Stable matter of 4th generation: hidden in the Universe and close to detection?

K. Belotsky∗, M. Khlopov†, K. Shibaev‡

Moscow Engineering Physics Institute, 115409 Moscow, Kashirskoe sh. 31, Russia

March 20, 2022

Abstract

Stable neutrino and U quark of 4th generation are excluded neither by experimental data, nor by astrophysical constraints. Moreover, excess of stable \( \bar{U} \) quarks in the Universe can lead to an exciting composite nuclear-interacting form of dark matter, which can even dominate in large scale structure formation.

1 Stable pieces of 4th generation matter

The problem of existence of new families of quarks and leptons is among the most important in the modern high energy physics. If these quarks and/or leptons are stable, they should be present around us and the reason for their evanescent nature should be found. Here we concentrate on the recent development of the approach [1](see also [3], [2, 4]), which involves minimal number of parameters, but illustrates all the problems, related with stable matter, composed of heavy charged particles.

Precision data on Standard model parameters admit [3] the existence of 4th generation and the results of this analysis determine our choice for masses of \( N (m_N = 50 \text{ GeV}) \) and \( U (m_U = 350 S \text{ GeV}) \).

4th generation can follow from heterotic string phenomenology and its difference from the three known light generations can be explained by a new gauge charge (\( y \)-charge), possessed only by its quarks and leptons [1, 2, 4]. Similar to electromagnetism this charge is the source of a long range Coulomb-like \( y \)-interaction. Strict conservation of \( y \)-charge makes the lightest particle of 4th family (4th neutrino \( N \)) absolutely stable, while the lifetime of \( U \) can exceed the age of the Universe, if \( m_U < m_D \) [2, 4].

The following conditions fix \( y \)-charges (\( Q_y \)) of \( (N, E, U, D) \). Cancellation of \( Z - \gamma - y \) anomaly implies \( Q_{yE} + 2 \cdot Q_{yU} + Q_{yD} = 0 \); while cancellation of \( Z - y - y \) anomaly needs \( Q_{yN}^2 - Q_{yE}^2 + 3 \cdot (Q_{yU}^2 - Q_{yD}^2) = 0 \).

\[ \]

∗e-mail: k-belotsky@yandex.ru
†e-mail: Maxim.Khlopov@roma1.infn.it
‡e-mail: shibaev01@yandex.ru
\( N - E \) and \( U - D \) transitions of weak interaction assume \( Q_{yN} = Q_{yE} \) and \( Q_{yU} = Q_{yD} \). From these conditions follows \( Q_{yE} = Q_{yN} = -3 \cdot Q_{yU} = -3 \cdot Q_{yD} \) so that \( y \)-charges of \((N, E, U, D)\) are \((1, 1, -1/3, -1/3)\).

\( U \)-quark can form lightest \((Uud)\) baryon and \((U\bar{u})\) meson. The corresponding antiparticles are formed by \( \bar{U} \) with light quarks and antiquarks. Owing to large chromo-Coulomb binding energy \( \propto \alpha_c^2 \cdot m_U \), where \( \alpha_c \) is the QCD constant) stable double and triple \( U \) bound states \((UUq)\), \((UUU)\) and their antiparticles \((U\bar{U}\bar{u})\), \((\bar{U}\bar{U})\) can exist [2, 4]. Formation of these double and triple states in particle interactions at accelerators and in cosmic rays is strongly suppressed, but they can form in early Universe and strongly influence cosmological evolution of 4th generation hadrons. As shown in [4], anti- \( U \)-triple state called antium or \( \Delta_{3U}^- \) is of special interest.

2 Cosmological evolution of 4th generation matter

In charge symmetric case, which assumes no primordial excessive particles (or antiparticles) of 4th generation, cosmological evolution was studied separately for \( N \) and \( U \) in [1, 2, 3].

In the absence of particle (or antiparticle) excess primordial particles of 4th generation with the considered masses can not contribute significantly to total density. However, \( N \) and \( \bar{N} \) condensation in galaxies can result in significant effect of their annihilation in cosmic fluxes of positrons, antiprotons and in gamma background [1]. They can even provide simultaneous explanation of these data and results of the direct WIMP searches [1], but in this case annihilation in terrestrial matter of \( N \) and \( \bar{N} \), captured by Earth, should lead to an up-going muon fluxes, exceeding the observed in underground detectors.

The main problem of new stable quark is that it can form stable positively charged hadrons. In charge symmetric case the pregaletic abundance of +2 charge \((UUU)\) and \((UUu)\) is by 10 orders above the terrestrial limits for anomalous helium \((r < 10^{-19})\). For the abundance of +1 charge \((Uud)\) the situation is even more dramatic, since it exceeds the limits on anomalous hydrogen \((r < 10^{-30})\) by 20 orders of magnitude [2].

To satisfy the experimental upper limits, anomalous isotope abundance in Earth should be reduced. The mechanisms for such reduction [2] imply recombination of \( U \)- and \( \bar{U} \)- hadrons in dense objects of ordinary matter and their rapid annihilation in bound \((U\bar{U})\) states. These mechanisms involve \( y \)-attraction, which prevents fractionating of \( U \)- and \( \bar{U} \)-hadrons in matter. In the result the primordial abundance of anomalous isotopes in terrestrial matter can be reduced down to \( r < 10^{-28} \), so that the problem of anomalous hydrogen can not be resolved in this way. Moreover, these mechanisms, being sufficiently effective in the case of anomalous helium, are accompanied by effects of energy release, which are strongly constrained by the observed \( \gamma \) background and by the data from large volume detectors. All the above listed problems of charge symmetric \( N \) and \( U \) matter can be avoided in the case of primordial excess of \( U \) and \( \bar{N} \).
The model [2] admits that in the early Universe an antibaryon asymmetry for 4th generation quarks can be generated [3]. Due to $y$-charge conservation $\bar{U}$ excess should be compensated by $\bar{N}$ excess. $\bar{U}$-antibaryon density can be expressed through the modern dark matter density $\Omega_{\text{CDM}} = \frac{k \cdot \Omega_{\text{CDM}}}{k_\gamma} = 0.224$ ($k \leq 1$), saturating it at $k = 1$.

In the early Universe at temperatures highly above their masses $\bar{U}$ and $\bar{N}$ were in thermodynamical equilibrium with relativistic plasma. It means that at $T > m_{\bar{U}}$ ($T > m_{\bar{N}}$) the excessive $\bar{U}$ ($\bar{N}$) were accompanied by $U\bar{U}$ ($\bar{N}\bar{N}$) pairs.

Due to $\bar{U}$ excess frozen out concentration of deficit $U$-quarks is suppressed at $T < m_{\bar{U}}$ for $k > 0.04$. It decreases further exponentially, when the frozen out $U$ quarks begin to bind with antiquarks $\bar{U}$ into charmonium-like state ($\bar{U}U$) and annihilate. On this line $\bar{U}$ excess binds by chromo-Coulomb forces dominantly into $(\bar{U}\bar{U}U)$ anutium states with electric charge $Z_\Delta = -2$ and mass $m_\Delta = 1.05\Sigma_3$ TeV, while remaining free $\bar{U}$ anti-quarks and anti-diquarks $(\bar{U}\bar{U})$ form after QCD phase transition normal size hadrons $(\bar{U}u)$ and $(\bar{U}\bar{U}\bar{q})$. Then at $T = T_{\text{QCD}} \approx 150$ MeV additional suppression of remaining $U$-quark hadrons takes place in their hadronic collisions with $\bar{U}$-hadrons, in which $(\bar{U}U)$ states are formed and $U$-quarks successively annihilate.

Owing to weaker interaction, effect of $\bar{N}$ excess in the suppression of deficit $N$ is less pronounced but it still takes place at $T < m_{\bar{N}}$ for $k > 0.02$. At $T \sim I_{NN} = \alpha_y^2 M_N/4 \sim 15$ MeV (for $\alpha_y = 1/30$ and $M_N = 50$ GeV) due to $y$-interaction the frozen out $N$ begin to bind with $\bar{N}$ into charmonium-like states ($\bar{N}N$) and annihilate. At $T < I_{NU} = \alpha_y^2 M_N/2 \sim 30$ MeV $y$-interaction causes binding of $N$ with $\bar{U}$-hadrons (dominantly with anutium) but only at $T \sim I_{NU}/30 \sim 1$ MeV this binding is not prevented by back reaction of $y$-photo-destruction.

To the period of Standard Big Bang Nucleosynthesis (SBBN) $\bar{U}$ are dominantly bound in anutium $\Delta_{\bar{U}}$ with small fraction ($\sim 10^{-6}$) of neutral $(\bar{U}u)$ and doubly charged $(\bar{U}\bar{U}\bar{q})$ hadron states. The dominant fraction of anutium is bound by $y$-interaction with $\bar{N}$ in $(\bar{N}\Delta_{\bar{U}})$ “atomic” state. Owing to early decoupling of $y$-photons from relativistic plasma presence of $y$-radiation background does not influence SBBN processes [2,4].

After $^4\text{He}$ is formed in SBBN, at $T \leq T_{^4\text{He}} \sim I_o/\log(n_o/n_{\text{He}}) \approx I_o/27 \approx 60$ keV, where $I_o = \frac{Z^2 Z_{\text{He}}^2 \alpha^2 m_{\text{He}}}{2} \approx 1.6$ MeV [4], neutral Anti-Neutrino-O-helium (ANO-helium, ANOH) $(^4\text{He}^+ [\bar{N}\Delta_{\bar{U}}])$ “molecule” with mass $m_o \approx 15\Sigma_3$ TeV is produced in the reaction $\Delta_{\bar{U}}^+ - \gamma + (^4\text{He}^+ \Delta_{\bar{U}}^-)$. The size of this “molecule” is $R_o \sim 1/(Z\Sigma Z_{\text{He}} m_{\text{He}}) \approx 2 \cdot 10^{-13}$ cm and it can play the role of a dark matter component and a nontrivial catalyzing role in nuclear transformations.

In nuclear processes ANO-helium looks like an $\alpha$ particle with shielded electric charge. It can closely approach nuclei due to the absence of a Coulomb barrier and opens the way to form heavy nuclei in SBBN. This path of nuclear transformations involves the fraction of baryons not exceeding $10^{-7}$ [4] and it can not be excluded by observations.

As soon as ANO-helium is formed, it catalyzes annihilation of deficit $U$-hadrons and $N$. Charged $U$-hadrons penetrate neutral ANO-helium,
expel $^4\text{He}$, bind with anutium and annihilate falling down the center of this bound system. The rate of this reaction is $\langle \sigma v \rangle = \pi R_o^2$ and an $\bar{U}$ excess $k = 10^{-3}$ is sufficient to reduce the primordial abundance of $(Uud)$ below the experimental upper limits. $N$ capture rate is determined by the size of $(\bar{N}\Delta)$ "atom" in ANO-helium and its annihilation is less effective.

Interaction of the $^4\text{He}$ component of $(ANO\text{He})$ with a $\frac{2}{3}Q$ nucleus can lead to formation of $\frac{1}{2}+\frac{1}{2}Q$ nucleus. The final nucleus is formed in the excited $[\alpha, M(A,Z)]$ state, which can rapidly experience $\alpha$- decay, giving rise to $(ANO\text{He})$ regeneration and to effective quasi-elastic process of $(ANO\text{He})$-nucleus scattering. It leads to possible suppression of ANO-helium catalysis of nuclear transformations in matter.

The composite nature of ANO-helium makes it more close to warm dark matter. This dark matter plays dominant role in formation of large scale structure at $k > 1/2$.

The first evident consequence of the proposed scenario is the inevitable presence of ANO-helium in terrestrial matter, which is opaque for $(ANO\text{He})$ and stores all its in-falling flux. If its interaction with matter is dominantly quasi-elastic, this flux sinks down the center of Earth. If ANO-helium regeneration is not effective and $\Delta$ remains bound with heavy nucleus $Z$, anomalous isotope of $Z - 2$ element appears. This is the serious problem for the considered model.

Even at $k = 1$ ANO-helium gives rise to less than 0.1 \cite{4} of expected background events in XQC experiment \cite{4}, thus avoiding for all $k \leq 1$ severe constraints on Strongly Interacting Massive particles SIMPs obtained in \cite{5} from the results of this experiment. In underground detectors $(ANO\text{He})$ "molecules" are slowed down to thermal energies far below the threshold for direct dark matter detection. However, $(ANO\text{He})$ destruction can result in observable effects. Therefore a special strategy in search for this form of dark matter is needed.

At $10^{-3} < k < 0.02$ $U$-baryon abundance is strongly suppressed, while the modest suppression of primordial $N$ abundance might not exclude explanation of DAMA, HEAT and EGRET data in the framework of hypothesis of 4th neutrinos \cite{1}, making the effect of $N$ annihilation in Earth consistent with the experimental data.

### 3 Discussion

Owing to excess of $\bar{U}$ anti-quarks primordial abundance of $(Uud)$ is exponentially suppressed and anomalous isotope over-production is avoided. Excessive anti-$U$-quarks should retain dominantly in the form of anutium, which binds with excessive $\bar{N}$ and then with $^4\text{He}$ in neutral ANO-helium. Galactic cosmic rays destroy ANO-helium, striking off $^4\text{He}$. It can lead to appearance of a free anutium-$\bar{N}$ component in cosmic rays, which can be as large as $[\bar{N}\Delta_{\bar{N}}]/^4\text{He} \sim 10^{-7}$ and accessible to PAMELA and AMS experiments. In the context of composite dark matter like \cite{4} accelerator search for new stable quarks and leptons acquires the meaning of critical test for existence of its charged components.
Figure 1. Cross sections of production of 4th generation particles in experiment ATLAS. Dash line shows the lower (conservative) level of LHC sensitivity for 1st year of its operation.

Acknowledgments

The work was supported by Khalatnikov-Starobinsky school. M.Kh. thanks LPSC (Grenoble, France) for hospitality and D. Rouable for help.

References

[1] D. Fargion et al., JETP Lett. 69, 434 (1999); astro-ph-9903086; K.M. Belotsky, M.Yu. Khlopov and K.I. Shibaev. Gravitation and Cosmology 6 Supplement, 140 (2000); K.M. Belotsky, D. Fargion, M.Yu. Khlopov and R. Konoplich, hep-ph/0411093; K.M. Belotsky, D. Fargion, M.Yu. Khlopov, R. Konoplich and K.I. Shibaev, Gravitation and Cosmology 11, 16 (2005) and references therein.

[2] K.M. Belotsky, D. Fargion, M.Yu. Khlopov, R. Konoplich, M.G. Ryskin and K.I. Shibaev, Gravitation and Cosmology 11, 3 (2005).

[3] M. Maltoni et al., Phys.Lett. B 476, 107 (2000); V.A. Ilyin et al., Phys.Lett. B 503, 126 (2001); V.A. Novikov et al., Phys.Lett. B 529, 111 (2002); JETP Lett. 76, 119 (2002).

[4] M.Yu. Khlopov, JETP Lett. 83, 3 (2006); astro-ph/0511796 and references therein.

[5] D. McCammon et al., Nucl.Instr.Meth. A 370, 266 (1996); D. McCammon et al., Astrophys.J. 576, 188 (2002), astro-ph/0205012.

[6] B.D. Wandelt et al., astro-ph/0006344; P.C. McGuire and P.J. Steinhardt, astro-ph/0105567; G. Zaharijas and G.R. Farrar, Phys.Rev. D 72, 083502 (2005), astro-ph/0406531.