National Research Nuclear University “MEPhI”

Department 40 (Physics of Elementary Particles)

Report of the course “Introduction into MicroCosmophysics”

**Anomalous Isotopes as a Probe for**

**New Stable Forms of Matter**

Done by 5th year student

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9. **Introduction.**

The question about existence of new quarks and leptons is among the most important in the modern particle physics. Possibility of existence of new (meta) stable quarks which form new (meta) stable hadrons is of special interest. New stable hadrons can play the role of strongly interacting dark matter [1–3]. This question is believed to find solution in the framework of future Grand Unified Theory.

A natural extension of the Standard model can lead in the heterotic string phenomenology to the prediction of fourth generation of quarks and leptons [4, 5] with a stable 4th neutrino [6–9]. The comparison between the rank of the unifying group E6 (r = 6) and the rank of the Standard model (r = 4) can imply the existence of new conserved charges. These charges can be related with (possibly strict) gauge symmetries. New strict gauge U(1) symmetry (similar to U(1) symmetry of electrodynamics) is excluded for known particles but is possible, being ascribed to the fermions of 4th generation only.

This provides theoretic motivation for stability of the lightest fermion of 4th generation, assumed to be neutrino. Under the condition of existence of strictly conserved charge, associated to 4th generation, the lightest 4th generation quark Q (either U or D) can decay only to 4th generation leptons owing to GUT-type interactions, what makes it sufficiently long living.

Whatever physical reason was for a stability of new hypothetical particles, it extends potential for testing respective hypothesis due to its implications in cosmology.

If the lifetime of the lightest 4th generation quark exceeds the age of the Universe, primordial Q-quark (and -quark) hadrons should be present in the modern matter. If this lifetime is less than the age of the Universe, there should be no primordial 4th generation quarks, but they can be produced in cosmic ray interactions and be present in cosmic ray fluxes. The search for this quark is a challenge for the present and future accelerators.

It is assumed that up-quark of 4th generation (U) is lighter than its down-quark (D). The opposite assumption is found to be virtually excluded, if D is stable. The reason is that D-quarks might form stable hadrons with electric charges ±1 (, , ), which eventually form hydrogen-like atoms (hadron is combined with into +1 bound state), being strongly constrained in surrounding matter.

The following hadron states containing (meta)stable U-quarks (U-hadrons) are expected to be (meta) stable and created in early Universe: “baryons” , , ; “antibaryons” , ; meson (¯U u)0. The absence in the Universe of the states (), (U ¯u) containing light antiquarks are suppressed because of baryon asymmetry. Stability of double and triple U bound states (UUu), (UUU) and (), () is provided by the large chromo-Coulomb binding energy (∝ \_2 QCD ·mQ) [10,11]. Formation of these states in particle interactions at accelerators and in cosmic rays is strongly suppressed, but they can form in early Universe and cosmological analysis of their relics can be of great importance for the search for 4th generation quarks.

An electromagnetic binding of with into neutral nucleus-size atom-like state (O-Helium ) should be accompanied by a nuclear fusion of (Uud)+ and into lithium-like isotope [4He(Uud)] in early Universe. The realization of such a fusion requires a marginal supposition concerning respective cross section. Furthermore, assumption of U(1)-gauge nature of the charge, associated to U-quarks, is needed to avoid a problem of overproduction of anomalous isotopes by means of an y-annihilation of U-relics ([4He(Uud)], (UUu), (UUU), 4He, 4He, ()). Residual amount of U-hadrons with respect to baryons in this case is estimated to be less than in Universe in toto and less than at the Earth.

A negative sign charge asymmetry of U-quarks in Universe can provide a nontrivial solution for dark matter (DM) problem. For strictly conserved charge such asymmetry in implies corresponding asymmetry in leptons of 4th generation. In this case the most of in Universe are contained in O-Heliumstates [4He] and minor part of them inmesons . On the other hand the set of direct and indirect effects of relic U-hadrons existence provides the test in cosmic ray and underground experiments which can be decisive for this hypothesis.

1. **Freezing out of U-quarks.**

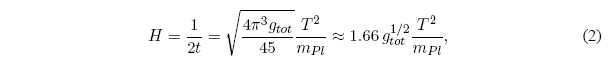
In the early Universe at temperatures highly above their masses fermions of 4th generation were in thermodynamical equilibrium with relativistic plasma. When in the course of expansion the temperature T falls down below the mass of the lightest U-quark, m, equilibrium concentration of quark-antiquark pairs of 4th generation is given by



where = 6 is the effective number of their spin and color degrees of freedom. We use

the units ħ= c = k = 1 throughout this paper.

The expansion rate of the Universe at RD-stage is given by the expression



where temperature dependence follows from the expression for critical density of the Universe

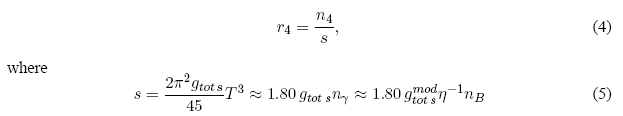


When it starts to exceed the rate of quark-antiquark annihilation



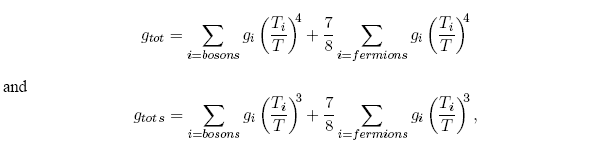
in the period, corresponding to T = < m, quarks of 4th generation freeze out, so that

their concentration does not follow the equilibrium distribution Eq.(1) at T < . For a convenience we introduce the variable



is the entropy density of all matter. In Eq.(5) s was expressed through the thermal photon number density and also through the baryon number density , for which at the modern epoch we have .

Under the condition of entropy conservation in the Universe, the number density of the frozen out particles can be simply found for any epoch through the corresponding thermal photon number density n. Factors  and  take into account the contribution of all particle species and are defined as



where and are the number of spin degrees of freedom and temperature of ultra-relativistic bosons or fermions. For epoch T ≪ ≈ 0.5MeV it is assumed that only photons and neutrinos with give perceptible contribution into energy (until the end of RD-stage) and entropy (until now) densities so one has



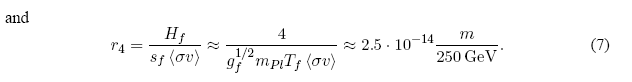
For modern entropy density we have 

From the equality of the expressions Eq.(2) and Eq.(3) one gets

with being the proton mass and obtains, taking



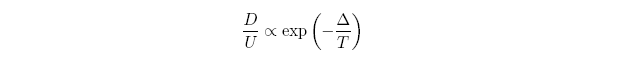




Index ”f” means everywhere that the corresponding quantity is taken at T = . Note, that the result Eq.(7), obtained in approximation of ”instantaneous” freezing out, coincides with more accurate one if and  can be considered (as in given case) to be constant. Also it is worth to emphasize, that given estimation for r4 relates to only 4th quark or 4th antiquark abundances, assumed in this part to be equal to each other.

Note that if , where is the mass of D-quark (assumed to be heavier, than U-quark) the frozen out concentration of 4th generation quarks represent at > T > Δ a mixture of nearly equal amounts of and pairs.

At T < Δ the equilibrium ratio



is supported by weak interaction, provided that β-transitions (U → D) and (D → U) are in equilibrium. The lifetime of D-quarks, τ, is also determined by the rate of weak (D → U) transition, and at t ≫ τ all the frozen out pairs should decay to pairs.

At the temperature annihilation of U-quarks to gluons and to pairs of light quarks→ gg, terminates and pairs are frozen out. The frozen out concentration is given by Eq.(7). Even this value of primordial concentration of U-quarks with the mass m = 250 GeV would lead to the contribution into the modern density , which

is by an order of magnitude less than the baryonic density, so that in the charge symmetric case U-quarks cannot play a significant dynamical role in the modern Universe.

The actual value of primordial U-particle concentration should be much smaller due to QCD, hadronic and radiative recombination, which reduce the abundance of frozen out U-particles. y-Interaction can play essential role in successive evolution to be considered. It accounts for radiative recombination and plays crucial role in galactic evolution of U-hadrons.

1. **Hadronic recombination.**

After QCD phase transition at T = ≈ 150MeV quarks of 4th generation combine with light quarks into U-hadrons. In baryon asymmetrical Universe only excessive valence quarks should enter such hadrons. Multiple U states formation can start only in processes of hadronic recombination for U-quark mass m < 700 GeV.

As it was revealed in [4,5] in the collisions of such mesons and baryons recombination of U and into unstable ( ) ”charmonium -like” state can take place, thus successively reducing the U-hadron abundance. Hadronic recombination should take place even in the absence of long range y-interaction of U-particles. So, we give first the result without the account of radiative recombination induced by this interaction. Also there is a large uncertainties in the estimation of hadronic recombination rate.

For the smallest allowed mass of U-quark, diquarks (UU), () and the triple U (and ) states (UUU), () cannot form before QCD phase transition. Therefore U-baryonic states (UUu), (UUU) and their antiparticles should originate from single U (and ) hadron collisions. The rate of their creation shares the same theoretical uncertainty as in the case of () formation, considered above. Moreover, while baryon (UUu) can be formed (e.g. in reaction (Uud) + (Uud) → (UUu) + n), having no energetic threshold, formation of antibaryon () may be suppressed at smallest values of m by the threshold of nucleon production in reaction ()+() → ()+p+, which can even exceed binding energy. In further consideration we will not specify -hadronic content, assuming that (), () and () can be present with appreciable fraction, while the content of residual U-hadrons is likely to be realized with multiple U-states and with suppressed fraction of single U-states. Nevertheless it cannot be ignored that single U-baryonic states (Uud) because only reliable inference on their strong suppression would avoid opposing to strong constraint on +1 heavy particles abundance.

1. **U-hadrons in galactic matter.**

In the astrophysical body with atomic number density the initial U-hadron abundance  can decrease with time due to recombination. It is referred that U-quark abundance as U-hadron one (as if all U-hadrons were composed of single U-quarks).

Under the neutrality condition the relative U-hadron abundance  is governed by the equation

 (8)

The solution of this equation is given by

 (9)

By definition , where  is the averaged atomic weight of the considered matter and is the initial U-hadron to baryon ratio.

Taking for averaged atomic number density in the Earth ≈ , one finds that during the age of the Solar system primordial U-hadron abundance in the terrestrial matter should have been reduced down to ≈ . One should expect similar reduction of U-hadron concentration in Sun and all the other old sufficiently dense astrophysical bodies. Therefore in our own body we might contain just one of such heavy hadrons. However, the persistent pollution from the galactic gas nevertheless may increase this relic number density to much larger value ( ≈ ).

The principal possibility of strong reduction in dense bodies for primordial abundance of exotic charge symmetric particles due to their recombination in unstable charmonium like systems was first revealed in [12] for fractionally charged colorless composite particles(fractons). The U-hadron abundance in the interstellar gas strongly depends on the matter evolution in Galaxy, which is still not known to the extent.

1. **ANO-helium catalyzed processes.**

As soon as ANO-helium is formed, it catalyzes annihilation of deficit U-hadrons and N. Charged U-hadrons penetrate neutral ANO-helium, expel , bind with anutium and annihilate falling down the center of this bound system. The rate of this reaction is and an excess k = is sufficient to reduce the primordial abundance of (Uud) below the experimental upper limits. N capture rate is determined by the size of () ”atom” in ANO-helium and its annihilation is less effective.

The size of ANO-helium is of the order of the size of 4He and for a nucleus A with electric charge Z > 2 the size of the Bohr orbit for a (Z) ion is less than the size of nucleus A. This means that while binding with a heavy nucleus penetrates it and effectively interacts with a part of the nucleus with a size less than the corresponding Bohr orbit. This

size corresponds to the size of , making O-helium the most bound (Z)-atomic state.

The cross section for interaction with hadrons is suppressed by factor  , where and are quark transverse momenta in normal hadrons and in anutium, respectively. Therefore anutium component of (ANOHe) can hardly be captured and bound with nucleus due to strong interaction. However, interaction of the component of (ANOHe) with a  nucleus can lead to a nuclear transformation due to the reaction , provided that the masses of the initial and final nuclei satisfy the energy condition , where = 1.6MeV is the binding energy of O-helium and M(4, 2) is the mass of the nucleus. The final nucleus is formed in the excited  state, which can rapidly experience \_- decay, giving rise to (ANOHe) regeneration and to effective quasi-elastic process of (ANOHe)-nucleus scattering. It leads to possible suppression of ANO-helium catalysis of nuclear transformations in matter.

1. **Signatures for U-hadrons in accelerator experiments**

Metastable U-quark within a wide range of expected mass can be searched on LHC and Tevatron. In spite on that its mass can be quite close to that of t-quark, strategy of their search should be completely different. U-quark in framework of considered model is metastable and will form metastable hadrons at accelerator contrary to t-quark.

Detailed analysis of possibility of U-quark search requires quite deep understanding of physics of interaction between metastable U-hadrons and nucleons of matter. However, strategy of U-quark search can be described in general outline, by knowing mass spectrum of U-hadrons, (differential) cross sections of their production. LHC certainly will provide a better possibility for U-quark search than Tevatron. Cross section of U-quark production in pp-collisions at the center mass energy 14 TeV is presented on the Fig. 1. For comparison, cross sections of 4th generation leptons are shown too. Cross sections of U- and D- quarks does not virtually differ.

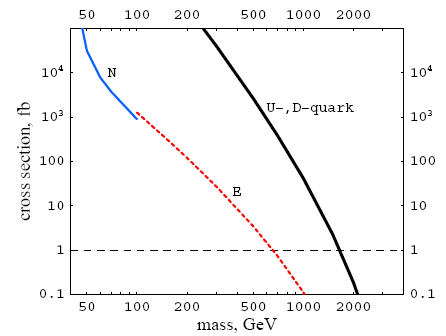
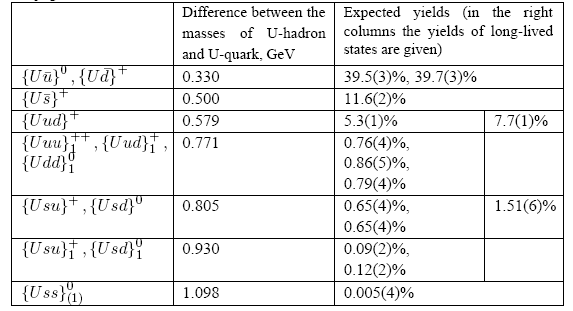


Figure 1. Cross sections of production of 4th generation particles (N, E, U, D) at LHC. Horizontal dashed line shows approximate level of sensitivity to be reached after first year of LHC operation.

Heavy metastable quarks will be produced with high transverse momentum , velocity less than speed of light. In general, simultaneous measurement of velocity and momentum enables to find the mass of particle. Information on ionization losses is, as a rule, not so good thereto. All these features are typical for any heavy particle, while there can be subtle differences in the shapes of its angle-, -distributions, defined by concrete model which it predicts.

It is peculiarities of long-lived hadronic nature what can be of special importance for clean selection of events of U-quarks creation. U-quark can form a whole class of U-hadronic states which can be perceived as stable in condition of experiment contrary to their relics in Universe. However, as we pointed out, double, triple U-hadronic states cannot be virtually created in collider. Many other hadronic states whose lifetime is >∼ s should look like stable. In the Table 1 expected mass spectrum of U-hadrons, obtained with the help of code Pythia [13], is presented.

Table 1. Mass spectrum and relative yields in LHC for U-hadrons. The same is for charged conjugated states.



The lower indexes in notation of U-hadrons in the Table 1 mean (iso)spin (I) of the light quark pair. From comparison of masses of different U-hadrons it follows that all I = 1 U-hadrons decay quickly emitting π-meson or γ-quantum, except (Uss)-state. In the right column the expected relative yields are present. Unstable I = 1 U-hadrons decay onto respective I = 0 states, increasing their yields.

There are two mesonic states being quasi-degenerated in mass: () and () (we skip here discussion of strange U-hadrons). In interaction with medium composed of u and d quarks transformations of U-hadrons into those ones containing u and d are preferable (as it is the case in early Universe). From these it follows, that created pair of quarks will fly out from the vertex of pp-collision in form of U-hadron with positive charge in about 60% of such events and with neutral charge in 40% and in form of anti-U-hadron with negative charge in 60% and neutral in 40%. After traveling through detectors a few nuclear lengths from vertex, U-hadron will transform in (roughly) 100% to positively charged hadron (Uud) whereas anti-U-hadron will transform in 50% to negatively charged U-hadron () and in 50% to neutral U-hadron ().

This feature will enable to discriminate the considered model of U-quarks from variety of alternative models, predicting new heavy stable particles. Note that if the mass of Higgs boson exceeds 2m, its decay channel into the pair of stable will dominate over the , 2W, 2Z and invisible channel to neutrino pair of 4th generation [14]. It may be important for the strategy of heavy Higgs searches.

1. **Conclusion.**

To conclude, the existence of hidden stable or metastable quark of 4th generation can be compatible with the severe experimental constraints on the abundance of anomalous isotopes in Earth’s atmosphere and ground and in cosmic rays, even if the lifetime of such quark exceeds the age of the Universe. Though the primordial abundance f = r4/rb of hadrons, containing such quark (and antiquark) can be hardly less than f ∼ in case of charge symmetry, their primordial content can strongly decrease in dense astrophysical objects (in the Earth, in particular) owing to the process of recombination, in which hadron, containing quark, and hadron, containing antiquark, produce unstable charmonium-like quark-antiquark state.

It was shown in the present paper that if U-quark is the lightest quark of the 4th generation, and the lightest free U-hadrons are doubly charged (UUU)- and (UUu)-baryons and electrically neutral ()-meson, the predicted abundance of anomalous helium in Earths atmosphere and ground as well as in cosmic rays is below the existing experimental constraints but can be within the reach for the experimental search in future. To realize this possibility nuclear binding of all the (Uud)-baryons with primordial helium is needed, converting potentially dangerous form of anomalous hydrogen into less dangerous anomalous lithium. Then the whole cosmic astrophysics and present history of these relics are puzzling and surprising, but nearly escaping all present bounds.

First year operation of the accelerator LHC has good discovery potential for U(D)-quarks with mass up to 1.5 TeV. U-hadrons born at accelerator will distinguish oneself by high pt, low velocity, by effect of a charge flipping during their propagation through the detectors. All these features enable strongly to increase efficiency of event selection from not only background but also from alternative hypothesis.

We believe that a tiny trace of heavy hadrons as anomalous helium and stable neutral O−Helium and mesons1 may be hidden at a low level in our Universe 

and even at much lower level here in our terrestrial matter a density in case of charge symmetry. There are good reasons to bound the 4th quark mass below TeV energy.

Therefore the mass window and relic density is quite narrow and well defined, open to a

final test. In case of charge asymmetry of 4th generation quarks, a nontrivial solution of the problem of dark matter (DM) can be provided due to neutral O−Helium-like U-hadrons states (ANO-helium in case of y-interaction existence). Such candidates to DM have many interesting implications in BBN, large scale structure of Universe and physics of DM. It should catalyze new types of nuclear transformations, reminding alchemists’ dream on the philosopher’s stone. It challenges direct search for species of such composite dark matter and its constituents. A very low probability for their existence is strongly compensated by the expectation value of their discovery.

**8. References**

1. S. Dimopoulos et al., Phys. Rev. D41 (1990), 2388.

2. C.B. Dover; T.K. Gaisser; G. Steigman, Phys. Rev. Lett. 42 (1979), 1117. S.Wolfram, Phys. Lett. B82 (1979), 65. G.D. Starkman et al., Phys. Rev. D41 (1990), 3594. D. Javorsek et al., Phys. Rev. Lett. 87 (2001), 231804. S. Mitra, Phys. Rev. D70 (2004), 103517; arXiv:astro-ph/0408341. G.D. Mack, J.F. Beacom, G. Bertone, Phys. Rev. D76 (2007), 043523; arXiv:0705.4298 [astro-ph].

3. B.D. Wandelt et al., arXiv:astro-ph/0006344. P.C. McGuire, P.J. Steinhardt, arXiv:astro-ph/0105567. G. Zaharijas, G.R. Farrar, Phys. Rev. D72 (2005), 083502; arXiv:astro-ph/0406531.

4. M.Yu. Khlopov, K.I. Shibaev, Gravitation and Cosmology, Suppl. 8 (2002), 45.

5. K.M. Belotsky, M.Yu. Khlopov, K.I. Shibaev, Gravitation and Cosmology, Suppl. 6 (2000), 140.

6. D. Fargion et al., JETP Letters 69 (1999), 434; arXiv:astro/ph-9903086.

7. D. Fargion et al., Astropart. Phys. 12 (2000), 307; arXiv:astro-ph/9902327.

8. K.M. Belotsky, M.Yu. Khlopov, Gravitation and Cosmology, Suppl. 8 (2002), 112.

9. K.M. Belotsky, M.Yu. Khlopov, Gravitation and Cosmology 7 (2001), 189.

10. S.L. Glashow, arXiv:hep-ph/0504287.

11. D. Fargion, M. Khlopov, arXiv:hep-ph/0507087.

12. M.Yu. Khlopov, JETP Lett. **33** (1981), 162.

13. T. Sj¨ostrand et al., Computer Phys. Commun. **135** (2001), 238; arXiv:hep-ph/0010017.

14. K.M. Belotsky et al., Phys. Rev. **D68** (2003), 054027; arXiv:hep-ph/0210153