symmetry

MDPI

Article

Cosmic Ray Antihelium Probe for the Origin of the Baryonic Matter in the Universe

Vladislav Golubkov [1,†], Maxim Khlopov [1,2,3,†], Anastasia Kirichenko [1,2,†], Alexandra Kravtsova [1,†], Andrey Mayorov [1,2,*,†] and Rustam Yulbarisov [1,†]

[1] Institute of Nuclear Physics and Engineering, National Research Nuclear University MEPhI, 115409 Moscow, Russia
[2] Research Institute of Physics, Southern Federal University, Stachki 194, 344090 Rostov on Don, Russia
[3] Virtual Institute of Astroparticle Physics, 75018 Paris, France
* Correspondence: agmayorov@mephi.ru
† These authors contributed equally to this work.

Abstract: Several candidates for antihelium events have been found in the AMS-02 experiment. They cannot be created by natural astrophysical sources and, if confirmed, imply the existence of antimatter stars in our galaxy. This immediately reduces the class of inflationary models with baryosynthesis to those that can provide the creation of an antimatter domain of surviving size together with the general baryon asymmetry of the Universe. To confront the future results of experimental searches for cosmic antihelium with predictions of this hypothesis, we develop numerical studies of the creation and propagation of antihelium flux from antimatter globular clusters in the Galaxy. This article presents the results of such a simulation: a function of the magnetic cut-off for the penetration of antihelium nuclei into the Galaxy disk and an estimate of the energy range in which the search and detection of antihelium is most optimal.

Keywords: antimatter; cosmic rays; globular clusters of anti-stars; search for antihelium; baryon asymmetry of the Universe

check for updates

Citation: Golubkov, V.; Khlopov, M.; Kirichenko, A.; Kravtsova, A.; Mayorov, A.; Yulbarisov, R. Cosmic Ray Antihelium Probe for the Origin of the Baryonic Matter in the Universe. *Symmetry* **2022**, *14*, 1953. https://doi.org/10.3390/sym14091953

Academic Editor: Davide Pagano

Received: 3 August 2022
Accepted: 14 September 2022
Published: 19 September 2022

1. Introduction

Antiparticles are of interest to science from the moment of their prediction and first discovery to the present day. The study of the properties of antiparticles is extremely valuable in various areas of modern physics, including the physics of elementary particles and fundamental interactions, cosmology and astrophysics, and cosmic ray physics.

The possibility of the existence of antimatter was proposed in 1898 by A. Schuster who, after the discovery of electron by J.J. Thompson, put forward a hypothesis about the symmetry of the world with respect to the electric charge, and hence the existence of a positively charged "partner" of electrons. About 30 years later, P. Dirac predicted the existence of antiparticles mathematically, as a result of solving the equations he derived. P. Dirac himself believed that antiparticles could be obtained in laboratories if the necessary energy was spent on the formation of a particle–antiparticle pair. However, in the laboratories of that time, the necessary approaches did not exist, and the energies used were insufficient.

Nevertheless, the first antiparticle was discovered soon, and this was facilitated by the growth of interest and active research on cosmic rays (CRs)—fluxes of charged particles coming from space to the upper boundary of the atmosphere. Discovered by V. Hess, they brought many fundamental discoveries. In 1932, K. Anderson studied cosmic radiation using a cloud chamber located in a magnetic field. After studying the ionization, the length of the trajectory, the deviation, and the radius of the trajectory of some events, he came to the conclusion that these particles have the mass of an electron, but a positive electric charge. Therefore, the positron was experimentally discovered [1].

It was not possible to discover the antiproton in CRs for a long time because of the rarity of such events and the high background. However, the active development of technical capabilities made it possible to build more powerful particle accelerators and, having calculated the energy necessary for the birth of an antiproton, in 1955, this antiparticle was discovered by a group of physicists in a laboratory in Berkeley (USA) [2]. A year later, the antineutron was also discovered there [3]. It became clear that antinuclei could be made from these antiparticles. In 1965, antideuterons were detected at the Brookhaven (USA) [4], and two years later, antinuclei of tritons and helium-3 were discovered at the accelerator in Serpukhov (USSR) [5]. Finally, in 2011, helium-4 antinuclei were detected in the STAR experiment at the RHIC accelerator in Brookhaven [6].

High-energy CRs contain the component of antiprotons, produced in pp-collision during CR propagation in the interstellar medium, but such a source cannot provide an observable amount of heavier cosmic antinuclei [7]. It may relate the origin of antihelium flux, accessible to the AMS-02 experiment, to the existence of macroscopic antimatter in a baryon asymmetrical universe, which reflects the specific physical conditions of generation of baryon excess [8,9]. The co-existence of macroscopic antimatter with matter of a baryon asymmetrical universe is possible only provided that the region of antibaryon excess is sufficiently large to survive after annihilation at its border and that effect of such annihilation is compatible with the observed gamma ray background [8–10]. The combination of these conditions leaves a narrow space of $10^3 M_\odot < M < 10^5 M_\odot$ for the total mass of macroscopic antimatter that can be present in our Galaxy. The indicated interval corresponds to the typical mass of globular clusters (GCs), and the hypothesis of antimatter GCs in our Galaxy was put forward as the probe for the mechanism of generation of the baryon asymmetry in the Universe [8]. Rough estimation of the expected flux of antinuclei from such a GC, in which antihelium is of special interest, predicts that it can be within the sensitivity of the AMS-02 experiment [8,9]. However, to confront the prediction of this hypothesis with the results of antihelium search at AMS-02, which are awaited in the coming years, more detailed analysis of propagation of antihelium in the Galaxy is needed, with the account of both diffusion in the galactic magnetic fields and inelastic interaction with interstellar medium. The first results of the development of this analysis are the subject of the present work.

2. Primordial Antimatter in the Galaxy

2.1. General Overview

Antimatter in the Universe could have three possible origins:

- Primordial antimatter is formed with ordinary matter in the early Universe and persists to the present day in macroscopic quantities in scenarios of inhomogeneous baryosynthesis;
- Secondary antimatter is created in the collisions of the nucleus in CRs with supernova shell remnants or interstellar gas;
- Antimatter can be also created from exotic sources, such as the decay/annihilation of particles of dark matter or from an evaporation of hypothetical primary black holes.

The problem of the existence of detectable amount of primordial antimatter is connected with the problem of baryon asymmetry of the Universe—the phenomenon that explains the presence of the excess of matter over antimatter. An explanation of the presence of such excess was firstly proposed by A. D. Sakharov [11] and V.A. Kuzmin [12], with the necessary conditions:

- Violation of conservation law of baryon charge in the early stages of evolution of the Universe;
- Violation of charge C- and combined CP-symmetry;
- Violation of local thermodynamic equilibrium in the early stages of evolution of the Universe.

It was shown in [13–16] that almost all existing mechanisms of baryosynthesis allow the existence of domains with an excess of antimatter, and this shows strong nonhomogeneity of baryosynthesis. The size of the domains is dependent on the specific mechanism: they can be various sizes, from small to the size of the present metagalaxy. The evolution of macroscopic matter and antimatter are the same, with the same temperature, density, and size. This can be predicted from the experiments on accelerators that synthesize antimatter, neglecting the small effect of CP-parity violation [17].

However, an object of antimatter with a size smaller than the size of a GC could not survive during the evolution of the Universe [18]. Such an antimater object would be annihilated with by surrounding matter before the formation of the Galaxy. Sizes greater than globular cluster are limited by fluxes of gamma ray radiation. Domains of antimater could be formed as GCs of antistars during the formation of the Galaxy and may have stayed there until now. The effect of the existence of a GC of antistars could be the registration of antinuclei or the creation of a limit on their flux in the BESS, PAMELA, and AMS-02 experiments [19,20].

2.2. GCs in the Galactic Halo

A GCs in the halo is an association of stars distributed within a sphere and rotating around the core of the Galaxy. These structures are very closely connected by gravity, which gives them a spherical shape and a relatively high density of stars at the center of the cluster. Today, we know about ∼150 GCs in the halo of the Milky Way galaxy [21].

Observations of GCs show that these stellar formations originate mainly in regions of effective star formation, where the interstellar medium is denser than normal star-forming regions. Currently, none of the known GCs show active star formation; they are free of gas and dust, and it is assumed that all the gas and dust were long ago either turned into stars or blown out of the cluster during the initial explosion of star formation. This is consistent with the opinion that GCs are the oldest objects in the Galaxy, with low metallicities [22,23], and were among the first clusters of stars.

The trajectories of the GCs are eccentric and inclined to the plane of the Galaxy. Orbiting the "outskirts" of a galaxy, GCs take several hundred million years to complete one orbit. Stars can reach a density of 100 to 1000 stars per cubic parsec in the center of a GC. This is different from the density of stars around our Sun, which is estimated at about 0.14 stars per cubic parsec [24].

3. Simulation of CR Propagation in Galaxy

The toolkit for simulation of a particle's propagation though the interstellar space consists of separate modules, each of which is responsible for a certain physical process or experimental data and models. They are organized in a chain and run as necessary during a simulation. The current version of the toolkit includes: a module for tracing charged particles in a magnetic field; a module describing the Galactic magnetic field; the interstellar medium definition module; a module for modeling the interaction of CR with matter; and a CR spectrum generator. These modules are discussed in more detail below.

3.1. Tracing Algorithm

The tracing algorithm is based on the Boris method [25,26], which is a particular case of applying the particle-in-cell, often used to solve Maxwell and hydrodynamic differential equations [27]. The method itself is simple and convenient for simulation of the motion of electrons and plasma ions in an electromagnetic field.

The motion of a particle m with a charge q in an electromagnetic field E, B is described by the equation:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v} \tag{1}$$

$$\frac{d(\gamma \boldsymbol{v})}{dt} = \frac{q}{m}(\boldsymbol{E} + [\boldsymbol{v} \times \boldsymbol{B}]) \tag{2}$$

where $\boldsymbol{x}$ and $\boldsymbol{v}$ are the coordinate and velocity vectors of the particle; $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ is the relativistic factor; t is time; c is speed of light.

After discrediting (1) and (2) over a finite time interval proposed by Boris, the equations are as follows:

$$\frac{\boldsymbol{x}^{i+1/2} - \boldsymbol{x}^{i-1/2}}{\Delta t} = \boldsymbol{v}^i \tag{3}$$

$$\frac{\gamma^{i+1}\boldsymbol{v}^{i+1} - \gamma^i\boldsymbol{v}^i}{\Delta t} = \frac{q}{m}\left(\boldsymbol{E}^{i+1/2} + \left[\frac{\gamma^{i+1}\boldsymbol{v}^{i+1} - \gamma^i\boldsymbol{v}^i}{2\bar{\gamma}^{i+1/2}} \times \boldsymbol{B}^{i+1/2}\right]\right) \tag{4}$$

where $\bar{\gamma}^{i+1/2}$ is the gamma factor taken at the middle of the time step:

$$\bar{\gamma}^{i+1/2} = \sqrt{1 + \left(\gamma^i v^i + \frac{q\Delta t}{2m}E^{i+1/2}\right)} = \sqrt{1 + \left(\gamma^{i+1}v^{i+1} - \frac{q\Delta t}{2m}E^{i+1/2}\right)} \tag{5}$$

The Buneman–Boris procedure, modified by Vay [28], makes it possible to solve the circuit without involving costly matrix calculations and preserving the phase volume [29].

The method is distinguished by a relatively short computation time in comparison with other algorithms (such as the Runge–Kutta fourth-sixth orders) with comparable accuracy [30].

3.2. Spectra Generator

The flux of galactic cosmic rays (GCR) is modeled with a spectrum generator, which plays out the particles and their characteristics, namely:

- Initial coordinates;
- Unit vector of initial velocity;
- Kinetic energy or rigidity;
- Particle type.

A Cartesian coordinate reference system is used with the point (0, 0, 0) located at the center of the Galaxy. The initial positions of particles are points lying on the surface sphere with some radius, which is one of the input parameters of the generator. Their uniform distribution over the surface of the sphere is played out. The center of the sphere can be shifted at any position, for example, to the center of some GC. The directions of the initial velocity vectors are simulated isotropically.

3.3. Source Function

The paper considers a one or few GCs of the Galaxy as a prototype of a GC of antistars, which could be a source of antinuclei, including antihelium (namely M4 GC).

We assume several possible mechanisms for antihelium nuclear injection into CRs from the GCs:

- **Stationary fluxes of antimatter from the surface of hypothetical antistars (energy scale $\sim$ MeV).**
  If the regions of propagation of antimatter from a GC's antistars cross the galactic disk, then the stellar wind can penetrate into the disk and further into the solar system. In this case, we consider stationary fluxes of antimatter in a GC. All stars lose part of their mass, and the amount of particles from a GC could be high. However, this case assumes poor energies, and we need a process of further acceleration of antiparticles to effectively overcome the solar modulation.
- **Flares on antistars (energy scale $\sim$ GeV).**
  As a result of flares on antistars in a GC, particles can receive high energy, forming the anti-nuclear component of GCRs. Antiparticles from hypothetical flares on antistars could receive high energy and become a component of CRs.
- **Explosions of hypothetical antisupernovae in a GC of antistars (energy scale $\sim 10^{15}$ eV).**

A supernova explosion is a process with the ejection of a major amount of particles with $\sim 10^{51}$ erg energies. Antisupernovae could be the main source of the antimatter component in GCRs, because supernovae are the primary source of CRs in general.

The study of the processes of formation of an antimatter domain, its evolution, and injection of particles into CRs in this work is based on the symmetry of the properties of matter and antimatter. Therefore, the power spectrum for the source coincides with the classical power spectrum for the source of CRs.

3.4. Interstellar Medium

The fluxes of antinucleons from hypothetical GCs of antistars in GCR should be calculated numerically. This requires knowledge about the structure and size of the Galaxy and the properties of interstellar matter. In order to take into account an influence of the medium on the propagation of particles in the Galaxy, it is necessary to use the matter density distribution function. For its construction, we took the analytical model of interstellar matter distribution in the Galaxy proposed in [31]. The input parameters are coordinates in the Galaxy and the output parameters are concentrations of ionized, atomic, and molecular hydrogen at this location.

The amount of matter is summed along the trajectory and when a certain threshold is reached, the simulation of inelastic reactions starts.

3.5. Galactic Magnetic Field

We use the well-known JF12 magnetic field model [32] with modifications [33] for the irregular component. The model describes the magnetic field of the Galaxy with good accuracy.

It represents the division of the total magnetic field into regular and irregular components of the magnetic field. The regular part is divided into three more fields, describing separately the arms, the halo field, and the X-shaped field. The irregular component is the sum of the isotropic and anisotropic components.

The anisotropic irregular field is related to the large-scale magnetic field by a scalar parameter and describes irregular fields in a spiral disk with halo components. The isotropic irregular field is independent of the large-scale model, and its disk and halo components are determined separately.

3.6. Inelastic Interactions

In the process of iterative calculation of the trajectory of the primary particle in interstellar space, the amount of matter passed in the interstellar medium is summed. When it exceeds some threshold, the program is responsible for modeling nuclear inelastic interactions. This program is based on the GEANT4 [34] software package and returns information about the interaction of the particle along the trajectory. The output includes information about new state of the primary particle and secondaries (if they exist), namely, their type, energy, and direction.

Tracing of secondaries can start automatically or manually, depending on the initial settings of the simulation.

As an example, we present the results of modeling the interactions of antihelium with matter in the interstellar medium. We have generated 10^7 antihelium nuclei with energies ranging from 10 GeV to 100 GeV, distributed according to the local interstellar spectrum of helium nuclei (spectral index is -2.7). They are transported through 6.5 g/cm^2 of matter (this number is taken as a characteristic amount of matter that a particle can accumulate when moving in the Galaxy); part of them ($\sim$46%) experience inelastic interaction and produce secondary particles. Figure 1 shows the number of secondary nuclei and gamma with energies greater than 0.1 GeV that are formed as a result of inelastic collisions of antihelium nuclei with protons of the interstellar medium.

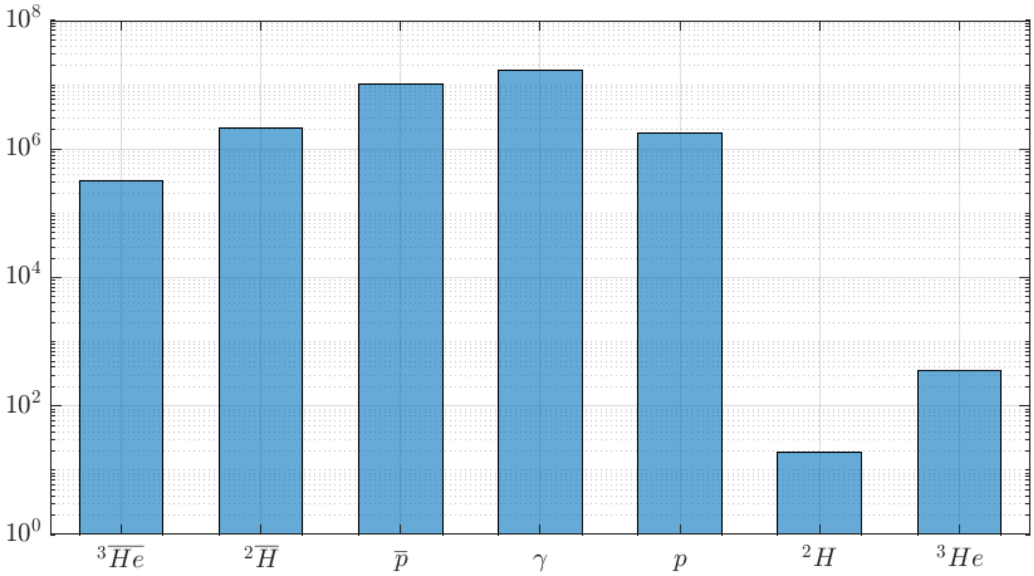

Figure 1. Distribution of secondary nuclei and gamma from the interaction of antihelium nuclei with the interstellar medium.

Figure 2 shows the gamma ray flux from the interaction of antihelium nuclei with matter in the interstellar medium. This is compared with a similar gamma ray flux from the interaction of CR protons. To obtain it, we simulated the same number of protons in the same energy range and then multiplied the resulting gamma spectrum by 10^8, based on the ratios of fluxes $\overline{He}/He < 10^{-7}$ and $He/p \sim 10^{-1}$.

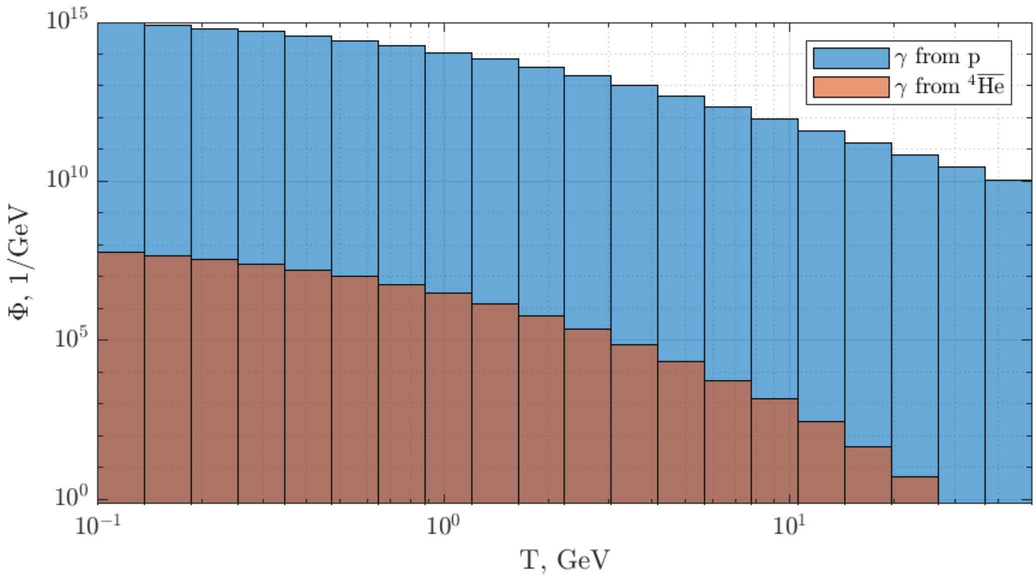

Figure 2. Spectrum of gamma rays from the interaction of protons (blue) and antihelium nuclei (brown) with the interstellar medium.

4. Results

We calculate the dependence of the fraction of events that penetrate into the galactic disk from the GCs as a function of particle energy. On the Figure 3, we show an example for the antihelium events originating from the M4 GC.

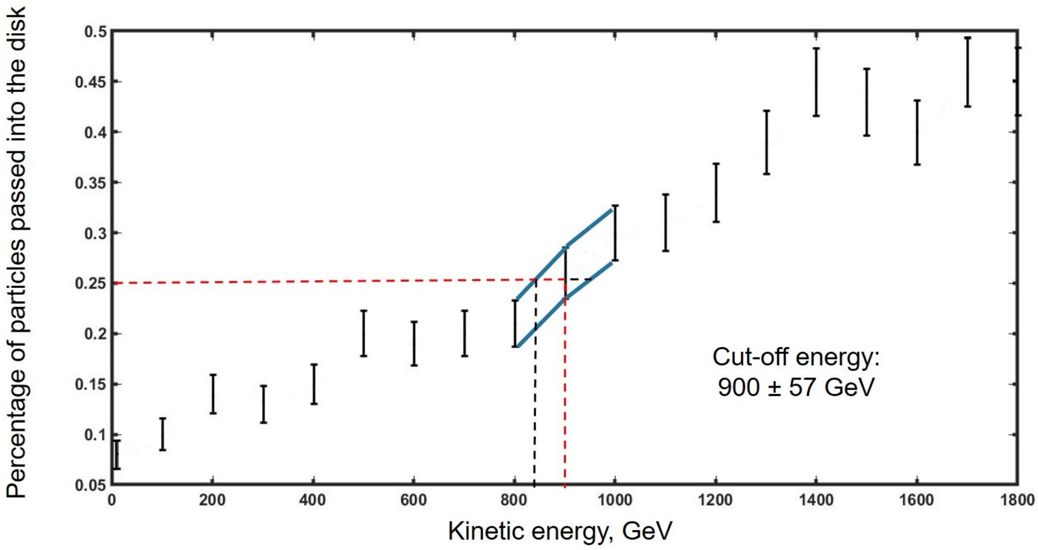

Figure 3. Dependence of the percentage of particles penetrating the galactic disk on their energy.

The graph defines the energies at which the smoothed curves cross the 0.25 level, i.e., the width at half height. Since the graph tends to ∼0.5 with increasing energy, this corresponds to the geometric factor of the plane. The energy that corresponds to the selected level is called the cutoff energy. Its value for the penetration of antihelium nuclei into the galactic disk in the magnetic field of the Galaxy is estimated as 900 ± 57 GeV.

This value sets a limit on the propagation of the initial antihelium flux into the disk region and indicates a strong suppression of the flux at energies below ∼1 TeV. On the other hand, as a zero approximation, the source function at high energies can be approximated by a classical power spectrum, decreasing with energy as $\propto E^{-2.7}$. The combination of these two factors makes it possible to qualitatively estimate the energy range in which the search for cosmic antihelium would be optimal for observation by the AMS-02 experiment. Figure 4 shows the result of multiplying the spectrum $E^{-2.7}$ and the resulting magnetic cut-off function.

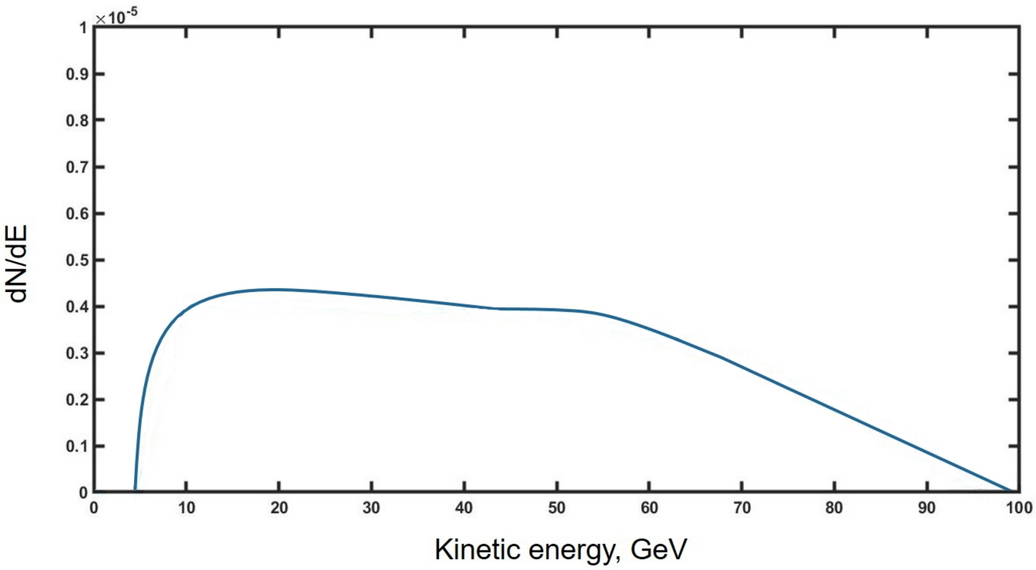

Figure 4. Qualitative prediction of the optimal energy range in searches for cosmic antihelium. The initial spectrum decreasing with energy as $\propto E^{-2.7}$ combined with the magnetic cut off leads to an energy range of 10–100 GeV, in which the expected antihelium flux would be optimal for searches in the AMS-02 experiment.

It can be seen from the figure that the optimal window for searching for antihelium is 10–100 GeV. We neglect the effect of solar modulation, since it has little effect on the flux at energies above 10 GeV.

5. Conclusions

With a very specific combination of parameters of inflation and baryosynthesis, generation of baryon excess in the early Universe may be strongly nonhomogeneous and lead to the existence of regions with antibaryon excess in a baryon asymmetrical universe (see e.g., [35] for recent review). Such regions can evolve in GCs of antimatter stars in our Galaxy, which can be the source of the antihelium component of CRs. This makes searches for cosmic antihelium a unique probe for the physical mechanism of the generation of baryon asymmetry in the inflationary Universe.

The article provides a general description of the approach used to calculate the flux of the antinuclei component of GCRs in the galactic disk in general, and in the vicinity of the solar system in particular. This is based on the hypothesis of the primary nature of antiparticles, the source of which can be a GC of antistars in the Galactic halo. The initial spectrum of particles is generated, trajectories in the magnetic field of the Galaxy are calculated, and inelastic interactions with matter in the interstellar medium are taken into account. We estimate the spectrum of helium antinuclei that can be formed in the vicinity of the solar system. The largest flux of these antinuclei is expected at energies from 10 to 100 GeV, i.e., in the energy range available for observations in the precision experiment AMS-02.

Further work is aimed at the precision simulation of fluxes of different antinuclei components in near-Earth orbit, including isotopes, the effects of solar modulation, and geomagnetic cutoff, which comes from different GCs of hypothetical antistars.

Author Contributions: The work was completely performed by the authors: Conceptualization and validation, M.K.; software, V.G., A.M. and R.Y.; draft preparation, A.K. (Anastasia Kirichenko) and A.M.; resources, A.K. (Alexandra Kravtsova); writing, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: The work by M.K., Anastasia Kirichenko and A.M. has been supported by the grant of the Russian Science Foundation No-18-12-00213-P https://rscf.ru/project/18-12-00213/ (accessed on 1 September 2022) and performed in Southern Federal University.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CR	Cosmic Ray
GCR	Galactic Cosmic Ray
GC	Globular Cluster

References

1. Anderson, C. The Positive Electro. *Phys. Rev.* **1933**, *43*, 491. [CrossRef]
2. Chamberlain, O.; Segrè, E.; Wiegand, C.; Ypsilantis, T. Observation of antiprotons. *Phys. Rev.* **1955**, *43*, 100.
3. Cork, B.; Lambertson, G.R.; Piccioni, O.; Wenzel, W.A. Antineutrons Produced from Antiprotons in Charge-Exchange Collisions. *Phys. Rev.* **1956**, *104*, 1193–1197. [CrossRef]
4. Dorfan, D.E.; Eades, J.; Lederman, L.M.; Lee, W.; Ting, C.C. Observation of antideuterons. *Phys. Rev. Lett.* **1965**, *14*, 1003–1006. [CrossRef]
5. Antipov, Y.M.; Denisov, S.P.; Donskov, S.V.; Gorin, Y.P.; Kachanov, V.A.; Khromov, V.P.; Kutyin, V.M.; Landsberg, L.G.; Lapshin, V.G.; Lebedev, A.A.; et al. Observation of antihelium-3. *Nucl. Phys. B* **1971**, *31*, 235–252. [CrossRef]
6. Agakishiev, H.; Aggarwal, M.M.; Ahammed, Z.; Alakhverdyants, A.V.; Alekseev, I.; Alford, J.; Anderson, B.D.; Anson, C.D.; Arkhipkin, D.; Averichevet, G.S.; et al. Observation of the antimatter helium-4 nucleus. *Nature* **2011**, *473*, 353–356.

7. Poulin, V.; Salati, P.; Cholis, I.; Kamionkowski, M.; Silk, J. Where do the AMS-02 anti-helium events come from? *Phys. Rev. D* **2019**, *99*, 023016. [CrossRef]
8. Khlopov, M.Y. An antimatter globular cluster in our Galaxy: A probe for the origin of matter. *Gravit. Cosmol.* **1998**, *4*, 69–72.
9. Belotsky, K.M.; Golubkov, Y.A.; Khlopov, M.Y.; Konoplich, R.V.; Sakharov, A.S. Anti-helium flux as a signature for antimatter globular clusters in our galaxy. *Phys. Atom. Nucl.* **2000**, *63*, 233–239. [CrossRef]
10. Golubkov, Y.; Khlopov, M. Anti-protons annihilation in the galaxy as a source of diffuse gamma background. *Phys. Atom. Nucl.* **2001**, *64*, 1821–1829. [CrossRef]
11. Kuzmin, V.A. CP violation and baryon asymmetry of the universe. *JETP Lett.* **1970**, *12*, 228.
12. Sakharov, A.D. Violation of CP-invariance, C-asymmetry and baryon asymmetry of the Universe. *JETP Lett.* **1967**, *5*, 32.
13. Chechetkin, V.M.; Sapozhnikov, M.G.; Khlopov, M.Y.; Zeldovich, Y.B. Astrophysical aspects of antiproton interaction with He (Antimatter in the Universe). *Phys. Lett.* **1982**, *118B*, 359–362.
14. Chechetkin, V.M.; Khlopov, M.Y.; Sapozhnikov, M.G. Antiproton interactions with light elements as a test of GUT cosmologies. *Riv. Nuovo C.* **1982**, *5*, 1–80. [CrossRef]
15. Dolgov, A.D.; Illarionov, A.F.; Kardashev, N.S.; Novikov, I.D. Cosmological model of a baryon island. *Sov. Phys. JETP* **1988**, *67*, 1517–1524.
16. Khlopov, M.Y.; Rubin, S.G.; Sakharov, A.S. Possible Origin of Antimatter Regions in the Baryon Dominated Universe. *Phys. Rev. D* **2000**, *62*, 083505. [CrossRef]
17. Charlton, M.; Eriksson, S.; Shore, G.M. Fundamental Physics in Antihydrogen Experiments. *arXiv* **2020**, arXiv:2002.09348.
18. Khlopov, M.Y.; Konoplich, R.V.; Mignani, R.; Rubin, S.G.; Sakharov, A.S. Evolution and observational signature of diffused antiworld. *Astropart. Phys.* **2000**, *12*, 367–372. [CrossRef]
19. Abe, K.; Fuke, H.; Haino, S.; Hams, T.; Hasegawa, M.; Horikoshi, A.; Itazaki, A.; Kim, K.C.; Kumazawa, T.; Kusumoto, A.; et al. Search for Antihelium with the BESS-Polar Spectrometer. *Phys. Rev. Lett.* **2012**, *108*, 131301. [CrossRef]
20. Mayorov, A.G.; Galper, A.M.; Adriani, O.; Bazilevskaya, G.A.; Barbarino, G.; Bellotti, R.; Boezio, M.; Bogomolov, E.A.; Bonvicini, V.; Bongi, M.; et al. Upper limit on the antihelium flux in primary cosmic rays. *JETP Lett.* **2011**, *93*, 628–631. [CrossRef]
21. Harris, W.E. A Catalog of Parameters for Globular Clusters in the Milky Way. *Astron. J.* **1996**, *112*, 1487. Available online: http://gclusters.altervista.org/ (accessed on 1 September 2022). [CrossRef]
22. A Guide to GLOBULAR CLUSTERS. Available online: https://www.astro.keele.ac.uk/workx/globulars/globulars.html (accessed on 1 September 2022).
23. Kalirai, J.S.; Richer, H.B. Star clusters as laboratories for stellar and dynamical evolution. *R. Soc. Publ.* **2009**, *368*, 2010. [CrossRef] [PubMed]
24. Paul, M. *Star Clusters. Encyclopedia of Astronomy and Astrophysics*; CRC Press: Boca Ration, FL, USA, 2001.
25. Golubkov, V.S.; Mayorov, A.G. Software for Numerical Calculations of Particle Trajectories in the Earth's Magnetosphere and Its Use in Processing PAMELA Experimental Data. *Bull. Russ. Acad. Sci. Phys.* **2021**, *85*, 383–385. [CrossRef]
26. Boris, J. *The Acceleration Calculation from a Scalar Potential*; MATT-152; Plasma Physics Laboratory, Princeton University: Princeton, NJ, USA, 1970.
27. Pukhov, A. Particle-In-Cell Codes for Plasma-based Particle Acceleration. *arXiv* **2016**, arXiv:1510.01071. https://doi.org/10.5170/CERN-2016-001.181.
28. Vay, J.-L. Simulation of beams or plasmas crossing at relativistic velocity. *Phys. Plasmas* **2008**, *15*, 056701. 1.2837054. [CrossRef]
29. Qin, H.; Zhang, S.; Xiao, J.; Liu, J.; Sun, Y.; Tang, W.M. Why is Boris algorithm so good? *Phys. Plasmas* **2013**, *20*, 084503. [CrossRef]
30. Mao, H.; Wirz, R. Comparison of Charged Particle Tracking Methods for Non-Uniform Magnetic Fields. In Proceedings of the 42nd AIAA Plasmadynamics and Lasers Conference, Honolulu, HI, USA, 27–30 June 2011.
31. Strong, A.W.; Moskalenko, I.V. Secondary antiprotons and propagation of cosmic rays in the galaxy and heliosphere. *Astrophys. J.* **2001**, *564*, 280–296.
32. Jansson, R.; Farrar, G.R. A New Model of the Galactic Magnetic Field. *Astrophys. J.* **2012**, *757*, 14. [CrossRef]
33. Beck, M.C.; Beck, A.M.; Strong, A.W. New constraints on modelling the random magnetic field of the MW. *J. Cosmol. Astropart. Phys.* **2016**, *2016*, 056. [CrossRef]
34. Agostinelli, S.; Allison, J.; Amako, K.; Apostolakis, J.; Araujo, H.; Arce, P.; Asai, M.; Axen, D.; Banerjee, S.; Barrand, G.; et al. Geant4—A simulation toolkit. *Nucl. Instrum. Methods Phys. Res. Sect. A* **2003**, *506*, 250–303. [CrossRef]
35. Khlopov, M. Cosmoparticle physics of Dark Universe. *Symmetry* **2022**, *14*, 112. [CrossRef]