AMS-Shuttle test for antimatter stars in our Galaxy *

K.M. Belotsky,\textsuperscript{a,b} Yu.A. Golubkov,\textsuperscript{a,d,†} M.Yu.Khlopov,\textsuperscript{a,b,c,‡} R.V. Konoplich,\textsuperscript{a,c,§} S.G. Rubin\textsuperscript{a,c,¶} and A.S.Sakharov\textsuperscript{a,c,∥}

\textsuperscript{a}Center for CosmoParticle Physics "Cosmion", Miusskaya Pl., 4, 125047 Moscow, Russia
\textsuperscript{b}Institute of Applied Mathematics, Miusskaya Pl., 4, 125047 Moscow, Russia
\textsuperscript{c}Moscow State Engineering Physics Institute (Technical University), Kashirskoe Sh., 31, 115409 Moscow, Russia
\textsuperscript{d}Moscow State University, Institute of Nuclear Physics, Vorobjevy Gory, 119899 Moscow, Russia

Abstract

The AMS–Shuttle experiment is shown to be sensitive to test the hypothesis on the existence of antimatter globular cluster in our Galaxy. The hypothesis follows from the analysis of possible tests for the mechanisms of baryosynthesis and uses antimatter domains in the matter dominated Universe as the probe for the physics underlying the origin of the matter. The total mass for the antimatter objects in our Galaxy is fixed from the below by the condition of antimatter domain survival in the matter dominated Universe and from above by the observed gamma ray flux. For this mass interval the expected fluxes of antinuclei can lead to up to ten antihelium events in the AMS-Shuttle experiment.

The modern big bang theory is based on inflationary models with baryosynthesis and nonbaryonic dark matter. The physical basis for all the three phenomena lies outside the experimentally proven theory of elementary particles. This basis follows from the extensions of the standard model. Particle theory considers such extensions as aesthetical appealing (grand unification), necessary to remove internal inconsistencies in the standard model (supersymmetry, axion) or simply theoretically possible (neutrino mass, lepton and baryon number violation). Most of these theoretical ideas can not be tested directly and particle theory considers cosmological relevance as the important component of their indirect test. In the absence of direct methods of study one

\footnote{*Invited talk on the 3d Int. Conf. on Cosmoparticle Physics "COSMION-97". Russia, Moscow, December 8–14, 1997.}
\footnote{†e-mail: golubkov@elma01.npi.msu.su}
\footnote{‡e-mail: mkhlopov@orc.ru}
\footnote{¶e-mail: sgrubin@orc.ru}
\footnote{∥e-mail: sakhas@landau.ac.ru}
should analyse the set of indirect effects, which specify the models of particles and cosmology. AMS experiment Ref. [1] turns to be important tool in such analysis. The expected progress in the measurement of cosmic rays fluxes and gamma background and in the search for antinuclei and exotic charged particles make this experiment important source of information on the possible cosmological effects of particle theory. Its operation on Alpha Station will shed light on WIMP annihilation in the Galaxy, on primordial black hole evaporation, on possible existence of exotic charged particles and many other important clues on the hidden parameters of the modern cosmology, following from the hidden sector of particle theory. The first step in this direction may be done on the base of AMS-Shuttle experiment.

The COSMION-ETHZ programme assumes joint systematic study of AMS experiment as the basement for experimental cosmoparticle physics. The specifics of AMS-Shuttle experimental programme puts stringent restriction on the possible choice of cosmic signatures for the new physics. At this stage no clear detection of positrons, gamma rays or multi GeV antiprotons will be possible. It makes us to reduce the analysis to the antinuclear signal as the profound signature of new physics and cosmology.

The generally accepted motivation for baryon asymmetric Universe is the observed absence of the macroscopic amounts of antimatter up to the scales of clusters of galaxies. According to the Big Bang theory baryon symmetric homogeneous mixture of matter and antimatter can not survive after local annihilation, taking place at the first millisecond of cosmological evolution. Spatial separation of matter and antimatter can provide their survival in the baryon symmetric Universe but should satisfy severe constraints on the effects of annihilation at the border of domains. The most recent analysis finds that the size of domains should be only few times smaller than the modern cosmological horizon to escape the contradictions with the observed gamma ray background Ref. [2]. In baryon asymmetric Universe the big bang theory predicts the exponentially small fraction of primordial antimatter and practically excludes the existence of primordial antinuclei. The secondary antiprotons may appear as a result of cosmic ray interaction with the matter, when galaxies are formed. In such interaction it is impossible to produce any sizeable amount of secondary antinuclei. Thus non exponentially small amount of antiprotons in the Universe in the period from $10^{-3}$ s to $10^{16}$ s and antinuclei in the modern Universe are the profound signature for new phenomena, related to the cosmological consequences of particle theory. The inhomogeneity of baryon excess generation and antibaryon excess generation as the reflection of this inhomogeneity represents one of the most important example of such consequences. It turned out Refs. [3, 4, 5, 6], that practically all the existing mechanisms of baryogenesis can lead to generation of antibaryon excess in some places, the baryon excess, averaged over the whole space, being positive. So domains of antimatter in baryon asymmetric Universe provide a probe for the physical mechanism of the matter generation.

The original Sakharov’s scenario of baryosynthesis Ref. [7] has found physical grounds in GUT models. It assumes CP violating effects in out–of–equilibrium B–non–conserving processes, which generate baryon excess proportional to CP violating phase. If sign and magnitude of this phase varies in space, the same out–of–equilibrium B–non–conserving processes, leading to baryon asymmetry, result in $B < 0$ in the regions, where the phase is negative. The same argument is appropriate for the models of baryosynthesis, based on electroweak baryon charge nonconservation at high temperatures as well as on its combination with lepton number violation processes, related
to the physics of Majorana mass of neutrino. In all these approaches to baryogenesis independent on the physical nature of B-nonconservation the inhomogeneity of baryon excess and generation of antibaryon excess is determined by the spatial dependence of CP violating phase.

Spatial dependence of this phase is predicted in models of spontaneous CP violation, modified to escape the supermassive domain wall problem (see Refs. [3, 4, 8] and Refs. therein).

In this type of models CP violating phase acquires discrete values $\phi_+ = \phi_0 + \phi_{sp}$ and $\phi_- = \phi_0 - \phi_{sp}$, where $\phi_0$ and $\phi_{sp}$ are, respectively, constant and spontaneously broken CP phase, and antibaryon domains appear in the regions with $\phi_- < 0$, provided that $\phi_{sp} > \phi_0$.

In models, where CP violating phase is associated with the amplitude of invisible axion field, spatially–variable phase changes $\phi_{vr}$ continuously from $-\pi$ to $+\pi$. The amplitude of axion field plays the role of $\phi_{vr}$ in the period starting from Peccei–Quinn symmetry breaking phase transition until the axion mass is switched on at $T \approx 1$ GeV. The net phase changes continuously and if baryosynthesis takes place in the considered period axion induced baryosynthesis implies continuous spatial variation of the baryon excess given by Ref. [8]

$$b(x) = A + b \sin(\theta(x)) . \quad (1)$$

Here $A$ is the baryon excess induced by constant CP-violating phase, which provides the global baryon asymmetry of the Universe and $b$ is the measure of axion induced asymmetry. If $b > A$, antibaryon excess is generated along the direction $\theta = 3\pi/2$. The stronger is the inequality $b > A$, the larger interval of $\theta$ around the semisurface $\theta = 3\pi/2$ provides generation of antibaryon excess Ref. [8]. In the case $b - A = \delta \ll A$ the antibaryon excess is proportional to $\delta^2$ and the relative volume occupied by it is proportional to $\delta$.

The axion induced antibaryon excess forms the Brownian structure looking like an infinite ribbon along the infinite axion string (see Ref. [9]). The minimal width of the ribbon is of the order of horizon in the period of baryosynthesis and is equal to $m_{Pl}/T_{BS}^2$ at $T \approx T_{BS}$. At $T < T_{BS}$ this size experiences red shift and is equal to

$$l_h(T) \approx \frac{m_{Pl}}{T_{BS}T} \quad (2)$$

This structure is smoothed by the annihilation at the border of matter and antimatter domains. When the antibaryon diffusion scale exceeds $l_h(T)$ the infinite structure decays on separated domains.

The size and amount of antimatter in domains, generated as the result of local baryon–non–conserving out–of–equilibrium processes, is related to the parameters of models of CP violation and/or invisible axion (see Refs. [3, 5, 10]). SUSY GUT motivated mechanisms of baryon asymmetry imply flatness of superpotential relative to existence of squark condensate. Such a condensate, being formed with $B > 0$, induces baryon asymmetry, after squarks decay on quarks and gluinos. The mechanism doesn’t fix the value and sign of $B$ in the condensate, opening the possibilities for inhomogeneous baryon charge distribution and antibaryon domains Refs. [4, 8]. The size and amount of antimatter in such domains is determined by the initial distribution of squark condensate.

Thus the antimatter domains in the baryon asymmetric Universe are related to practically all the mechanisms of baryosynthesis, and serve as the probe for the mechanisms of CP violation and
primordial baryon charge inhomogeneity. The size of domains depends on the parameters of these mechanisms Refs. [3, 4, 10].

General parameters of the averaged effect of the domain structure are the relative amount of antimatter \( \omega_a = \rho_a / \rho_{\text{crit}} \), where \( \rho_a \) is the averaged over domain density of antimatter and \( \rho_{\text{crit}} \) is the critical density, and the mean size of domains (the characteristic scale in their distribution on sizes) or for small domain sizes the time scale of their annihilation with the matter.

To compare the effect of antimatter domain annihilation with the observational data one should introduce the relative amount of annihilated antimatter relative to the total amount of matter. One may easily find (see for details Ref. [11]) that this ratio \( r \) is given by:

\[
    r \approx \frac{bf(l \leq l_a)}{A},
\]

where \( l_a \) is the maximal size of domains annihilated by the considered period and \( f(l) \) is the volume fraction of domains with the size \( l \). In the case of discrete spontaneous CP violation discussed above \( b = A \).

One of the features expected for antimatter domains in baryon asymmetrical Universe is the possibility of diffused antiverse. It corresponds to the antibaryon matter density much smaller, than the baryon matter density. One of the interesting consequences of diffused antiverse hypothesis is the possibility of unusual light antimatter abundance. At antibaryon densities, much smaller, than the baryon density, anti–deuterium and anti–helium–3 may be more abundant, than antihelium–4. However diffused antiverse with very low antibaryon density can not lead to formation of antimatter objects and gamma ray search for annihilation in diffused antimatter clouds is the most promising in this case. The possibility of antibaryon density in domains comparable or even higher than the mean baryon density is much more interesting for AMS-Shuttle programme in cosmoparticle physics.

As it was recently shown Ref. [8], in the case when axion induced CP violation dominates in the process of Baryosynthesis, the antimatter density within the surviving domains should be larger than the mean baryon density. On the other hand the SUSY GUT squark condensate may induce large scale modulation of this distribution. Since both axion and SUSY are considered as the necessary extensions of the standard model one should consider at least the combination of axion– and squark–condesate– induced inhomogeneous baryosynthesis as the minimally realistic case. With the account for the other possible mechanisms for inhomogeneous baryosynthesis, predicted on the base of various and generally independent extensions of the standard model, the general analysis of possible domain distributions is rather complicated. Fortunately, the test for the possibility of the existence of antistars in our Galaxy, offered in Ref. [8], turns to be practically model independent and as we show here may be accessible for AMS-Shuttle Experiment. Let us assume some distribution of antimatter domains, which satisfies the constraints on antimatter annihilation in the early Universe. Domains, surviving after such annihilation, should have the mass exceeding

\[
    M_{\text{min}} \approx \left( \frac{b}{A} \right) \rho_b l_a^3,
\]

where \( \rho_b \) is the mean cosmological baryon density. The mass fraction \( f \) of such domains relative to total baryon mass is strongly model dependent. Note that since the diffusion to the border of antimatter domain is determined on RD stage by the radiation friction, the surviving scale fixes
the size of the surviving domain. On the other hand the constraints on the effects of annihilation put the upper limit on the mass of annihilated antimatter.

The modern antimatter domain distribution should be cut at masses given by the Eq. (4) due to annihilation of smaller domains and it is the general feature of any model of antibaryosynthesis in baryon asymmetrical Universe. The specific form of the domain distribution is model dependent. At the scales smaller than those given by Eq. (4) the spectrum should satisfy the constraints on the relative amount of annihilating antimatter. Provided these constraints are satisfied, one may consider the conditions for antimatter objects formation. One should take into account that the estimation of the annihilation scale after recombination (see Ref. [11]) gives for this scale the value close the Jeans mass in the neutral baryon gas after recombination. So the development of gravitational instability may take place in antimatter domains resulting in the formation of astronomical objects of antimatter.

Formation of antimatter object has the time scale being of the order of \( t_f \approx (\pi G \rho)^{-1/2} \). The object is formed, provided that this time scale is smaller than the time scale of its collision with the matter clouds. The latter is the smallest in the beginning of the object formation, when the clouds forming objects have large size.

Note that the isolated domain can not form astronomical object smaller than globular cluster Ref. [8]. The isolated anti–star can not be formed in matter surrounding since its formation implies the development of thermal instability, during which cold clouds are pressed by hot gas. Pressure of the hot matter gas on the antimatter cloud is accompanied by the annihilation of antimatter. Thus anti–stars can be formed in the antimatter surrounding only, what may take place when such surrounding has at least the scale of globular cluster.

One should expect to find antimatter objects among the oldest population of the Galaxy Ref. [8]. It should be in the halo, since owing to strong annihilation of antimatter and matter gas the formation of secondary antimatter objects in the disk component of our Galaxy is impossible. So in the estimation of antimatter effects we can use the data on the spherical component of our Galaxy as well as the analogy with the properties of the old population stars in globular clusters and elliptical galaxies.

In the spherical component of our Galaxy the antimatter globular cluster should move with high velocity (what follows from the velocity dispersion in halo, \( v \approx 150 \text{ km/s} \)) through the matter gas with very low number density \( n \approx 3 \cdot 10^{-4} \text{ cm}^{-3} \). Owing to small density of antimatter gas effects of annihilation with the matter gas within the antimatter globular cluster are small. These effects, however, deserve special analysis for future search for antimatter cluster as the gamma source.

The integral effects of antimatter cluster may be estimated by the analysis of antimatter pollution of the Galaxy by the globular cluster of antistars.

There are two main sources of such pollution: the antistellar wind (the mass flow from antistars) and the antimatter Supernova explosions. The first source provides the stationary in-flow of antimatter particles with the velocity \( 10^7 \div 10^8 \text{ cm/s} \) to the Galaxy. From the analogy with the elliptical galaxies, for which one has the mass loss \( 10^{-12}M_\odot \) per Solar mass per year, one can estimate the stationary admixture of antimatter gas in the Galaxy and the contribution of its annihilation into the gamma ray background. The estimation strongly depends on the distribution of magnetic fields in the Galaxy, trapping charged antiparticles. Crude estimation
of the gamma flux from the annihilation of this antimatter flux is compatible with the observed gamma background for the total mass of antimatter cluster less than $10^5 M_\odot$. This estimation puts upper limit on the total mass fraction of antimatter clusters in our Galaxy. Their integral effect should not contradict to the observed gamma ray background.

The uncertainty in the distribution of magnetic fields causes even more problems in the reliable estimation of the expected flux of antinuclei in cosmic rays. It is also accomplished by the uncertainty in the mechanism of cosmic ray acceleration. The relative contribution of disc and halo particles into the cosmic ray spectrum is also unknown. To get some feeling of the expected effect we may assume that the mechanisms of acceleration of matter and antimatter cosmic rays are similar and that the contribution of antinuclei into the cosmic ray fluxes is proportional to the mass ratio of globular cluster and Galaxy. Putting together the lower limit on the mass of the antimatter globular cluster from the condition of survival of antimatter domain and the upper limit on this mass following from the observed gamma ray background one obtains Ref. [8] the expected flux of antihelium nuclei in the cosmic rays with the energy exceeding 0.5 GeV/nucleon to be $10^{-8} \div 10^{-6}$ of helium nuclei observed in the cosmic rays. The results of numerical calculation of the expected antihelium flux in Ref. [11] together with the expected sensitivity of AMS experiment Ref. [1] are given in Fig. 1.

![Figure 1: Ratios of fluxes $^4\bar{He}/^4He$ (dashed) and $^3\bar{He}/^4He$ (dot–dashed). Two upper curves correspond to the case of the maximal possible mass of antimatter globular cluster $M_{\text{max}} = 10^5 M_\odot$ and the two lower curves to the case of the minimal possible mass of such cluster $M_{\text{min}} = 10^3 M_\odot$. The results of calculations are compared with the expected sensitivity of AMS experiment Ref. [1] (solid lines).](image)

Such estimation assumes that annihilation does not influence the antinuclei composition of cosmic rays, which fact may take place if the cosmic ray antinuclei are initially relativistic. If the
process of acceleration takes place outside the antimatter globular cluster one should take into account the Coulomb effects in the annihilation cross section of non relativistic antinuclei, which may lead to suppression of their expected flux.

On the other side the antinuclei annihilation invokes new factor in the problem of their acceleration, which is evidently absent in the case of cosmic ray nuclei. This factor may play very important role in the account for antimatter Supernovae as the possible source of cosmic ray antinuclei. From the analogy with elliptical galaxies one may expect Ref. [8] that in the antimatter globular cluster Supernovae of the I type should explode with the frequency about $2 \cdot 10^{-13}/M_\odot$ per year. On the base of theoretical models and observational data on SNI (cf. Ref. [12]) one expects in such explosion the expansion of a shell with the mass of about $1.4M_\odot$ and velocity distribution up to $2 \cdot 10^9$ cm/s. The internal layers with the velocity $v < 8 \cdot 10^8$ cm/s contain anti-iron $^{56}Fe$ and the outer layers with higher velocity contain lighter elements such as anti-calcium or anti-silicon. Another important property of Supernovae of the I type is the absence of hydrogen lines in their spectra. Theoretically it is explained as the absence of hydrogen mantle in Presupernova. In the case of antimatter Supernova it may lead to strong relative enhancement of antinuclei relatively to the antiprotons in the cosmic rays. Note that similar effect is suppressed in the nuclear component of cosmic rays, since Supernovae of the II type are also related to the matter cosmic ray origin in our Galaxy, in which massive hydrogen mantles (with the mass up to few solar masses) are accelerated.

In the contrast with the ordinary Supernova the expanding antimatter shell is not decelerated owing to acquiring the interstellar matter gas and is not stopped by its pressure but annihilate with it Ref. [8]. In the result of annihilation with hydrogen, of which the matter gas is dominantly composed, semi-relativistic antinuclei fragments are produced. The reliable analysis of such cascade of antinuclei annihilation may be based on the theoretical models and experimental data on antiproton nucleus interaction. This programme is now under way. The important qualitative result is the possible nontrivial contribution into the fluxes of cosmic ray antinuclei with $Z \leq 14$ and the enhancement of antihelium flux.

Another important qualitative effect of annihilation in the expected composition of cosmic ray antinuclei is the possible presence of significant fraction of anti–helium–3. One can expect Ref. [8] this fraction to be of the order of 0.2 of the expected flux of anti–helium–4. This estimation follows from the experimental data on antiproton–helium interaction measured in the experiment PS 179 at LEAR CERN Ref. [13].

The estimations of Ref. [8] assumed stationary in-flow of antimatter in the cosmic rays. In case Supernovae play the dominant role in the cosmic ray origin the in–flow is defined by their frequency. One may find from Ref. [8] that the interval of possible masses of antimatter cluster $(3 \cdot 10^3 \div 10^5)M_\odot$ gives the time scale of antimatter in–flow $1.6 \cdot 10^9 \div 5 \cdot 10^7$ years, which value exceeds the generally estimated life time of cosmic rays in the Galaxy. The succession of antinuclear annihilations may result in this case in the dominant contribution of antihelium–3 into the expected antinuclear flux.

To conclude, with all the reservations mentioned above on the base of the hypothesis on antimatter globular cluster in our Galaxy one may predict at the level of the expected 600 antiprotons up to ten antihelium events in the AMS–Shuttle experiment. Their detection will be exciting indication favouring this hypothesis. Even the upper limit on antihelium flux will lead to important...
constraint on the fundamental parameters of particle theory and cosmology to be discussed in our successive publications.

Acknowledgments
The Russian side of COSMION–ETHZ collaboration expresses its gratitude to ETHZ for the permanent support of studies undertaken in the framework of International projects ”Astrodamus” and ” COSMION– ETHZ”.

References

[1] H.Hofer, F.Pauss, *Gravitation & Cosmology* 4, Supplement, Cosmoparticle Physics pt.1, 56 (1998); J. Ulbricht, *This volume*

[2] A.G.Cohen, A.De Rujula, S.L.Glashow, *Astrophys. J.* 495, 539 (1997)

[3] V.M.Chechetkin, M.Yu.Khlopov and M.G.Sapozhnikov, *Rivista Nuovo Cim.* 5, 1 (1982)

[4] V.M.Chechetkin, M.Yu.Khlopov, M.G.Sapozhnikov and Ya.B.Zeldovich, *Phys. Lett.* 118B, 329 (1982)

[5] M.Yu.Khlopov, *in: Cosmion’94*, Proc. 1 International conference on cosmoparticle physics Eds. M.Yu.Khlopov, M.E.Prokhorov, A.A.Starobinsky, J.Tran Thanh Van, Editions Frontieres, 67 (1996)

[6] A.D.Dolgov, *Phys. Rep.* 222, 311 (1992); A.D.Dolgov, J.Silk, *Phys. Rev.* 47D, 4244 (1993)

[7] A.D.Sakharov, *JETP Lett.* 5, 17 (1967)

[8] M.Yu.Khlopov, *Gravitation & Cosmology* 4, 69 (1998)

[9] M.Yu.Khlopov, A.S.Sakharov, *Phys. Atom. Nucl.* 57, 485 (1994); M.Yu.Khlopov, A.S.Sakharov, D.D.Sokoloff, [hep–ph/9812286](https://arxiv.org/abs/hep-ph/9812286)

[10] F.W.Steker, *Nucl. Phys.* 252B, 25 (1985)

[11] K.M.Belotsky et al, *INP MSU Preprint 98-31/532* (1998); [astro-ph/9807027](https://arxiv.org/abs/astro-ph/9807027)

[12] N.N.Chugai, S.I.Blinnikov, T.A.Lozinskaya, *Preprint ITEP– 43*, 1986.

[13] F.Balestra et al, *JINR Rapid Comm.* 6, 11 (1985)