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ANTIPROTON INTERACTION WITH ^{4}He AS A TEST OF GUT COSMOLOGY

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The following GUT predictions are well known: the decay of proton, the $n-\bar{n}$ oscillation, the value of sin θ_W, the baryon asymmetry of the Universe, etc. We suggest a new possibility of checking some GUT models on the basis of, at first,the analysis of their cosmological consequences and, secondly, on the experimental study of low energy $\bar{p}\,{}^4He$ interaction. We intend to show in this note, that the investigation of $\bar{p}\,{}^4He$ annihilation may provide some useful information not only for nuclear physics, but also for checking the GUT cosmology owing to the restrictions on the parameters of GUT models.

The obsetvational data of γ-astronomy lead to the conclusion that, at present, there is no antimatter on a macroscopic scale. On the other hand, modern cosmology predicts that antimatter inevitably existed in the very early Universe (at $t \ll 10^{-3}$ s from the beginning) and the number of antibaryons was comparable with the number of protons ($n_B \approx n_{\bar{B}} \approx n_\gamma$, where n_γ is the number of photons). However, the subsequent annihilation resulted in the practically full disappearance of the antibaryons and only the small excess of baryons should have been survived and just this excess is observed now

$$n_B / n_\gamma \approx 10^{-8 \pm 2} \quad .$$

But there is some GUT models, with spontaneous CP-breaking, which predicts the generation of the baryon excess in one place and the generation of the antibaryon excess in another place. That leads to formation of matter-antimatter domains in the Universe. The antimatter domains may survive for rather long time.

There is another interesting possibility for the late annihilation (at $t \gg 10^{-3}$s) in the Universe. Some GUTs predict the existence of superheavy ($M \geq 10^{11}$ GeV), metastable ($\tau \geq 10^{-18}$ s) neutral fermions. As is shown in /1/, the presence of these superheavy particles in the early Universe inevitably leads to formation of primordial black holes (PBH). The evapora[illegible] PBH results in creation of baryon-antybaryon

The common important feature of all sources of antimatter, predicted by GUT, is the following: the annihilation proceeds only in the limited time interval. If the annihilation took place after the big-bang nucleosynthesis ($t > 10^3$s), then the interaction of $\bar{p}$ with ^{4}He leads to creation of neutrons and light nuclei (d, ^{3}H, ^{3}He). Therefore, the presence of $\bar{p}$ in the Universe after $t > 10^3$s could have influenced abundance of light elements. One can obtain the restrictions on the amount of antimatter (and, consequently, on the parameters of GUT models which determine the sources of antimatter) knowing cross sections of $\bar{p}\,^4$He annihilation and supposing that the annihilation in the early Universe could not create more D and ^{3}He than their presently observed abundance.

2. Let us now consider what restrictions on the relative average amount of annihilated antimatter in the early Universe $R = n_{\bar{B}}/n_B$ can be obtained from the study of $\bar{p}\,^4$He annihilation.

After the big-bang nucleosynthesis, the $\bar{p}\,^4$He annihilation leads to disintegration of ^{4}He resulting in the creation of free neutrons and nuclei-fragments (d, ^{3}H, ^{3}He). As was shown in /2/ free neutrons, being created during the period $10^3 \le t \le t_D$ ($t_D = 4.5 \cdot 10^6\, \Omega_b^{2/3}$ (s) , $\Omega_b = n_B/n_C$ and n_C is the critical density), succeed, before their decay, in combining with protons in the reaction $n + p \rightarrow d + \gamma$ and forming deuterium. (Neutrons may form deuterium in this reaction earlier than 10^3 s also, however, all the deuterium produced will be burned in successive thermonuclear transformations). When $t > t_D$ free neutrons produced in annihilation do not succed in forming an appreciable quantity of deuterium. The additional amount of D being created due to $\bar{p}\,^4$He annihilation is

$$\Delta n_D \begin{cases} = n_{He} \cdot (f_D + f_n) \cdot R & 10^3 \le t \le t_D \qquad (1) \\ = n_{He} \cdot f_D \cdot R & t > t_D \qquad (2) \end{cases}$$

For ^{3}He it is, correspondingly,

$$\Delta n_{^3He} = n_{He} \cdot f_{^3He} \cdot R. \qquad (3)$$

The n_{He} in (1)-(3) is the concentration of ^{4}He; f_n, f_D and $f_{^3He}$ are the average numbers of n, D and ^{3}He created in the annihilation. If we assume that Δn_D and $\Delta n_{^3He}$ do not exceed the observed abundances of D and ^{3}He the following restrictions on the value of R are obtained

$$R \le \begin{cases} \dfrac{2X_D}{X_{^4He}(f_n + f_D)} & 10^3 \le t \le t_D \qquad (4) \\ 2X_D/(X_{^4He} f_D) & t_D < t \le t_{rec} = 10^{13}\text{ s}, \qquad (5) \end{cases}$$

where X_D and $X_{^4He}$ are the observed weight concentrations of D and ^{4}He.

If one assumes, for a rough estimation, that all annihilation channels for ^{4}He have equal cross sections and $\sigma_{ann} = 0.5\,\sigma_{tot}$, then $R \le 10^{-4}$. In the experiments one should also measure the output of the tritium ($f_{^3H}$) too, since subsequent decay of the tritium, formed due to $\bar{p}\,^4$He annihilation in the Universe should increase the concentration of ^{3}He.

3. The estimation of R based on the experimental information on $\bar{p}\,^4$He annihilation, may lead to a number of interesting concequences:

a) The existence of strong density fluctuations in the early Universe could lead to the formation of primordial black holes (PBH) /3/. According to /4/ PBH with a mass M may evaporate during the time $t_{ev} = 10^{-27}\, M^3$(g), being sources of radiation with a temperature $T = 10^{13}$ (GeV)/M(g). PBH's with $M < 10^{13}$ g which evaporated by $t < 10^{12}$ s have a temperature $T \sim 1$ GeV and therefore antibaryons should be present in their radiation spectrum. The density of antibaryons $n_{\bar{B}}$ created due to evaporation of PBH with mass M is /2/.

$$n_{\bar{B}} = \frac{a(M) f_{\bar{B}}\, n_\gamma}{(m_{Pl} \cdot t_{ev})^{1/6}} = \frac{a(M) f_{\bar{B}}\, n_B}{\Omega_b (t_{ev}/1s)^{1/6}}\ , \qquad (6)$$

where $m_{Pl} = 10^{-5}$g, $a(M)$ is the relative contribution of the PBH density to the total cosmological density $a(M) = n_{PBH}/n_C$, $f_{\bar{B}} \sim 0.01$-0.05 is the fraction of antibaryons in the radiation spectrum of PBH's and n_B, n_γ are the densities of baryons and photons. In the radiation dominance era all antinucleons created by PBH must annihilate.

As is seen from (6), one can obtain the restriction on the relative amount of PBH's with mass M. From an astrophysical point of view, the knowledge of $a(M)$ can give information about the spectrum of inhomogeneities in the early Universe and, in principle, about inhomogeneities appearing in the course of GUT phase transition, cf. /5/.

Besides that, the knowledge of $a(M)$ allows one to obtain some restrictions on the parameters of superheavy particles predicted in the unified gauge theories. As is shown in refs. /1,6/, the existence of any superheavy weakly interacting longlived particles inevitable leads to formation of PBH with a definite mass spectrum, determined by the properties of these particles. An interesting example of such particles is represented by superheavy ($M_F \sim 10^{11}$ GeV), metastable ($\tau_F \sim 10^{-18}$ s) neutral fermions, predicted in some GUT's. In ref. /7/ it was shown that the value of $\alpha(M)$ in this case depends on the lifetime of the fermions τ_F and on the initial inhomogeneity δ

$$\alpha(M) = \delta^{13/2} \left(\frac{M}{m_{Pl}}\right)^{3/2} \left(\frac{t_{Pl}}{\tau_F}\right)^{1/2} \quad \text{for} \quad M < 10^{13} \text{ g}, \tag{7}$$

where $t_{Pl} = 10^{-43}$ s. Superheavy fermions with $M_F = (1-3)\ 10^{13}$ GeV may form PBHs with masses $10^{10} \leq M \leq 10^{11}$ g which evaporate during the time interval $10^3 \leq t \leq t_D$. Then, combining (6) and (7) one can obtain

$$R = f_{\bar{B}} \frac{\alpha(M)}{r_B} \left(\frac{m_{Pl}}{M}\right)^{1/2} \approx 10^9 \delta^{13/2} \left(\frac{10^{-15}}{\tau_F}\right)^{1/2}, \tag{8}$$

where $r_B = n_B/n_\gamma$. Superheavy fermions with $M_F \sim 10^{12}$ GeV will form PBHs with masses $10^{11} \leq M \leq 10^{13}$ g which evaporate during the time interval $t_D \leq t \leq t_{rec} = 10^{13}$ s. Then

$$R = 10^{11} \delta^{13/2} (10^{-15}/\tau_F)^{1/2}. \tag{9}$$

One can see that the value of R depends strongly on the amplitude of the density perturbations δ. Estimations of the value δ lead to $\delta \geq 10^{-3}$. If $\delta \sim 10^{-2}$ and $\tau_F \sim 10^{-18}$s, then from (9) one obtains $R \sim 0.3$. Therefore, if the sum of the average output f_n and f_D in the $\bar{p}\,{}^4He$ annihilation is greater than $5 \cdot 10^{-8}$ (that is very probable), then eqs. (6)-(9) practically exclude either the possibility of existence of superheavy fermions with mass $10^{12} \leq M_F \leq 10^{13}$ GeV or the existence of the perturbations with $\delta > 10^{-2}$ in the early Universe.

b) The GUTs with spontaneous breaking of CP-parity predict the existence of domains of antimatter. These are created due to a phase transition in the early Universe according to the following scenario. Assume that α_1 is the constant phase of CP-breaking ("hard violation") which provides for the total baryon asymmetry of the Universe and α_2 is the phase corresponding to the spontaneous breaking of CP ("soft violation"). When $\alpha_2 > \alpha_1$, in the region where the phase transition takes place to the state $\alpha_1 - \alpha_2$, subsequent nonequilibrium processes involving nonconservation of the baryon charge lead to the generation of an excess of antibaryons. The excess of baryons is generated in the regions with $\alpha_1 + \alpha_2$. As is shown in /8/, dense walls are formed on the boundaries of these regions but, according to /9/, with the decrease of temperature

$\alpha_2 \to 0$ and the walls disappear. The value $R = (\alpha_2 - \alpha_1)/(\alpha_2 + \alpha_1)$ in the period of generation of the baryon and antibaryon excess (when $\alpha_2 \neq 0$), determines the relative amount of created antinucleons. The number of antibaryons in a domain $N_{\bar{B}}$ depends on the scale of the domain. Serval mechanisms of inflation of the scales in GUT phase transitions exist /10,11/. This inflation may be induced by a succession of transitions in which anomalous (symmetric) vacuum dominates, so in each transition the scale is enhanced by a factor $N_0 \sim (\Lambda/T_c)^3$, where Λ is an energy scale of the grand unification $\sim 10^{14} - 10^{15}$ GeV and T_c is the temperature at which transition to the ordinary vacuum occurs. In a specific model /11/ kinetics of transition leads to exponential growth of scales:

$$N_{\bar{B}} = r_B \cdot R \cdot N_0 \exp(3 \cdot H \cdot t), \tag{10}$$

where $r_B = n_B/n_\gamma$, $H \sim \Lambda^2/m_{Pl}$. The duration of the stage of exponential growth is determined by the temperature T_c. According to /12,13/, the diffusion of antineutrons and positrons limits the possible scale of domains annihilating at $10^3 \leq t \leq t_{rec}$:

$$r_B \cdot R \cdot 10^{62} \leq N_{\bar{B}} \leq 1.6 \cdot 10^{67} \cdot r_B \cdot R. \tag{11}$$

Therefore, if the fraction of annihilated matter R is known, then, combining (10) and (11) one can obtain the restrictions on the duration of the stage of exponential growth and ultimately on the temperature T_c at which the phase transition occurs. Besides, as we mentioned above, the knowledge of R provides information about the relationship between phases of CP-breaking α_1 and α_2. Note, that intensive burning of domains (11) starts only in the period immediately preceding the recombination of hydrogen. Therefore, the burning of antimatter domains may lead to a distortion of the spectrum of background radiation.

4. In conclusion, the study of annihilation of antiprotons with ${}^4He$ may provide a) limits on the possible amount of antimatter in the early Universe, b) limits on the probability of formation of PBHs, c) restrictions on the GUT parameters determining the properties of domains of antimatter.

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REFERENCES

1. Khlopov M.Yu., Polnarev A.G. Phys.Lett., 1980, 97B, p.383.
2. Zeldovich Ya.B. et al. Pis'ma Astr.Zh., 1977, 3, p. 208.
3. Zeldovich Ya.B., Novikov I.D. Astr.Zh., 1966, p.758, 43,
4. Hawking S.W. Comm.Math.Phys., 1975, 43, p. 199.
5. Sato K. Phys.Lett., 1981, 99B, p. 66;
   Brown R., Stecker F. Phys.Rev.Lett., 1979, 43, p. 315.
6. Polnarev A.G., Khlopov M.Yu. Astr.Zh., 1981, p. 76.
7. Polnarev A.G., Khlopov M.Yu. Preprint Space Research Institute, Moscow, 1981, No. 646.
8. Zeldovich Ya.B., Okun L.B., Kobzarev I.Yu. ZhETP, 1974, 40, p. 1.
9. Kuzmin V.A., Shaposhnikov M.E., Tkachev I.I. Phys.Lett., 1981, 102B, p. 357.
10. Kuzmin V.A., Shaposhnikov M.E., Tkachev I.I. Proc. 2 Workshop on Quantum Gravitation, Moscow, 1981.
11. Linde A.D. Preprint Lebedev Physical Institute, 1981, No.229.
12. Zeldovich Ya.B., Novikov I.D. Structure and Evolution of the Universe, (nauka, Moscow, 1975).
13. Steigman G. Ann.Rev.Astr.Astroph., 1977, 11, p. 339.

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Предлагается новая возможность для проверки предсказаний некоторых моделей великого объединения, которая основана на анализе их космологических следствий, а также на экспериментальном изучении $\bar{p}\,{}^4\mathrm{He}$ взаимодействия.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1982

Chechetkin V.M. et al. Antiproton Interaction with $\bar{p}\,{}^4\mathrm{He}$ as a Test of GUT Cosmology E2-82-386

A new possibility of checking some GUT models is suggested, basing on the analysis of their cosmological consequences and the experimental study of $\bar{p}\,{}^4\mathrm{He}$ interaction.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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