Mognet, S. Nutter, I.H. Park, N. Picot-Clemente, A. Putze, E.S. Seo, J. Smith, J. Wu, Proton and helium spectra from the CREAM-III flight, Astrophys. J. 839 (2017) 5, https://doi.org/10.3847/1538-4357/aa68e4.

[12] A. Panov, E. Atkin, N. Gorbunov, V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, M. Merkin, D. Podorozhny, S. Porokhovoy, V. Shumikhin, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, Energy spectra of cosmic ray heavy nuclei in the NUCLEON space experiment after two years of data acquisition, in: Proceedings of Science. The 35th International Cosmic Ray Conference, 12-20 July 2017, Busan, Korea, Proceedings of Science, 2017, p. 213.

[13] O. Adriani, Y. Akaike, K. Asano, Y. Asaoka, M.G. Bagliesi, E. Berti, G. Bigongiari, W.R. Binns, S. Bonechi, M. Bongi, P. Brogi, A. Bruno, J.H. Buckley, N. Cannady, G. Castellini, C. Checchia, M.L. Cherry, G. Collazuol, V. Di Felice, K. Ebisawa, H. Fuke, T.G. Guzik, T. Hams, N. Hasebe, K. Hibino, M. Ichimura, K. Ioka, W. Ishizaki, M.H. Israel, K. Kasahara, J. Kataoka, R. Kataoka, Y. Katayose, C. Kato, N. Kawanaka, Y. Kawakubo, K. Kohri, H.S. Krawczynski, J.F. Krizmanic, T. Lomtadze, P. Maestro, P.S. Marrocchesi, A.M. Messineo, J.W. Mitchell, S. Miyake, A.A. Moiseev, K. Mori, M. Mori, N. Mori, H.M. Motz, K. Munakata, H. Murakami, S. Nakahira, J. Nishimura, G.A. de Nolfo, S. Okuno, J.F. Ormes, S. Ozawa, L. Pacini, F. Palma, P. Papini, A.V. Penacchioni, B.F. Rauch, S.B. Ricciarini, K. Sakai, T. Sakamoto, M. Sasaki, Y. Shimizu, A. Shiomi, R. Sparvoli, P. Spillantini, F. Stolzi, J.E. Suh, A. Sulaj, I. Takahashi, M. Takayanagi, M. Takita, T. Tamura, T. Terasawa, H. Tomida, S. Torii, Y. Tsunesada, Y. Uchihori, S. Ueno, E. Vannuccini, J.P. Wefel, K. Yamaoka, S. Yanagita, A. Yoshida, K. Yoshida, Direct measurement of the cosmic-ray proton spectrum from 50 GeV to 10 TeV with the calorimetric electron telescope on the international space station, Phys. Rev. Lett. 122 (2019) 181102, https://doi.org/10.1103/PhysRevLett.122.181102.

[14] Q. An, R. Asfandiyarov, P. Azzarello, et al., DAMPE Collaboration, Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite, Sci. Adv. 5 (2019) eaax3793, https://doi.org/10.1126/sciadv.aax3793.

[15] P. Lipari, S. Vernetto, The shape of the cosmic ray proton spectrum, Astropart. Phys. 120 (2020) 102441, https://doi.org/10.1016/j.astropartphys.2020.102441.

[16] M. Aguilar, D. Aisa, B. Alpat, et al., AMS Collaboration, Observation of the identical rigidity dependence of He, C, and O cosmic rays at high rigidities by the alpha magnetic spectrometer on the international space station, Phys. Rev. Lett. 119 (2017) 251101, https://doi.org/10.1103/PhysRevLett.115.251101.

[17] D.E. Karmanov, I.M. Kovalev, I.A. Kudryashov, A.A. Kurganov, A.D. Panov, D.M. Podorozhny, A.N. Turundaevskiy, O.A. Vasiliev, Spectra of protons and alpha particles and their comparison in the NUCLEON experiment data, JETP Lett. 111 (2020) 363–367, https://doi.org/10.1134/S002136402007005X.

[18] S. Thoudam, J.R. Horandel, Anomaly in the cosmic-ray energy spectrum at GeV–TeV energies, J. Phys. Conf. Ser. 632 (2015) 012026, https://doi.org/10.1088/1742-6596/632/1/012026.

[19] Y. Ohira, K. Ioka, Cosmic-ray helium hardening, Astrophys. J. Lett. 729 (2011) L13, https://doi.org/10.1088/2041-8205/729/1/L13.

[20] V.I. Zatsepin, N.V. Sokolskaya, Three component model of cosmic ray spectra from 10 GeV to 100 PeV, Astron. Astrophys. 458 (2006) 1–5, https://doi.org/10.1051/0004-6361:20065108.

[21] Y.Y. Keum, P. Salati, The TeV-scale cosmic ray proton and helium spectra: contributions from the local sources, Pramana J. Phys. 86 (2016) 369–377, https://doi.org/10.1007/s12043-015-1157-7.

[22] N. Tomassetti, Origin of the proton-to-helium ratio anomaly in cosmic rays, Astrophys. J. Lett. 815 (2015) L1, https://doi.org/10.1088/2041-8205/815/1/L1.

[23] S. Thoudam, J.R. Horandel, Nearby supernova remnants and the cosmic ray spectral hardening at high energies, Mon. Not. R. Astron. Soc. 421 (2012) 1209–1214, https://doi.org/10.1111/j.1365-2966.2011.20385.x.

[24] S. Thoudam, J.R. Horandel, Revisiting the hardening of the cosmic ray energy spectrum at TeV energies, Mon. Not. R. Astron. Soc. 435 (2013) 2532–2542, https://doi.org/10.1093/mnras/stt1464.