COMPOSITE DARK MATTER FROM STABLE CHARGED CONSTITUENTS

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Heavy stable charged particles can exist, hidden from us in bound atomlike states. Models with new stable charged leptons and quarks give rise to realistic composite dark matter scenarios. Significant or even dominant component of O-helium (atomlike system of He4 nucleus and heavy -2 charged particle) is inevitable feature of such scenarios. Possible O-helium explanation for the positron excess in the galactic bulge and for the controversy between the positive results of DAMA and negative results of other experiments is proposed.

1 Introduction

The widely shared belief is that the dark matter, corresponding to 25% of the total cosmological density, is nonbaryonic and consists of new stable particles. One can formulate the set of conditions under which new particles can be considered as candidates to dark matter (see e.g. [1][2][3] for review and reference): they should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of matter dominated stage. The easiest way to satisfy these conditions is to involve neutral weakly interacting particles. However it is not the only particle physics solution for the dark matter problem. As we show here, new stable particles can have electric charge, but escape experimental discovery, because they are hidden in atom-like states maintaining dark matter of the modern Universe.

Recently several elementary particle frames for heavy stable charged particles were proposed: (a) A heavy quark of fourth generation[4][5][6], accompanied by heavy neutrino[7], which can avoid experimental constraints[8][9] and form composite dark matter species; (b) A Glashow’s “sinister” heavy tera-quark $U$ and tera-electron $E$, forming a tower of tera-hadronic and tera-atomic bound states with “tera-helium atoms” ($UUEE$) considered as dominant dark matter[10][11]. (c) AC-leptons, predicted in the extension[12] of standard model, based on the approach of almost-commutative geometry[13], can form evanescent AC-atoms, playing the role of dark matter[12][14][16]. Finally, it was recently shown in[15] that an elegant composite dark matter solution is possible in the framework of walking technicolor models (WTC)[16].

In all these models (see review in[6][3][17]), the predicted stable charged particles form neutral atom-like states, composing the dark matter of the modern Universe. It offers new solutions 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. This problem is unresolvable, if the model predicts stable particles with charge -1, as it is the case for tera-electrons[10][11].

The possibility of stable doubly charged particles $A^{--}$ and $C^{++}$, revealed in the AC model,
offered a candidate for dark matter in the form of elusive (AC)-atoms. In the charge symmetric case, when primordial concentrations of $A^{-}\text{-}A$ and $C^{++}$ are equal, a significant fraction of relic $C^{++}$, which is not bound in (AC)-atoms, is left in the Universe and the suppression of this fraction in terrestrial matter involves new long range interaction between A and C, making them to recombine in (AC)-atoms inside dense matter bodies.

In the asymmetric case, corresponding to excess of -2 charge species, as it was assumed for $(\bar{U}\bar{U})^{--}$ in the model of stable $U$-quark of a 4th generation, their positively charged partners effectively annihilate in the early Universe. The dark matter is in the form of nuclear interacting O-helium - atom-like bound states of -2 charged particles and primordial helium, formed as soon as $He$ is produced in the Standard Big Bang Nucleosynthesis (SBBN). Such an asymmetric case was realized in WTC, where it was possible to find a relationship between the excess of negatively charged anti-techni-baryons $(\bar{U}\bar{U})^{--}$ and/or technileptons $\zeta^{--}$ and the baryon asymmetry of the Universe.

It turned out that the necessary condition for these scenarios, avoiding anomalous isotopes overproduction, is absence of stable particles with charge -1, so that stable negatively charged particles $X^{--}$ should only have charge -2. After it is formed in SBBN, $^4He$ screens the $X^{--}$ charged particles in composite $(^4He^{++}X^{--})$ O-helium “atoms”\(^3\). For different models of $X^{--}$ they are also called ANO-helium\(^5,6\), Ole-helium\(^14,15\) or techni-O-helium\(^15\). We’ll call them all O-helium ($OH\text{e}$) in our further discussion.

In all these forms of O-helium $X^{--}$ 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\(^18,19\). 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\(^14,15\) and challenges the experimental search for various forms of O-helium and its charged constituents. O-helium scenario might provide explanation for the observed excess of positrons in the galactic bulge and for the controversy between positive results of dark matter searches in DAMA/NaI (see for review\(^20\)) and DAMA/Libra\(^21\) experiments and negative results of other experimental groups.

2 O-helium Universe

Following\(^4,5,6,15\) consider charge asymmetric case, when excess of $X^{--}$ provides effective suppression of positively charged species.

In the period $100\text{s} \leq t \leq 300\text{s}$ at $100\text{keV} \geq T \geq T_o = I_o/27 \approx 60\text{keV}$, $^4He$ has already been formed in the SBBN and virtually all free $X^{--}$ are trapped by $^4He$ in O-helium “atoms” $(^4He^{++}X^{--})$. Here the O-helium ionization potential is\(^6\) $I_o = Z_x^2 Z_{He}^2 \alpha^2 m_{He}/2 \approx 1.6\text{MeV}$, where $\alpha$ is the fine structure constant, $Z_{He} = 2$ and $Z_x = 2$ stands for the absolute value of electric charge of $X^{--}$. The size of these “atoms” is\(^11,14\)

$$R_o \sim 1/(Z_x Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13}\text{cm} \quad (1)$$

O-helium, being an $\alpha$-particle with screened electric charge, can catalyze nuclear transformations, which can influence primordial light element abundance and cause primordial heavy element formation. These effects need a special detailed and complicated study. The arguments of\(^4,11,15\) indicate that this model does not lead to immediate contradictions with the observational data.

\(^a\)The account for charge distribution in $He$ nucleus leads to smaller value $I_o \approx 1.3\text{MeV}$\(^22\).
Due to nuclear interactions of its helium constituent with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (RD) stage, while the energy and momentum transfer from plasma is effective. The radiation pressure acting on the plasma is then transferred to density fluctuations of the O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon.

At temperature $T < T_{od} \approx 200S_{3}^{2/3}$ eV the energy and momentum transfer from baryons to O-helium is not effective because $n_{B} \langle \sigma v \rangle (m_{p}/m_{o})t < 1$, where $m_{o}$ is the mass of the $OHe$ atom and $S_{3} = m_{o}/(1 \text{ TeV})$. Here

$$\sigma \approx \sigma_{o} \sim \pi R_{o}^{2} \approx 10^{-25} \text{ cm}^{2},$$

(2)

and $v = \sqrt{2T/m_{p}}$ is the baryon thermal velocity. Then O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12}$ s at $T \leq T_{RM} \approx 1$ eV 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 $T > T_{RM}$ the total mass of the $OHe$ gas with density $\rho_{d} = (T_{RM}/T)\rho_{od}$ is equal to

$$M = \frac{4\pi}{3} \rho_{d} l_{h}^{3} = \frac{4\pi}{3} \frac{T_{RM}}{T} m_{Pl}(\frac{m_{Pl}}{T})^{2}$$

within the cosmological horizon $l_{h} = t$. In the period of decoupling $T = T_{od}$, this mass depends strongly on the O-helium mass $S_{3}$ and is given by

$$M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl}(\frac{m_{Pl}}{T_{od}})^{2} \approx 2 \cdot 10^{44} S_{3}^{-2} \text{ g} = 10^{11} S_{3}^{-2} M_{\odot},$$

(3)

where $M_{\odot}$ is the solar mass. O-helium is formed only at $T_{o}$ and its total mass within the cosmological horizon in the period of its creation is $M_{o} = M_{od}(T_{od}/T_{o})^{3} = 10^{37}$ g.

On the RD stage before decoupling, the Jeans length $\lambda_{J}$ of the $OHe$ gas was restricted from below by the propagation of sound waves in plasma with a relativistic equation of state $p = \epsilon/3$, being of the order of the cosmological horizon and equal to $\lambda_{J} = l_{h}/\sqrt{3} = t/\sqrt{3}$. After decoupling at $T = T_{od}$, it falls down to $\lambda_{J} \sim v_{o}t$, where $v_{o} = \sqrt{2T_{od}/m_{o}}$. Though after decoupling the Jeans mass in the $OHe$ gas correspondingly falls down

$$M_{J} \sim v_{o}^{3} M_{od} \sim 3 \cdot 10^{-14} M_{od},$$

one should expect a strong suppression of fluctuations on scales $M < M_{o}$, as well as adiabatic damping of sound waves in the RD plasma for scales $M_{o} < M < M_{od}$. It can provide some suppression of small scale structure in the considered model for all reasonable masses of O-helium. The significance of this suppression and its effect on the structure formation needs a special study in detailed numerical simulations. In any case, it can not be as strong as the free streaming suppression in ordinary Warm Dark Matter (WDM) scenarios, but one can expect that qualitatively we deal with Warmer Than Cold Dark Matter model.

Being decoupled from baryonic matter, the $OHe$ gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies. It can be easily seen that O-helium gas is collisionless for its number density, saturating galactic dark matter. Taking the average density of baryonic matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryonic objects like stars and planets are opaque for it.
3 Detection of O-helium

The composite nature of O-helium dark matter results in a number of observable effects.

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 $X^{--}$ in the Galaxy. Assuming a universal mechanism of cosmic ray acceleration the anomalous low $Z/A$ component of $-2$ charged $X^{--}$ 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. Our first estimations show that the expected signal should be below the observed gamma background.

However, taking into account that in the galactic bulge with radius $r_h \sim 1$ kpc the number density of O-helium can reach the value $n_\circ \approx 3 \cdot 10^{-3}/S^3$ cm$^{-3}$, one can estimate the collision rate of O-helium in this central region: $dN/dt = n_\circ^2 \sigma v \frac{4 \pi r_h^3}{3} \approx 3 \cdot 10^{42} S^{-2} \cdot 3^{-1}$ s$^{-1}$. At the velocity of $v_h \sim 3 \cdot 10^7$ cm/s energy transfer in such collisions is $\Delta E \approx 1$ MeV$S^3$. These collisions can lead to excitation of O-helium. If $2S$ level is excited, pair production dominates over two-photon channel in the de-excitation by $E0$ transition and positron production with the rate $3 \cdot 10^{42} S^{-2}$ s$^{-1}$ is not accompanied by strong gamma signal. According to these studies this rate of positron production for $S^3 \sim 1$ is sufficient to explain the excess in positron annihilation line from bulge, measured by INTEGRAL (see 24 for review and references). If $OH\ e$ levels with nonzero orbital momentum are excited, gamma lines should be observed from transitions $(n > m) E_{nm} = 1.598 \text{MeV}(1/m^2 - 1/n^2)$ (or from the similar transitions corresponding to the case $I_o = 1.287 \text{MeV}$) at the level $3 \cdot 10^{-4} S^{-2} (\text{cm}^2 \cdot \text{s} \cdot \text{MeV} \cdot \text{s})^{-1}$.

The evident consequence of the O-helium dark matter is its inevitable presence in the terrestrial matter, which appears opaque to O-helium and stores all its in-falling flux.

If the $OH\ e$ diffusion in matter is determined by elastic collisions, the in-falling $OH\ e$ particles are effectively slowed down after they fall down terrestrial surface. Then they drift, sinking down towards the center of the Earth with velocity

$$V = \frac{g}{n \sigma v} \approx 80 S^3 A^{1/2} \text{cm/s}. \quad (4)$$

Here $A \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A$ is the number of terrestrial atomic nuclei, $\sigma v$ is the rate of nuclear collisions and $g = 980 \text{ cm/s}^2$.

Near the Earth’s surface, the O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes. Such neutral ($^4\He^{++} X^{--}$) “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, $X^{--}$ capture by nuclei, heavier than helium, can lead to production of anomalous isotopes, but the arguments, presented in 14,15 indicate that their abundance should be below the experimental upper limits.

It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints imposed by the XQC experiment. Therefore, a special strategy of direct O-helium search is needed, as it was proposed in 26.

In underground detectors, $OH\ e$ “atoms” are slowed down to thermal energies and give rise to energy transfer $\sim 2.5 \cdot 10^{-4} \text{ eV/A}/S^3$, far below the threshold for direct dark matter detection. It makes this form of dark matter insensitive to the severe CDMS constraints. However, $OH\ e$ induced nuclear transformations can result in observable effects.

At a depth $L$ below the Earth’s surface, the drift timescale is $t_{dr} \sim L/V$, where $V \sim 400 S^3 \text{ cm/s}$ is given by Eq. (1). It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth $L \sim 10^5 \text{ cm/s}$ to the corresponding...
change in the equilibrium underground concentration of $OH_e$ on the timescale $t_{dr} \approx 2.5 \times 10^2 S^{-1}$. Such rapid adjustment of local fraction of $OH_e$ provides annual modulations of inelastic processes inside the bodies of underground dark matter detectors.

One can expect two kinds of inelastic processes in the matter with nuclei $(A, Z)$, having atomic number $A$ and charge $Z$

$$(A, Z) + (HeX) \rightarrow (A + 4, Z + 2) + X^{- -},$$

and

$$(A, Z) + (HeX) \rightarrow [(A, Z)X^{- -}] + He.$$  

The first reaction is possible, if the masses of the initial and final nuclei satisfy the energy condition

$$M(A, Z) + M(4, 2) - I_o > M(A + 4, Z + 2),$$

where $I_o = 1.6 \text{MeV}$ is the binding energy of O-helium and $M(4, 2)$ is the mass of the $^4\text{He}$ nucleus. It is more effective for lighter nuclei, while for heavier nuclei the condition is not valid and reaction should take place.

In the both types of processes energy release is of the order of MeV, which seems to have nothing to do with the signals in the DAMA experiment. However, in the reaction such energy is rapidly carried away by $He$ nucleus, while in the remaining compound state of $[(A, Z)X^{- -}]$ the charge of the initial $(A, Z)$ nucleus is reduced by 2 units and the corresponding transformation of electronic orbits with possible emission of two excessive electrons should take place. The energy difference between the $K$ orbits of the lowest lying electronic $1s$ level of the initial nucleus with the charge $Z$ and the respective levels of its compound system with $X^{- -}$ is given by

$$\Delta E = Z^2\alpha^2m_e/2 - (Z - 2)^2\alpha^2m_e/2 \approx Z\alpha^2m_e.$$  

Here we took into account that the energy difference comes from the change in the nuclear charge with the initially unchanged structure of electronic shells. It is interesting that the energy release in such transition for two $1s$ electrons in $^{53}\text{I}_{127}$ is about 2 keV, while for $^{81}\text{Tl}_{205}$ it is about 4 keV. Taking into account that the signal in the DAMA experiment was detected with similar energy of ionization, this idea deserves more detailed analysis, which might be useful for interpretation of this experiment. Since the experimental cuts in the CDMS experiment exclude events of pure ionization, which are not accompanied by phonon signal, if valid, the proposed mechanism could explain the difference in the results of DAMA and CDMS and other direct dark matter searches that imply nuclear recoil measurement, which should accompany ionization. We have discussed a possibility for such explanation in the framework of the minimal Walking Technicolor model in $^{28}$. 

An inevitable consequence of the proposed explanation is appearance in the matter of DAMA/NaI or DAMA/Libra detector anomalous superheavy isotopes of antimony (Sb with nuclear charge $Z = 53 - 2 = 51$) and gold (Au with nuclear charge $Z = 81 - 2 = 79$), created in the inelastic process and having the mass roughly by $m_o$ larger, than ordinary isotopes of these elements. 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.

Acknowledgments

I am grateful to P.Belli, K.Belotsky, J.Filippini, C.Kouvaris, F. Lebrun, A.Mayorov, P.Picozza, V.Rubakov, E.Soldatov and D.Spergel for discussions and to S.Katsanevas for support.
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