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A new concept of generation of the cosmological baryon excess along with the cold dark matter (CDM) in the Universe is proposed and corresponding scenarios are outlined, in particular, possible realizations of the idea in the framework of supersymmetric models. Among numerous consequences of the idea, there is the prediction of a quite natural existence of a charge-asymmetric component of CDM, in particular, an ~ 10^{-2} part of CDM might exist in the form of negatively electrically charged relic particles with masses $m \simeq 1$ TeV, dressed by protons. The charge-asymmetric component of CDM might be represented by very light, $m \approx 2$ GeV, very weakly interacting particles like right-handed sneutrinos, so that expected recoils in the target material are rare and have quite small energies, $E_{\rm recoil} \sim 1$ keV. Some new opportunities of nontraditional experimental search for predicted CDM particles are mentioned.

Предлагается новая концепция образования космологического барионного избытка (барионной асимметрии) совместно с холодной темной материей (ХТМ) во Вселенной и очерчены соответствующие сценарии, в частности, возможные реализации идеи в рамках суперсимметричных моделей. Среди многочисленных следствий концепции интересно предсказание вполне естественного существования зарядово-асимметричной компоненты холодной темной материи — конкретно, ~ 10^{-2} часть ХТМ может существовать в форме отрицательно электрически заряженных реликтовых частиц с массой $m \sim 1$ ТэВ, одетых протонами. Зарядово-симметричная компонента реликтовой ХТМ может существовать в форме очень легких, $m \approx 2$ ГэВ, очень слабо взаимодействующих частиц, подобных правым снейтрино, так что столкновения с ядрами мишени

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*Talk presented at the International Workshop on Future Prospects of Baryon Instability Search in p Decay and $n-\bar{n}$ Oscillation Experiments, Oak Ridge, Tennessee, March 28—30, 1996; at the Workshop «Aspects of Dark Matter in Astro- and Particle Physics», Heidelberg, Germany, September 16—20, 1996; at the International Workshop «Non-Accelerator New Physics», Dubna, July 7—11, 1997; hep-ph/9701269.

детектора являются редкими, а энергия отдачи ядра составляет E_{recoil} ~ 1 кэВ. Отмечаются некоторые новые экспериментальные возможности нетрадиционного поиска предсказываемых частиц ХТМ.

FOREWORD

Moissei Alexandrovich Markov, one of my Teachers, was among the first people who understood the fundamental importance of the problem of the Baryon Asymmetry of the Universe (BAU) and long ranging consequences of its possible solution. He was always interested in the corresponding efforts and contributed himself in finding the ways (very original and unusual ones) for solution of the BAU problem [1]. Another key modern problem, that of the dark matter in the Universe, interested M.A.Markov very much also, and here he proposed his own original way of solving the problem, too. According to him, superheavy maximons might constitute the cold dark matter in the Universe [2].

As I remember him, he knew and admired numerous wonderful details and achievements in rapidly progressing physics of the 20th century, but his own dream was always to penetrate and learn the very basics of the World Construction.

INTRODUCTION

Starting with the papers by Sakharov [3] and Kuzmin [4] where the principal ways of solving the problem of the BAU were outlined, there was a long list of various attempts of elaboration of the main concepts, most convincing in the framework of Grand Unified Theories (GUT) [5] which naturally provide all the necessary conditions for the creation of charge asymmetric state of the matter in the Universe starting with the symmetric one at high temperature. This is a beautiful concept, indeed. And, indeed everything seemed to be O.K. with the origin of the baryon asymmetry of the Universe in the framework of grand unified theories until 1985. However, after the discovery was made in 1985 in the paper by Kuzmin, Rubakov and Shaposhnikov [6] that electroweak sphaleron-induced baryon and lepton number nonconserving transitions might have been not suppressed in the $SU(2) \times U(1)$ unbroken phase at high temperatures $T \geq T_{EW} \sim M_W$, the GUT-based realizations of the scenario of the BAU generation were re-examined in view of this potentially dangerous washing-out of the baryon excess phenomenon and ideas were proposed of just exploration of sphaleron-mediated transitions for generation of the BAU. Of particular interest are mechanisms of sphaleron re-processing of a previously generated lepton-number excess considered by Fukugita and Yanagida [7] and by Langacker et al. [8] exploring the see-saw mechanism of effective lepton-number nonconservation. Efforts of generation of the BAU within the framework of the Standard Model (SM) started with the paper by Shaposhnikov [9] are being made as well. Hopefully, these efforts will result in a plausible explanation of the cosmological baryon excess. However, at present it seems quite problematic to solve the problem within the framework of the minimal standard model (SM).

And by the way, there is yet another problem which was under consideration after observation of presence of dark matter in the Universe, just the problem of its nature as well as of the origin. There is no room, I mean, no elementary particle candidate in the particle spectrum of the standard model which may serve as a candidate for the CDM in the Universe. The axion is the only possible exception. This is definitely still a good candidate.

It seems being taken at present (see, e.g., the paper by Primack [10]) that it is just the cold dark matter rather than the hot one which populates the Universe predominantly, $\Omega_{\mathrm{CDM}}\, h_0^2 \sim 0.7$, the most popular version of dark matter content being given by the mixed model, cold dark matter plus hot dark matter, something like $\Omega_{\mathrm{CDM}} \sim 0.7$, $\Omega_{\mathrm{HDM}} \sim 0.2$.

It is our impression that after all one has to extend the particle content beyond the standard model in order to find solution to both these problems, the BAU and CDM.

There was already a number of papers devoted to a combined solution of both the problems, of the BAU and of the CDM altogether (see, e.g., the papers by Barr et al. [ll], Kaplan et al. [12], Kuzmin et al. [13]), etc.) We would like to take part in the race, too, and again.

ELECTROWEAK SPHALERONS AND ANOMALOUS FERMION NUMBER NONCONSERVATION

In this Section we would like to remind shortly some properties of electroweak sphalerons and their role in fast anomalous baryon and lepton number nonconservation at high temperatures. As one will see, electroweak sphalerons are by themselves the very powerful tool for a solution of cosmological problems rather than destruction of nice constructions.

The crucial points for the anomalous fermion number nonconservation in the electroweak theory with the gauge symmetry $SU(2) \times U(1)$ are:

1. The anomaly in the fermionic currents discovered by Adler, Bell and Jackiw [14]

$$\partial_\mu J_\mu^B = \partial_\mu J_\mu^L = \frac{n_f}{32\pi^2}\left(-g^2 F_{\mu\nu}^a \tilde{F}_{\mu\nu}^a + g^2 F_{\mu\nu}^0 \tilde{F}_{\mu\nu}^0\right), \tag{1}$$

where J_μ^B and J_μ^L are the baryon and lepton currents, respectively, $F_{\mu\nu}^a$ is the $SU(2)$ field strength and n_f is the number of fermionic generations, which at the moment is known to be $n_f \geq 3$.

2. The nontrivial vacuum structure in non-Abelian gauge theories observed by Christ, Dashen and Jackiw [15].

Topologically distinct vacua are separated by the potential barrier of the minimal height $E_{\text{sph}} = 2M_W/\alpha_W B(\lambda/\alpha_W) = 8–14$ TeV for λ varying from 0 to infinity [16] (λ is the Higgs self-coupling constant, $\alpha_W \sim (1/30)$ is the $SU(2)$ fine structure constant). The label (sph) refers to the sphaleron, i.e., the static unstable solution to the classical equations of motion found by Klinkhamer and Manton [16]. This configuration belongs to the minimal energy path from one vacuum to the other.

The selection rules for the anomalous processes are:

$$\Delta n_f = 3n_f, \quad \Delta n_l = n_f, \quad \Delta B = \Delta L = n_f. \tag{2}$$

If bosonic configuration changes from one vacuum configuration to another one, there always takes place the creation of a net number of fermions (or antifermions!) proportional to the change of the Chern-Simons number [17].

In the case of zero temperature, low fermionic densities and low energies of colliding particles, the initial state of the system as well as the final state are close to the vacuum configurations. So, in order to provide the fermion number nonconservation the system has to tunnel through the energy barrier. This process might be described by instantons (see the paper by Belavin et al. [18]) and is strongly suppressed by the semiclassical exponent as was first shown by 't Hooft [19], $\exp(-2\pi/\alpha_W)$.

At nonzero temperature, the system experiences thermal fluctuations. Due to the equipartition distribution, every degree of freedom is excited and the average energy stored in it is of order of temperature. In particular, the sphaleron mode is excited as well.

If the energy of excitation is greater than the potential barrier height, then the system travels *classically,* from the vicinity of one topological vacuum to the other. The rate of these transitions leading to fermionic number nonconservation is proportional to the Boltzmann exponent $\exp(-E_{\text{sph}}(T)/T)$ determining the density of negative mode excitations with energies higher than the barrier energy [6] . Here $E_{\text{sph}}(T) = 2M_W(T)/\alpha_W B(\lambda/\alpha_W)$ is the effective sphaleron mass accounting for the temperature dependence of the Higgs vacuum expectation value, $M_W^2(T) = M_W^2(1 - T^2/T_c^2)$ at $T < T_c$, where T_c is the temperature of the electroweak phase transition as conjectured by Kirzhnits and Kirzhnits and Linde [20]. The calculations of the prefactor by Arnold and McLerran and Shaposhnikov [21, 9] give for the rate of the topological transitions per unit volume per unit time

$$\Gamma = \frac{T^4 \omega_-}{M_W(T)} \left(\frac{\alpha_W}{4\pi} \right)^4 N_{\rm tr} N_{\rm rot} \left(\frac{2M_W(T)}{\alpha_W T} \right)^7 \kappa \exp\left(-\frac{E_{\rm sph}(T)}{T} \right), \qquad (3)$$

where the factors $N_{\rm tr} \sim 26$, $N_{\rm rot} \simeq 5$ are due to the zero modes normalizations [21], $\kappa \sim 1$ is the determinant of nonzero modes around the sphaleron and $\omega_- \sim M_W(T)$ is the magnitude of the sphaleron negative mode. At $T < M_W$ quantum tunneling is more efficient than the classical transitions while for $T > E_{\rm sph}$ the saddle point approximation for the rate is not applicable. Moreover, at temperatures greater than the critical temperature T_c the $SU(2)$ symmetry is restored, the vacuum expectation value of the Higgs field is zero and the sphaleron saddle point solution does not exist anymore.

It is quite clear, however, that the rate of topological transitions changing fermion (baryon and lepton) number is not suppressed by any exponent in the temperature range $T > T_c$ due to the absence of the energy barrier between topologically different vacua.

With the use of scaling arguments it may be shown [9, 21] that

$$\Gamma = A(\alpha_W T)^4, \qquad (4)$$

where A is some factor which cannot be found by semiclassical methods. The real time numerical simulations give the value $A \approx 0.1$—1.0.

At temperatures larger than the critical one, $T > T_c$, the rate (Eq.(3)) of the anomalous processes with baryon number nonconservation greatly exceeds the rate of the Universe expansion rate, t_U,

$$t_U^{-1} = T^2 / M_0, \quad M_0 = M_{Pl} / 1.66 N_{\rm eff}^{1/2}, \qquad (5)$$

where $N_{\rm eff} \sim 100$ in the case of the SM is the effective number of massless degrees of freedom at this temperature.

Therefore, the anomalous reactions violating baryon and lepton numbers are in thermal equilibrium till the time of the electroweak phase transition. After the phase transition the Higgs field develops the nonvanishing vacuum expectation value and as a result the rate of baryon and lepton number violating processes decreases rapidly due to the Boltzmann exponential suppression.

Summarizing, one may say that at high temperatures, $T > T_c$, there are very fast transitions (we shall call them 'sphaleron-mediated' transitions) which result exactly in the following

$$|\,\text{vacuum}\rangle \to 9(\text{quarks}) + 3(\text{leptons}) \tag{6}$$

and

$$|\,\text{vacuum}\rangle \to 9(\text{antiquarks}) + 3(\text{antileptons}). \tag{7}$$

These are the processes which re-process any B- or L-excess in the normal SM fermionic sector distributing it correspondingly between quarks and leptons. The net B–L remains, of course, intact since in the SM B–L is conserved both perturbatively and nonperturbatively. Sphalerons do respect B–L conservation as well.

Now we are going to describe a possible scheme of the simultaneous genesis of the cosmological baryon excess and the CDM in the Universe.

THE MECHANISM

Let there exist in nature some new kind of baryon (lepton) number bearing particles (called in what follows R_q and R_l), interacting with the SM quarks and leptons. We are not going to assume *a priori* that there exist any new interactions in addition to the standard $SU(3) \times SU(2)_L \times U(1)$ ones, i.e., we extend just the particle content of the SM.

As Abdus Salam said: «We have to be economical in principles rather than in structures».

The crucial requirement to these new baryon (lepton) number bearing R particles is that unlike normal (left-handed) fermions they are to be 'EW-sphaleron-blind', i.e., the R currents are to be EW nonanomalous. This means that R particles should be either bosons (case 1) or $SU(2)_L$-singlet fermions with the ineffective enough, at least at some temperature, chirality equilibration rate (case 2). At present, let us restrict ourselves by the case 1, the R particles being just bosons (like sfermions in supersymmetric models).

Now our basic idea is as follows.

Let the state of cosmological plasma with $(B\text{-}L) \equiv (B\text{-}L)_{\text{init}} \neq 0$ in the normal SM sector and $(B\text{-}L) = -\,(B\text{-}L)_{\text{init}}$ in the R sector be somehow created at some temperature $T^* > T_{\rm EW} \sim 10^2$ GeV, $T_{\rm EW}$ being the effective temperature of switching-off unsuppressed electroweak transitions violating baryon, lepton and fermion numbers (see Fig.1).

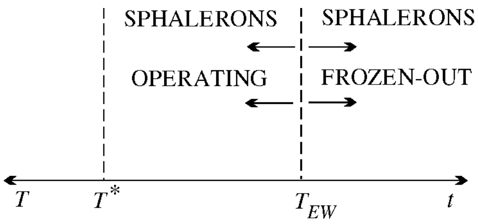

Fig.1. A schematic picture of a temperature evolution of the $B(L)$ distribution in cosmological plasma. At $T \simeq T^*$ plasma is symmetric with respect to B-L distribution between two sectors, the normal fermionic one and the new R_q sector. When temperature fell below $T < T^*$, plasma became asymmetric, $(B\text{-}L) \neq 0$ in both sectors

In other words, let there occur in the Universe an *asymmetrization* of plasma with respect to B-L distribution between the normal SM fermionic sector and the new sector R. For definiteness, let the normal left-handed fermionic sector acquire some $(B\text{-}L)_{\rm init} < 0$ and the R sector $(B\text{-}L)_{\rm init} > 0$, the overall B-L of plasma being exactly preserved. If such a phenomenon took place, then this might be all one needs to understand the origin of the baryon excess and the dark matter in the Universe.

We would like to emphasize that we want that in all the processes resulting in such an asymmetrization of plasma B, L, $(B\text{-}L)$ and any other global additive quantum numbers (or multiplicative quantum numbers like R parity or matter parity in supersymmetry) to be strictly conserved both globally and locally. Thus, after the asymmetrization the plasma remains fairly neutral with respect to electric charge, lepton and baryon numbers, B-L, etc. The only exception is obviously the fermion number which is not conserved perturbatively. However, this might have been not an expense at all if there were in the particle spectrum of the model the Majorana fermions coupled to standard fermions and R particles.

Concerning the possible mechanism of such an asymmetrization of cosmological plasma one might expect that it might have been provided by CP-violating out-of-equilibrium decays of some massive Majorana fermions (X fermions in what follows) onto SM fermions (antifermions) and anti-R bosons (R bosons) at some effective freezing-out temperature T^*, $T^* > T_{EW}$, without violating any quantum number except for fermion number,

$$X \to qR_q^c,\, q^cR_q \tag{8}$$

and

$$X \to lR_l^c,\, l^cR_l\,. \tag{9}$$

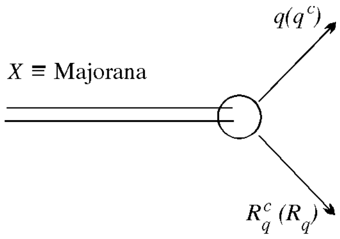

Fig.2. A scheme of (B-L) asymmetrization of plasma in charge asymmetric decays of X particles onto quarks (antiquarks) and R_q (R_q^c particles). The charge asymmetry might have taken place also in the decays $X \to lR_l^c,\ l^cR_l$

The charge asymmetry in X decays, for example,

$$\Gamma(X \to qR_q^c) \equiv \Gamma_1 \neq \Gamma(X \to q^cR_q) \equiv \Gamma_2, \tag{10}$$

and/or

$$\Gamma(X \to lR_l^c) \neq \Gamma(X \to l^cR_l), \tag{11}$$

might have arisen due to CP noninvariance in the interference of the tree-level diagrams and loop radiative corrections (see Fig.2), as usual (see, e.g., the book by Kolb and Turner [22] and the paper by Kuzmin and Shaposhnikov [23]).

In general, the amplitudes of charge-conjugated decays of X particles take on the form [24]:

$$A(X \to a_i b_i \ldots) = g_i + \Sigma g_{ik}' A_{ik}, \tag{12}$$

$$A(X \to \bar{a}_i \bar{b}_i \ldots) = g_i^* + \Sigma g_{ik}'^* A_{ik}, \tag{13}$$

g_{ik} being the product of corresponding coupling constants, generically $g_{ik} \sim f^3$ for one loop radiative corrections (f being the corresponding coupling constants in vertices), A_{ik} being radiative corrections to the tree diagram of the decay taken at unity values of coupling constants. From Eqs.(12) one obtains for the microscopic asymmetry ε,

$$\varepsilon \equiv (\Gamma - \Gamma_{CP})/\Gamma_{\text{tot}}, \tag{14}$$

$$\varepsilon = \left(\frac{1}{\Gamma_X}\right)(\Gamma_i B_i + \Gamma_{\bar{i}} B_{\bar{i}}) = (4\Sigma B_i \operatorname{Im}(g_i^* g_{ik}') \operatorname{Im} A_{ik})/(\Sigma(g_i g_i^*)), \tag{15}$$

where $\Gamma_i\,(\Gamma_{\bar{i}})$ are the partial decay widths of X into the channel $i(\bar{i})$ and $B_i\,(B_{\bar{i}})$ is the baryon number of normal fermion (or R particles) secondaries in the i-th ($\bar{i}$-th) channel.

The sign of the asymmetry is determined by the unknown CP-violating phase. One may take at the moment $\Gamma_1 < \Gamma_2$.

The protection of the created charge asymmetric component of R particles from disappearance due to the SM exchanges between two sectors might be achieved by the expense of attributing to new particles (X and R) some new conserved multiplicative quantum number R.

The net $-(B\text{-}L) \neq 0$ excess in the normal left-handed SM fermionic sector is now becoming a subject of re-processing in the usual way by unsuppressed electroweak transitions in the temperature range $T^* > T > T_{\mathrm{EW}}$ resulting at $T < < T_{\mathrm{EW}}$ in some baryon and lepton number asymmetries of plasma. The corresponding B-L excess in the R sector contained in R_q particles remained intact by sphalerons and got transported to the epoch $T < T_{\mathrm{EW}}$ just as it was created at T^*.

Having assumed that R particles bear the conserved quantum number R one may observe immediately that the lightest R-carrying particles might have survived until present epoch and serve as a candidate for the CDM population of the Universe.

Clearly, the number densities of excess quarks (antiquarks) and $R_q^c(R_q)$ particles are equal at the production time, $T = T^*$, while at the end of sphaleron operating epoch at $T = T_{\mathrm{EW}}$ the relation between them becomes $n_R \approx a n_B$, the factor a lying in between the extreme values $a = 4/3$ (if $B_{\mathrm{init}} \neq 0$, $L_{\mathrm{init}} = 0$) and $a = 4$ (if $B_{\mathrm{init}} = 0$, $L_{\mathrm{init}} \neq 0$). At present the relation between corresponding number densities is given by

$$n_R \approx a(1-b)\, n_B\,, \tag{16}$$

the factor b accounting for possible depletion of asymmetric R particle abundance on the way from $T = T_{\mathrm{EW}}$ to the present time. If the thermal charge symmetric component of R particle content of plasma completely annihilated in the course of the Universe expansion similarly to quarks and leptons, then identifying survived relic R particles with the CDM content of the Universe one arrives at the following estimate of their mass

$$m_R \approx (1/a(1-b))(c/d)\, m_p(\Omega_{\mathrm{CDM}}/\Omega_B), \tag{17}$$

m_p being proton mass and the factors $c \le 1$ and $d \le 1$ accounting for the fractions of the $\Omega_{\rm CDM}$ and the total observed Ω_B, respectively, attributed to our particular mechanism of the CDM and BAU generation. Clearly, it might be well not a unique one.

Taking $\Omega_{\rm CDM}/\Omega_B \approx 0.7/0.05 = 14$ in the mixed (CDM plus HDM) models one arrives in the extreme case $b = 0$, $c = 1$, $d = 1$ to the estimate

$$m_R \approx (14/a)\ \text{GeV}. \tag{18}$$

What is very important is the following. The ratios of the produced in such a way cosmological baryon excess and CDM content seem to be insensitive to the character of the electroweak phase transition (1st or 2nd order), in contrast to the common case when efforts are made to solve the cosmological baryon excess problem within the framework of the SM itself.

Thus, the essence of our scenario of a possible common genesis of the BAU and the CDM in the Universe is a preparation of a state of plasma with $(B\text{-}L) \neq 0$ in the fermionic sector of the SM and $-(B\text{-}L)$ in the new particle sector R, the standard fermions being involved in sphaleron-mediated $(B\text{-}L)$-nonconserving processes while the baryon or lepton number bearing R particles are sphaleron-blind. No violation of B and/or L other than that provided by sphalerons is necessary. Subsequent sphaleron re-processing of the $B\text{-}L$ excess in SM sector gives rise to the BAU and the lightest stable massive R particles contribution to the CDM.

Masses of X particles necessary to provide generation of the observed BAU,

$$\Delta \equiv n_B/n_\gamma \sim 10^{-10}, \tag{19}$$

might be found from consideration of the process of generation of the asymmetry and its washing-out [28]. The resulting macroscopic asymmetry in the out-of-equilibrium decay mechanism is known to be given generically by [28]

$$\Delta \sim (45\zeta(3)/4\pi^4 N)\ \Sigma N^i \varepsilon_i S_i\,, \tag{20}$$

where N is the effective number of degrees of freedom of massless at the given temperature T particles, ζ is the Riemann function, ε is the microscopic asymmetry in the decay of a parent particle, and S is the macroscopic suppression factor [28] arising due to baryon number dissipation in decay and inverse decay processes as well as scattering of the product particles. It is generically

$$S \le 10^{-2}. \tag{21}$$

One may conjecture that the asymmetry ε might be small enough in order to be able to explain the observed baryon asymmetry of the Universe. This might be just the case, indeed. However, even in this case the proposed mechanism of asymmetrization of cosmological plasma may provide the origin of a charge asymmetric CDM component of the Universe. This latter might be electrically neutral as well as (negatively) charged. This case is obviously of a special interest.

REALIZATIONS OF THE SCENARIO IN THE FRAMEWORK OF SUPERSYMMETRIC MODELS

Let us examine in this respect a supersymmetric extension of the standard model, for example, let us consider the Minimal Supersymmetric Standard Model (MSSM) in order to clarify its resources. One finds that there seems to be quite enough room even within this simplest supersymmetric model for a realization of the scheme, at least in a sense of some asymmetrization of plasma. Indeed, our R particles could be nothing but sfermions which bear baryon or lepton number. However, they are the Lorentz scalars and therefore are not affected by sphalerons. Further, there are Majorana fermions in the supersector, just gauginos, $\tilde{B}^0$ (bino), $\tilde{W}_3^0$ (wino) and $\tilde{g}$ (gluino) before $SU(2)_L \times U(1)$ breaking, so

$$X \equiv \tilde{B}^0, (\tilde{W}_3^0, \tilde{g}). \tag{22}$$

After $SU(2) \times U(1)$ breaking at electroweak scale, $T \sim M_W$, these become

$$\tilde{\gamma}, \tilde{Z}^0, \tilde{g} \tag{23}$$

in mixtures. There are also $\tilde{H}_1$ and $\tilde{H}_2$. In supergravity case it might be also that it is just gravitino which plays a role of a parent particle in baryogenesis and CDM genesis,

$$X \equiv \tilde{G}, \tag{24}$$

where $\tilde{G}$ denotes gravitino.

As an example, we shall consider just bino $\tilde{B}^0$ decays, the cases of $\tilde{W}_3^0$, $\tilde{g}$ or $\tilde{G}$ being quite similar.

It goes without saying that these gauginos are to be massive at $T > T^*$,

$$m_{\tilde{B}^0} > T^*, \tag{25}$$

i.e., we assume here that supersymmetry is broken at scales higher than T^*.

It is clear that there might have taken place two extreme cases, namely, the maximal B-L asymmetry in the normal sector being due to leptonic decays of X particles, or due to decays of X onto squarks (antisquarks) and $R_q(R_q^c)$, depending on the amount of CP violation, i.e., coupling constants and CP angles. This does not make any principal difference but two cases deserve detailed analysis. We shall restrict ourselves for demonstration purposes by the quite short description of the case when all the B-L asymmetry comes from decays of X into baryonic sector (i.e., $B_{\text{initial}} \neq 0$, $L_{\text{initial}} = 0$, see below.) Clearly, this is an oversimplifying description of what might have occurred. In fact, both asymmetries took place simultaneously and are to be taken into account.

By obvious reasons of the largest couplings to Higgs bosons of top quarks and top-squarks, one may expect that this will result in the largest radiative corrections to the tree-level diagrams of bino decays and therefore in the largest asymmetry in just these decays. We shall therefore be interested mainly just in the processes like

$$\tilde{B}^0 \to t\tilde{t}^c, t^c\tilde{t}. \tag{26}$$

All other decay channels of all the gauginos onto quarks of the 1st and 2nd generations,

$$\tilde{B}^0 \to q\tilde{q}^c, q^c\tilde{q}, q \equiv u, d, c, s, \tag{27}$$

or lepton decays,

$$\tilde{B}^0 \to l\tilde{l}^c, l^c\tilde{l}, \tag{28}$$

might be expected to be less efficient. We are not going though to overestimate the validity of such kind of arguments. This is simply an example of our line of reasoning. As soon as the model is specified, one needs not any further assumptions.

Clearly, one has to assume

$$m_B^0 > m_{\tilde{t}}. \tag{29}$$

In fact, as one can see, we have to require masses of all gauginos to be bigger than those of all the sfermions,

$$m_{\text{gaugino}} > m_{\text{sfermion}}. \tag{30}$$

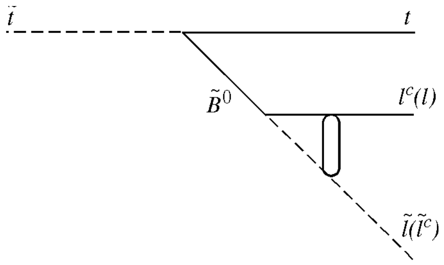

Fig.3. A diagram showing the return of the baryon number excess contained in supersymmetric sector to the normal quark sector of the standard model and creation of the final CDM content of the Universe in the form of sleptons (antisleptons)

This is not a commonly taken point of view. However, it might be not quite stupid while taking into account the renormalization group equation of evolution of coupling constants with proper values of m_0 and $m_{1/2}$.

We emphasize that no violation of R parity or B and/or L is necessary in these processes.

As soon as one does not assume any R parity violation, neither explicit nor spontaneous, the lightest sparticles (LSP) are stable, as usually.

What happened to the originated at $T = T^*$ charge asymmetric spartner component depends upon which of all sparticles is the LSP. There *is a priori* a number of possibilities. However, according to the very idea of the scenario, one has to require that after the temperature has fallen down to $T = T^*$ any B and L transfer from one sector to another was to be effectively switched off. Therefore, not only gauginos but higgsinos as well are to be heavier than sfermions,

$$m_{\tilde{H}} > m_{\tilde{f}}, \quad \tilde{H} \equiv \tilde{H}_1, \tilde{H}_2. \tag{31}$$

Otherwise there might have taken place too fast decays of squarks into ordinary quarks,

$$\tilde{q} \to q\tilde{H}, \tag{32}$$

before sphalerons got frozen-out of equilibrium. Such decays would just mean some returning of baryon number back to the normal sector. Choosing between two possibilities, a squark or a slepton being the LSP, one definitely prefers by several reasons the latter one. Therefore, the squark excess after $T = T_{EW}$ is to be converted into sleptons. This might have been fairly naturally provided by squark decays like (see Fig.3)

$$\tilde{t} \to tl\,\tilde{l}^c,\, tl^c\,\tilde{l}. \tag{33}$$

Thus, there takes place a quite remarkable total return of the «temporarily loaned» baryon number from the supersector to the normal SM quark sector.

However, it does not anymore compensate exactly the B excess in the normal sector since the latter has suffered from partial sphaleron re-processing.

The resulting output overall baryon excess (contained exclusively in the normal quark sector) is positive, $B_{\rm final} > 0$, and is given by

$$B_{\rm final} \approx (1/4) B_{\rm initial} . \tag{34}$$

This completes the story.

One can easily see that the freezing-out temperature of $\tilde{t}$ is to be lower than $T_{\rm EW}$ (i.e., $\tilde{t}$ should disappear from plasma after temperature had fallen down $T_{\rm EW}$) in order not to return the baryon excess contained in the supersector to the normal quark sector too early. This means that $\tilde{t}$ must be light enough,

$$m_{\tilde{t}} \leq 20\ T_{\rm EW} \approx 2\ \text{TeV}, \tag{35}$$

and there are sleptons in the spectrum which are light enough,

$$m_{\tilde{l}} < ((1/2)\, m_{\tilde{t}} - m_t) \leq 1\ \text{TeV}. \tag{36}$$

CHARGE SYMMETRIC SLEPTON COMPONENT OF CDM

If decays of $\tilde{t}$, Eq.(33), are charge symmetric and sleptons are the lightest (stable) superparticles then this will result in creation of charge symmetric (slepton) cold dark matter component of the Universe with their number density twice as large as the $\tilde{t}$'s. This will result in the very low estimate of their mass, Eq.(18), $m_{\tilde{l}} \sim 2$ GeV).

This is by no means acceptable for any left-handed sleptons due to corresponding contribution to the total Z^0 width.

Therefore, the charge symmetric component of these decays cannot represent the CDM. Having originated from these decays, it effectively disappears from plasma due to subsequent annihilation.

CHARGE ASYMMETRIC SLEPTON COMPONENT OF CDM

The very interesting point is however the following. The slepton-antislepton component originated from decays of squark excess might have had again a tiny charge asymmetry δ due to radiative corrections to the (virtual) bino vertex

$l^c \tilde{l} \tilde{B}^0$. The most promising asymmetric decay channels are presumably the ones with ν_τ, $\tilde{\nu}_\tau^c$ due to the largest Higgs couplings,

$$\tilde{t} \to t\, \tilde{\nu}_\tau \nu_\tau^c\,,\; t\, \tilde{\nu}_\tau^c \nu_\tau\,, \tag{37}$$

and decays with charged sleptons $\tau\tilde{\tau}^c$ in the final state

$$\tilde{t} \to t\, \tau\tilde{\tau}^c,\; t\, \tau^c\, \tilde{\tau}. \tag{38}$$

One may expect that this charge asymmetry, δ, might be presumably of order $\delta \leq 10^{-6}$. Hence, the relation between the excess baryon and asymmetric slepton number densities becomes

$$n_{\tilde{l}} \sim 4\delta n_B\,. \tag{39}$$

It is worth noting that this would-be CDM asymmetric slepton component has a nonthermal momentum spectrum.

Neglecting the depletion of slepton number density due to two slepton pair-annihilation processes after temperature has dropted below T_{EW}

$$\tilde{l}\tilde{l} \to ll, \tag{40}$$

which is possible because of R parity being a multiplicative quantum number, one obtains an estimate of the possible CDM content due to this asymmetric component using Eqs.(34) and (39):

$$\Omega_{\mathrm{CDM}} / \Omega_B \sim 4.10^{-3}, \tag{41}$$

in the case of all the observed BAU, $\Omega_B \approx 0.1$, being due to our mechanism, $\delta \leq 10^{-6}$ and $m_{\tilde{l}} \leq 1$ TeV.

Yet, two possibilities are now in turn in this charge asymmetric dark matter scenario, namely, the LSP being either 1) the left-handed sneutrino, or 2) the charged slepton. None of these seems to be excluded *a priori*.

1. Neutral $SU(2)_L$-Doublet Slepton as LSP. If just the ($SU(2)_L$-doublet) sneutrino is the LSP, then the overall output of the charge asymmetric CDM scenario is quite similar to the commonly used one except for the smallness of the corresponding CDM content, $\Omega_{\rm CDM}/\Omega_B \sim 4.10^{-3}$, Eq.(41), which being natural does not pretend nevertheless to explain all the CDM content of the Universe.

The estimate $m_{\tilde\nu} \le 1$ TeV does not come into contradiction with any known constraints on sneutrino mass. The counting rate in experiments devoted to direct searches of the flux of weakly interacting massive particles (WIMP) from the galactic halo is smaller than is usually expected.

2. Charged Slepton as LSP. Quite a different and exciting possibility might have been realized if just a charged slepton is the LSP. The possibility that stable charged particles, in particular, sleptons might constitute the CDM, was analyzed in the paper by De Rujula et al. [26] (where these particles were called champs). An exciting story of the evolution of the relic champs content in the Universe was pictured out and it was argued that the case of champs might be not excluded by current observations. We would like to add few remarks.

In our case, the CDM is assumed to be charge asymmetric and consists of negatively charged sleptons. It is interesting to note that our estimate of slepton mass, Eq.(36), $m_{\tilde l} \le 1$ TeV, does not stay catastrophically apart from the window of allowed champ masses 10—1000 TeV obtained by De Rujula et al. [26] from different arguments. Thus, we would consider our negative slepton (asymmetric component) as a reasonably good candidate for champs.

Starting with the time of origination from the excess squark decay at $T < T_{\rm EW}$ and down to the temperature of order $T \sim$ few hundreds keV nothing essential happened to $\tilde l$ excess. Drastic phenomena occurred [26] after T had fallen down to $T \sim$ few hundreds keV when the primordial nucleosynthesis began to proceed. Now $\tilde l$ came into play. They took part in nucleosynthesis processes catalyzing them to some extent as well as got starting to proceed through complicated kinetics of recombination processes. They were getting «dressed» by protons and α's and forming atoms like $(\tilde l p)$ (superhydrogen in what follows) with binding energy

$$E_b \approx 25 \text{ keV}, \tag{42}$$

as well as ions like $(\tilde l \alpha)$, ($E_b \approx 311$ keV [26]), and atoms of superhelium $(\tilde l \tilde l \alpha)$, with the binding energy of about 800 keV, etc. According to De Rujula et al. [26] «negative champs overwhelmingly bind to protons to pose as superheavy neutrons» called in [26] neutrachamps. In our case a neutrachamp is $(\tilde l p)$. For definiteness, let us take selectron, $\tilde e$, as the LSP.

Atoms ($\tilde{e}\,\tilde{e}\alpha$) in which two $\tilde{e}$ are getting dressed by α particle are in any case unstable and have short lifetimes in cosmological scales due to pair-annihilation process of two $\tilde{e}$ into ordinary leptons.

After finishing the $\tilde{e}$ recombination period and formation of superhydrogen atoms ($\tilde{e}p$) and then the recombination period for (normal) hydrogen and helium, the next important stage in the evolution is met right at formation of galaxies and clusters of galaxies. The gas of superhydrogen will presumably share the fate of all other gases at this stage, so it will be as abundant in the galactic matter at this time as it does in cosmological plasma.

Further, of all the neutral gases (hydrogen, helium, superhydrogen, etc.) the gas of neutral superhydrogen is the most collisionless because of compactness of the atom, the mean size of it being $r \sim 2.10^{-12}$ cm.

Therefore, one might expect that at the next important stage of the evolution, namely, star formation inside galaxies, superhydrogen atoms were not effectively involved in contraction processes due to lack of time and were left not clustered inside the Galaxy constituting a widely distributed CDM content with velocities $v \sim 10^{-3}$ and the local density somewhat about

$$\rho_{\tilde{e}p} \sim 4.10^{-3}\,\rho_{\mathrm{local}} \sim 10^{-3}\ \mathrm{GeV}/\mathrm{cm}^3, \tag{43}$$

according to Eq.(41). Here $\rho_{\mathrm{local}} \approx 0.3$ GeV/cm^3 is usually taken local dark matter density. The number density of superhydrogen atoms will be then

$$n_{\tilde{e}p} = \rho_{(\tilde{e}p)} / m_{\tilde{e}} \sim 10^{-6}\ \mathrm{cm}^{-3} \tag{44}$$

if the mass of ($\tilde{e}$) is about 1 TeV, Eq.(41). Hence, the local flux intensity of our superhydrogen atoms in the space might be expected to be of order

$$F_{(\tilde{e}p)} \sim 30\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{45}$$

If so, there would be quite small *primordial* abundance of superhydrogen inside the Sun and the Earth. These bodies got to start absorbing the flux of superhydrogen from the space as soon as would-be-star clouds became condensed enough.

The total amount of ($\tilde{e}p$) accumulated by the Earth through all the terrestrial history as condensed body might then be about 10^{36}, their average (over the Earth) relative abundance being about

$$n_{\tilde{e}p} / n_{\mathrm{nucl}} \sim 10^{-15}. \tag{46}$$

This is quite an admixture of wild isotopes to normal element abundances even on average!

Note that there takes place a quite remarkable phenomenon of fast enough changing by $\tilde{e}$'s their host nuclei from protons in superhydrogen to nuclei with larger atomic numbers. The energy release in this process is about $E \sim$ $\sim 25Z^2/A$ keV, i.e., for example, in the case of iron ^{56}Fe

$$(\tilde{e}p) + {}^{56}\mathrm{Fe} \to (\tilde{e}\,{}^{56}\mathrm{Fe}) + p + \pi' s + \gamma' s \tag{47}$$

it is about $E \sim 800$ MeV while in the case of oxygen it is about 1 MeV. Therefore, all the superhydrogen atoms falling down the Earth's atmosphere are captured by nuclei of nitrogen, oxygen, carbon, etc. Clearly, this will result in emission of quite characteristic hard Roentgen γ's from the top of the atmosphere with well determined energies. Obviously, this radiation is to be searched for.

The situation is even more exciting in case of the Moon. Here all the accumulated amount of $\tilde{e}$ transferred from superhydrogen atoms to heavier nuclei is contained in a quite thin layer of the Moon ground just near the surface, so the relative abundance of wild heavy isotopes should be larger by orders of magnitude than Eq.(46). It seems therefore that search of relic selectron abundance might be most promising by analysis of chemical content of samples of the Moon ground. Methods of laser spectroscopy providing sensitivity to contamination up to 10^{-16} might be well adequate.

Being binded to protons very strongly, $E_b = 25$ keV, selectrons are not probably taking part in acceleration processes resulting in cosmic-ray production in objects like supernovae, since temperatures are hardly high enough for ionization of superhydrogen atoms. However, nevertheless there should be some flux of bare negative selectrons in cosmic rays due to interaction of primary cosmic rays with the superhydrogen gas during their travel for ~ 20 million years inside the Galaxy. Clearly, the flux of bare selectrons from the space will be superpenetrative even in comparison with muons produced in the atmosphere because of selectrons' larger mass and stability. They might be looked for very deep underground.

The very intriguing at first sight issue, why the flux $F_{(\tilde{e}p)} \sim 30\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ of superhydrogen atoms from the outer space was not observed in experiments devoted to the CDM searches, is quite easy to explain. The flux of superhydrogen atoms is expected to be about 10^3 times less intensive than usually expected one in case of WIMPS with masses of the order of 100 GeV but the cross-section of interaction with nuclei is much bigger since they are interacting strongly and electromagnetically rather than weakly. So, the effect per ingoing particle is orders of magnitude bigger than in the case of WIMP's.

However, the main possible reason for nonobservation of superhydrogen atoms might be related to absorption of superhydrogen atoms en route to detectors. (One has to take into account that being aimed to look for rare events of nuclei getting small recoils due to weakly interacting particles of CDM these experiments are being carried out usually in underground laboratories. One has presumably to explore small or shallow depths, not to say satellites, where the effect itself would be bigger by the ratio of cross-sections, i.e., by many orders of magnitude since superhydrogen atoms are interacting with matter electromagnetically and strongly and do not penetrate too far deep.)

MSSM PLUS ν_R AND $\tilde{\nu}_R$

Until now we considered the case of the supersymmetrized version of the standard model without right-handed neutrinos and sneutrinos. If one takes into account possible existence of these particles, then one may arrive at the possible explanation of *all* the baryon excess and *all* the CDM content in the Universe, $\Omega_{\rm CDM} \sim 0.7$, as being produced simultaneously according to our mechanism.

In this case the number densities of ($\tilde{\nu}_R$ and $\tilde{\nu}^c$) are equal and each is about

$$n(\tilde{\nu}_R) \approx 4 n_B\,, \tag{48}$$

so, the mass of each of these species is

$$m(\tilde{\nu}_R) \approx 1.8 \text{ GeV}. \tag{49}$$

Note that in this case one arrives not at the constraint on the mass but just at the prediction of the concrete value of it according to Eq.(18). The uncertainty in Eq.(49) is only related with the ratio ($\Omega_{\rm CDM}/\Omega_B$). It is a very striking and straightforward consequence of the very concept.

It does not however seem to be quite an absurd from the point of view of renormalization group evolution of coupling constants with proper values of m_0 and $m_{1/2}$.

We have to note by the way that with this estimate of $\tilde{\nu}_R$ mass one should care about the see-saw mass for neutrino, lepton number violation due to Majorana neutrino mass, and so on. We will consider all this stuff in the forthcoming paper [29].

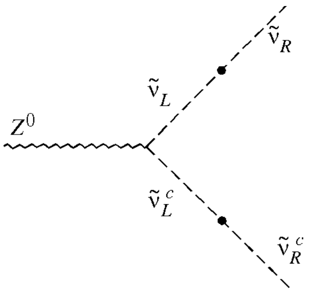

Fig.4. A diagram of decay $Z^0 \to \tilde{\nu}_R \tilde{\nu}_R^c$ (or $Z^0 \to \to \tilde{\nu}_L \tilde{\nu}_R^c$ if $m_{\tilde{\nu}_L} < m_Z - m_{\tilde{\nu}_R}$; in the latter case there is only one ($\tilde{\nu}_L$, $\tilde{\nu}_R$) mixing insertion). All the same refers to ν_R and ν_L

Being $SU(2)_L$ singlets they do not suffer any significant depletion of their number densities due to annihilation.

The contribution of $\tilde{\nu}_R$ and/or ν_R to Z^0 total width (see Fig.4) might have been dangerous in the case of large $\tilde{\nu}_R \tilde{\nu}_L$ and $\nu_R \nu_L$ mixing. Fortunately, such mixing is small enough and is not excluded by measurements of the total Z^0 width.

Two obvious circumstances make $\tilde{\nu}_R$ as a candidate for CDM very hard to observe.

1. The smallness of the $\tilde{nu}_R$ mass, Eq.(49), will lead to much smaller nuclei recoil energies, $E_{\text{recoil}} \sim 1$ keV, in comparison with usually expected $E_{\text{recoil}} \sim 50 - 100$ keV in underground experiments devoted to the searches for weak interacting particles with masses of an order of 100 GeV. Therefore, the signal from light $\tilde{\nu}_R$ scattering off nuclei will require very low thresholds.

2. In addition, the very rate of scatterings of $\tilde{\nu}_R$ should be very low because $\tilde{\nu}_R$ neutral $SU(2)_L$ singlet.

The partial width $Z^0 \to \tilde{\nu}_R \tilde{\nu}_R^c$ is proportional to $\sin^4 \theta$, θ being the $\tilde{\nu}_R \tilde{\nu}_L$ mixing angle. The mixing is due to the $SU(2)_L \times U(1)$ breaking. The θ might be expressed in terms of coupling constants and the Higgs' boson vacuum expectation value.

If $\tilde{\nu}_R$ is the lightest sparticle indeed, then we predict that there will be quite long-living spartners in the spectrum. This follows obviously from the fact of necessary mixing of left-handed and right-handed components of sneutrinos in this case which is small. Of particular interest is the prediction of existence of charged long-living sleptons. This should be taken into account in the searches for sparticles in accelerator experiments and, possibly, in deep underground cosmic-ray experiments. This is by itself a very striking consequence of the scenario.

CONCLUSIONS

In this paper we presented the new concept of a possible origin of the simultaneous production of the baryon excess and cold dark matter in the Universe. The basic expense is the assumption on the existence in Nature of particles (R particles) which bear baryon or lepton numbers but are sphaleron-blind. As an example, we considered the case of R particles being Lorentz scalars using for illustrative purposes supersymmetric models with their generic particle content.

It is interesting that generically any version of our scenario of simultaneous production of the cosmological baryon excess and cold dark matter in the Universe leads presumably to the prediction of the cold dark matter content in the form of superweak interacting and hard-to-observe in direct CDM search experiments for very light particles with masses of about 2 GeV.

In the case of supersymmetric realization of the basic idea, the CDM is nothing but right-handed sneutrinos with $m_{\nu_R} \approx 2$ GeV.

The very interesting version of the scenario is the one with the charge asymmetric CDM content, more specifically with charged sleptons as the LSP which got dressed by protons forming compact stable neutral superhydrogen atoms. The estimated masses are $m_{\tilde{l}} \leq 1$ TeV. These are not abundant very much, however, it is worthwhile to look for them.

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