National Research Nuclear University “MEPhI”

Department 40 (Physics of Elementary Particles)

Report on the course “Introduction into Cosmoparticle physics”

**Anomalous Isotopes as a Probe for**

**New Stable Forms of Matter**

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Moscow, 2011.

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10. **Introduction.**

It is known that Standard Big Bang Nucleosynthesis gives rise to formation of light elements only and its theory predicts negligible pre-galactic abundance of elements, heavier than lithium. Thispoint can change drastically, if there exist stable charged leptons and/or quarks. Several elementary particle frames for heavy stable charged particles were considered:

1. A heavy quark and heavy neutral lepton (neutrino with mass above half the Z-Boson mass) of fourth generation, which can avoid experimental constraints and form composite dark matter species [1];
2. A Glashow’s “Sinister” heavy tera-quark U and tera-electron E, which can form a tower of tera-hadronic and tera-atomic bound states with “tera-helium atoms” (UUUEE) considered as dominant dark matter [2];
3. AC-leptons, predicted in the extension of standard model, based on the approach of almost-commutative geometry, can form evanescent AC-atoms, playing the role of dark matter [3];
4. It was shown in [4], that an elegant solution is possible in the framework of walking Technicolor models and can be realized without an *ad hoc* assumption on charged particle excess, made in the approaches (a)-(c) [5];
5. 5th family of Norma Mankoc-Borstnik[6]

In all these models, predicting stable charged particles, the particles escape experimental discovery, because they are hidden in elusive atoms, maintaining dark matter of the modern Universe. It offers new solution for the physical nature of the cosmological dark matter. The main problem for these solutions is to suppress the abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium.

Indeed, it turned out that the necessary condition for the considered scenario, avoiding anomalous isotopes overproduction, is absence of stable particles with charge -1, so that stable negatively charged particles should only have charge -2.After it is formed in Big Bang Nucleosynthesis, $^{++}$ screens the $A^{--}$charged particles in composite ($^{++}A^{--}$) O-helium “atoms”. These neutral primordial nuclear interacting objects contribute the modern dark matter density and play the role of a nontrivial form of strongly interacting dark matter.

The active influence of this type of dark matter on nuclear transformations seems to be incompatible with the expected dark matter properties. However, it turns out that the considered scenario is not easily ruled out and challenges the experimental search for various forms of O-helium and its charged constituents.

Binding of various types of such particles with $$ results in different forms of O-helium atoms: O-helium, OLe-helium, ANO-helium or techni-O-helium. However, all these different forms of O-helium have the same size (see 3), the same cross section for interaction with baryonic matter and play the same role in nuclear transformations.

In all these forms of O-helium $O^{--}$ behave either as leptons or as specific ”hadrons” with strongly suppressed hadronic interaction. Therefore O-helium interaction with matter is determined by nuclear interaction of He. These neutral primordial nuclear interacting objects contribute the modern dark matter density and play the role of a nontrivial form of strongly interacting dark matter. I’ll call them all O-helium (OHe) in our further discussion. This work will be specified on the general case of OHe.

1. **Formation of O-helium.**

In the Big Bang Nucleosynthesis, $$ is formed with an abundance $r\_{He}$ =0.1$r\_{B}$ = 8·$10^{-12}$and, being in excess, binds all the negatively charged species into atom-like systems.

At a temperature T <$I\_{0}$ = $Z\_{TC}^{2}Z\_{He}^{2}α^{2}m\_{He}$/2 ~1.6MeV, where α is the fine structure constant, and $Z\_{TC}^{}$ = −2 stands for the electric charge of O,the reaction

$O^{--}$ + $^{++}$ → γ + OHe (1)

can take place. In these reactions neutral O-helium “atoms” (OHe) are produced. The size of these “atoms” is

(2)

Virtually all the free $O^{--}$ are trapped by helium and their remaining abundance becomes exponentially small.

For particles $O^{-}$with charge −1, as for tera-electrons in the sinister model [7],$$ trapping results in the formation of a positively charged ion $(^{++}O^{-})^{+}$,result in dramatic over-production of anomalous hydrogen. Therefore, only the choice of −2 electric charge for stable particles makes it possible to avoid this problem. In this case, 4He trapping leads to the formation of neutral O-helium *O-helium “atoms”* ($^{++}O^{--}$).

At temperature T < $T\_{od}$ ~ 200$S\_{2}^{2/3}$eV the energy and momentum transfer from baryons to O-helium is not effective because where $m\_{0}$ is the mass of the OHe atom and $S\_{2}$ = $m\_{0}$/(1TeV). Here and is the baryon thermal velocity. Then O-helium gas decouples from plasma. It starts to dominate in the Universe after at  and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding dark matter scenario.

At the total mass of the OHe gas with density is equal to within the cosmological horizon $l\_{h}$ = t. In the period of decoupling T = $T\_{od}$, this mass depends strongly on the O-helium mass $S\_{2}$ and is given by , $M\_{od}$ ~ $10^{11}S\_{2}^{-2}M\_{⊙}$, where $M\_{⊙}$ is the solar mass. O-helium is formed only at $T\_{0}$ and its total mass within the cosmological horizon in the period of its creation is It leads to a Warmer than Cold scenario for O-helium dark matter.

1. **Primordial heavy elements from O-helium catalysis.**

The main problem of calculation of abundances of anomalous isotopes in the composite dark matter model is in the nuclear physics of OHe, which is only in the process of its development. O-helium looks like an α particle with a shielded electric charge. It can closely approach nuclei due to the absence of a Coulomb barrier. Because of this in the presence of O-helium the character of Standard Big Bang Nucleosynthesis(SBBN) processes should change drastically. However, it might not lead to immediate contradictions with the observational data.

The interaction of the $$ component of ($^{++}A^{--}$) with a $$ nucleuscan lead to a nuclear transformation due to the reaction



provided that the masses of the initial and final nuclei satisfy the energy condition



where $I\_{0}$ = 1.6MeV is the binding energy of O-helium and M(4, 2) is the massof the $$ nucleus.

This condition is not valid for stable nuclei participating in reactions of the SBBN. However, tritium $$, which is also formed in SBBN with abundance$$/H ~$10^{-7}$ satisfies this condition and can react with O-helium, forming $$ and opening the path of successive O-helium catalyzed transformations to heavy nuclei. This effect might strongly influence the chemical evolution of matter on the pre-galactic stage and needs a self-consistent consideration within the Big Bang Nucleosynthesis network.

• On the path of reactions (4), the final nucleus can be formed in the excited(α,M(A,Z)) state, which can rapidly experience an α- decay, giving rise to O-helium regeneration and to an effective quasi-elastic process of($^{++}O^{--}$)-nucleus scattering. It leads to a possible suppression of the O-helium catalysis of nuclear transformations .

• The path of reactions (4) does not stop on $$ but goes further through$$, $$, $$, ... along the table of the chemical elements.

• The cross section of reactions (4) grows with the mass of the nucleus, making the formation of the heavier elements more probable and moving the main output away from a potentially dangerous Li and B overproduction.

 Charged massive particles Big Bang Nucleosynthesis(BBN), studying the influence of unstable negatively charged massive particles on BBN. Bound states of metastable singly charged particle $O^{-}$ with nuclei can catalyze formationof lithium and even elements with A> 8. The importantdifference of SBBN considered in these papers, from our approach, is that singly charged particles $O^{-}$ with charge −1 do not screen the +2 charge of He in a$(HeO)^{+}$ion-like bound system, and the Coulomb barrier of the $(HeO)^{+}$ioncan strongly hamper the path for the creation of heavy isotopes.

1. **O-helium catalyzed processes in the Earth.**

The first evident consequence of the proposed model is an inevitable presence of OHe in terrestrial matter. This is because terrestrial matter appears opaque to O-helium and stores all its in-falling flux.

If the OHe capture by nuclei is not effective, its diffusion in matter is determined by elastic collisions, which have a transport cross section per nucleon

 **** (6)

In atmosphere, with effective height $L\_{atm}$ = 106 cm and baryon number density $n\_{B}$=6·$10^{20}cm^{-3}$, the opacity condition is not strong enough. Therefore, the in-falling OHe particles are effectively slowed down only after they fall down terrestrial surface in 16$S\_{2}$meters of water (or 4$S\_{2}$ meters of rock). Then they drift with velocity cm/ s (where A ~30 is the average atomic weight in terrestrial surface matter, and g = 980 cm/$S\_{2}$),sinking down the center of the Earth on a timescale  s, where $R\_{E}$ is the radius of the Earth.

The in-falling O-helium flux from dark matter halo is ,where the number density of OHe in the vicinity of the Solar System is $n\_{0}$ =and the averaged velocity cm/ s. During the lifetime of the Earth, about  O-helium atoms were captured. If OHe dominantly sinks down the Earth, it should be concentrated near the Earth’s center within a radius , which is ≤ cm, for the Earth’s central temperature and density .

Near the Earth’s surface, the O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes. It gives

 **** (7)

This number density corresponds to the fraction

  (8)

relative to the number density of the terrestrial atoms

 These neutral ($^{++}O^{--}$) “atoms” may provide a catalysis of cold nuclear reactions in ordinary matter (much more effectively than muon catalysis). This effect needs a special and thorough investigation. On the other hand, if $O^{--}$capture by nuclei, heavier than helium, is not effective and does not lead to a copious production of anomalous isotopes , the ($^{++}O^{--}$) diffusion in matteris determined by the elastic collision cross section (6) and may effectively hide O-helium from observations.

1. **Direct search for O-helium.**

In underground detectors, OHe “atoms” are slowed down to thermal energies and give rise to energy transfer ~2.5·$10^{-3}$eVA/$S\_{2}$, far below the threshold for direct dark matter detection. It makes this form of dark matter insensitive to the CDMS constraints. However, OHe induced nuclear transformation can result in observable effects.

Therefore, a special strategy of such a search is needed, that can exploit sensitive dark matter detectors on the ground or in space. In particular, a few g of superfluid $$ detector, situated in ground based laboratory can be used to put constraints on the in-falling O-helium flux from the galactic halo.

1. **Detection of O-helium**

The nuclear interaction of O-helium with cosmic rays gives rise to ionization of this bound state in the interstellar gas and to acceleration of free $O^{--}$ in the Galaxy. Assuming a universal mechanism of cosmic ray acceleration the anomalous low Z/A component of −2 charged $O^{--}$can be present in cosmic rays and be within the reach for PAMELA and AMS02 cosmic ray experiments.

Inelastic interaction of O-helium with the matter in the interstellar space and its de-excitation can give rise to radiation in the range from few keV to few MeV. One can expect two kinds of inelastic processes in the matter with nuclei (A,Z), having atomic number A and charge Z: first one was described in (4) and (5) and the second one is

A + ($^{++}X^{--}$) → [A($^{++}X^{--}$)] + γ (9)

The explanation of the results of DAMA/NaI [10] and DAMA/LIBRA [11] experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nucleus, in which OHe is situated beyond the nucleus. Therefore the positive result of these experiments is explained by reaction (9) with nuclei in DAMA detector.

The nuclear potential depends on the relative distance between He and nucleus and we take it in the form

  (10)

Here $\rightharpoonaccent{r}$ is radius vector to nucleus, $\rightharpoonaccent{ρ}$ is the radius vector to He in OHe, $A\_{He}$ = 4 is atomic weight of helium, A is atomic weight of nucleus, μ and $g^{2}$ are the mass and coupling of σ meson - mediator of nuclear attraction.



Solutions of Schrodinger equation for each of the four regions, indicated on Fig. 1, and their sewing determines the condition, under which a low-energy OHe-nucleus bound state appears in the region III.





The energy of this bound state and its existence strongly depend on the parameters μ and $g^{2}$ of nuclear potential (10). On the Fig. 2 the regions of these parameters, giving 4 keV energy level in OHe bound state with sodium are presented. Radiative capture to this level can explain results of DAMA/NaI and DAMA/LIBRA experiments with the account for their energy resolution. The lower shaded region on Fig. 2 corresponds to the case of nuclear Yukawa potential $U\_{3m}$, averaged over the orbit of He in OHe, while the upper region corresponds to the case of nuclear Yukawa potential $U\_{3b}$ with the position of He most close to the nucleus at ρ = $r\_{0}$. The result is also sensitive to the precise value of $d\_{0}$, which determines the size of nuclei R = $d\_{0}A^{1/3}$. The two narrow strips in each region correspond to the experimentally most probable value $d\_{0}$ = 1.2/(200MeV). In these calculations the mass of OHe was taken equal to $m\_{0}$ = 1TeV , however the results weakly depend on the value of $m\_{0}$ > 1TeV .

If the atoms of these anomalous isotopes are not completely ionized, their mobility is determined by atomic cross sections and becomes about 9 orders of magnitude smaller, than for O-helium. It provides conservation in the matter of detector of at least 200 anomalous atoms per 1g, corresponding to the number of events, observed in DAMA experiment. Therefore mass-spectroscopic analysis of this matter can provide additional test for the O-helium nature of DAMA signal.

1. **Conclusion.**

To conclude, the existence of heavy stable particles can offer new solutions for dark matter problem. If stable particles have electric charge, dark matter candidates can be atom-like states, in which negatively and positively charged particles are bound by Coulomb attraction. In this case there is a serious problem to prevent overproduction of accompanying anomalous forms of atomic matter.

Indeed, recombination of charged species is never complete in the expanding Universe, and significant fraction of free charged particles should remain unbound. Free positively charged species behave as nuclei of anomalous isotopes, giving rise to a danger of their over-production. Moreover, as soon as 4He is formed in Big Bang nucleo synthesis it captures all the free negatively charged heavy particles. If the charge of such particles is -1 (as it is the case for tera electron in [12]) positively charged ion $(^{++}O^{-})^{+}$ puts Coulomb barrier for any successive decrease of abundance of species, over-polluting modern Universe by anomalous isotopes. It excludes the possibility of composite dark matter with −1 charged constituents and only −2 charged constituents avoid these troubles, being trapped by helium in neutral OLe-helium , O-helium (ANO-helium) or

techni-O-helium states.

The existence of −2 charged states and the absence of stable −1 charged constituents can take place in AC-model , in charge asymmetric model of 4th generation and in walking technicolor model with stable doubly charged technibaryons and/or technileptons . To avoid overproduction of anomalous isotopes, an excess of −2 charged particles over their antiparticles in the early Universe is sufficient. In the earlier realizations of composite dark matter scenario, this excess was put by hand to saturate the observed dark matter density. In walking technicolor model this abundance of -2 charged techibaryons and/or technileptons is connected naturally to the baryon relic density. These doubly charged $O^{--}$techniparticles bind with $^{}$ in the techni-O-helium neutral states. For reasonable values of the techniparticle mass, the amount of primordial 4He, bound in this atom like state is significant and should be taken into account in comparison to observations.

A challenging problem is the nuclear transformations , catalyzed by O-helium. The question about their consistency with observations remains open, since special nuclear physics analysis is needed to reveal what are the actual O-helium effects in SBBN and in terrestrial matter. However, qualitatively one can expect much easier path for O-helium catalysis of primordial heavy elements, than in CBBN [8] or in nonthermal Nucleosynthesis [9]).The destruction of O-helium by cosmic rays in the Galaxy releases free charged heavy stable particles particles, which can be accelerated and contribute to the flux of cosmic rays. In this context, the search for stable charged particles in cosmic rays and at accelerators acquires the meaning of a crucial test for existence of basic constituents of composite dark matter.

Models of composite dark matter enrich the class of possible stable particles, which can follow from extensions of the Standard Model and be considered as dark matter candidates. One can extend the generally accepted viewpoint that new stable particles should be neutral and weakly interacting as follows: they can also be charged and play the role of DARK matter because they are hidden in atom-like states, which are not the source of visible light. Formation of Ohelium and nuclear transformations, catalyzed by it, are inevitable consequences of this extension. It makes the existence of pregalactic heavy elements (like carbon, nitrogen, oxygen, neon etc) a signature for composite dark matter. Astronomical observations might favour this prediction. Still no astronomical objects are observed without heavy elements.

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