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**

Done by 5th year student

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10. **Introduction.**

It is known that Standard Big Bang Nucleosynthesis givesrise to formation of light elements only and its theory predicts negligible pre-galacticabundance 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 particleswere considered:

1. A heavy quark and heavy neutral lepton (neutrinowith mass above half the Z-Boson mass) of fourth generation, which canavoid experimental constraints and form composite dark matter species [1];
2. A Glashow’s “Sinister” heavy tera-quark U and tera-electronE, 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 theapproach 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 inthe framework of walking Technicolor models and can berealized without an *ad hoc*assumption on charged particle excess, made in theapproaches (a)-(c) [5];
5. 5th family of Norma Mankoc-Borstnik[6]

In all these models, predicting stable charged particles, the particles escapeexperimental discovery, because they are hidden in elusive atoms, maintainingdark matter of the modern Universe. It offers new solution for the physicalnature 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 withcharge -1, so that stable negatively charged particles should only have charge -2.After it is formed in Big Bang Nucleosynthesis, $^{++}$ screens the $A^{--}$chargedparticles in composite ($^{++}A^{--}$) O-helium “atoms”. These neutral primordialnuclear interacting objects contribute the modern dark matter density andplay the role of a nontrivial form of strongly interacting dark matter.

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

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 formsof O-helium have the same size (see 3), the same cross section for interaction withbaryonic 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 interactionwithmatterisdeterminedbynuclearinteraction 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 specifiedon 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 speciesinto 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 thefine structure constant, and $Z\_{TC}^{}$ = −2 stands for the electriccharge of O,the reaction

$O^{--}$ + $^{++}$ → γ + OHe (1)

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

(2)

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

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, onlythe choice of −2 electric charge for stable particles makes it possible toavoid this problem. In this case, 4He trapping leads to the formation of neutralO-helium *O-helium “atoms”* ($^{++}O^{--}$).

At temperature T <$T\_{od}$ ~ 200$S\_{2}^{2/3}$eV **[No, here was**$ S\_{3}=m\_{0}$/(1TeV) **not** $S\_{2}$**]** 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). **[No, here was**$ S\_{3}=m\_{0}$/(1TeV).  **not** $S\_{2}=m\_{0}$/(100GeV). **]**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 equ\_2al towithin 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 totalmass within the cosmological horizon in the period of its creation is It leads to a Warmer than Cold scenario for O-helium dark matter. **If you use here S\_2 you should re-calculate all the numbers, which were obtained for S\_3**

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 closelyapproach nuclei due to the absence of a Coulomb barrier. Because of this in thepresence of O-helium the character of Standard Big BangNucleosynthesis(SBBN) processes should change drastically.However, it might not lead to immediate contradictions with the observationaldata.

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 theSBBN. 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 heavynuclei. This effect might strongly influence the chemical evolution of matter onthe pre-galactic stage and needs a self-consistent consideration within the BigBang 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, givingrise to O-helium regeneration and to an effective quasi-elastic process of($^{++}O^{--}$)-nucleus scattering. It leads to a possible suppression of theO-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, makingthe formation of the heavier elements moreprobable and moving themain output away from a potentially dangerous Li and B overproduction.

 Charged massive particles Big Bang Nucleosynthesis(BBN), studying the influence of unstable negativelycharged massive particles on BBN. Boundstates 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 singlycharged 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 ofOHein terrestrial matter. This is because terrestrial matter appears opaqueto O-helium and stores all its in-falling flux.

If the OHecapture by nuclei is not effective, its diffusion in matter isdetermined 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 strongenough. Therefore, the in-falling OHeparticles are effectively slowed down onlyafter they fall down terrestrial surface in 16$S\_{2}$meters of water (or 4$S\_{2}$ meters ofrock). Then they drift with velocity cm/ s (where A ~30is 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 OHein the vicinity of the Solar System is $n\_{0}$ =and the averaged velocity cm/ s. During thelifetime of the Earth, about  O-helium atoms werecaptured. If OHedominantly sinks down the Earth, it should be concentratednear 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 theequilibrium between the in-falling and down-drifting fluxes. It gives

 **** (7)

This number density corresponds to thefraction

  (8)

relative to the number density of the terrestrial atoms

 These neutral ($^{++}O^{--}$) “atoms” may provide a catalysis of cold nuclearreactions in ordinary matter (much more effectively than muon catalysis). Thiseffect 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 acopious production of anomalous isotopes , the ($^{++}O^{--}$) diffusion in matteris determined by the elastic collision cross section (6) and may effectively hideO-helium from observations.

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

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

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

1. **Detection of O-helium**

The nuclear interaction of O-helium with cosmic rays gives rise to ionization of this boundstate in the interstellar gas and to acceleration of free $O^{--}$in the Galaxy. Assuming a universalmechanism 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 rayexperiments.

Inelastic interaction of O-helium with the matter in the interstellar space and its de-excitationcan 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), havingatomic 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 whichOHe is situated beyond the nucleus. Therefore the positive result of theseexperiments is explained by reaction (9) with nuclei in DAMA detector.

[**I think you can remove all these details and cut from here to the end of underlighned text. The both figures are also not necessary for your aims:** The nuclear potential depends on therelative 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, μand$g^{2}$ are the mass and coupling of σmeson - mediator of nuclear attraction.



Solutions of Schrodinger equation for each of the four regions, indicatedon Fig. 1, and their sewing determinesthe condition, under which a low-energy OHe-nucleus bound state appearsin the region III.





The energy of this bound state and its existence strongly depend on theparameters μand $g^{2}$of nuclear potential (10). On the Fig. 2 the regionsof these parameters, giving 4 keV energy level in OHe bound state withsodium are presented.  **You can cut your text up to here]**

Radiative capture to this level can explain resultsof DAMA/NaI and DAMA/LIBRA experiments with the account for theirenergy resolution. **[You can also cut this:** The lower shaded region on Fig. 2 corresponds tothe case of nuclear Yukawa potential $U\_{3m}$, averaged over the orbit of Hein OHe, while the upper region corresponds to the case of nuclearYukawapotential $U\_{3b}$ with the position of He most close to the nucleus at ρ= $r\_{0}$.Theresult is also sensitive to the precise value of $d\_{0}$, which determines the sizeof nuclei R = $d\_{0}A^{1/3}$. The two narrow strips in each region correspondto the experimentally most probable value $d\_{0}$ = 1.2/(200MeV).**]** In thesecalculations the mass of OHe was taken equal to $m\_{0}$ = 1TeV , however theresults weakly depend on the value of $m\_{0}$>1TeV .

If the atoms of these anomalous isotopes are not completely ionized, their mobilityis 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 anomalousatoms per 1g, corresponding to the number of events, observed in DAMA experiment. Thereforemass-spectroscopic analysis of this matter can provide additional test for the O-helium natureof 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 teraelectron 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 stateis 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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