Effect of Dark Atom in Structure Formation

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Abstract

The nonbaryonic dark matter of the Universe is assumed to consist of new stable particles. A specific case is possible, when new stable particles bear ordinary electric charge and bind in heavy "atoms" by ordinary Coulomb interaction. Such possibility is severely restricted by the constraints on anomalous isotopes of light elements that form positively charged heavy species with ordinary electrons. The trouble is avoided, if stable particles $X^{--}$with charge -2 are in excess over their antiparticles (with charge $+2$) and there are no stable particles with charges $+1$ and -1. Then primordial helium, formed in Big Bang Nucleosynthesis, captures all X^{--}in neutral "atoms" of O-helium (OHe), thus creating a specific Warmer than Cold nuclear-interacting composite dark matter. In the Galaxy, destruction of OHe and acceleration of free X^{--}can result in anomalous component of cosmic rays. Collisions of OHe atoms in the central part of Galaxy results in their excitation with successive emission of electron-positron pairs, what can explain excessive radiation of positron annihilation line. Slowed down in the terrestrial matter, OHe is elusive for direct methods of underground dark matter detection based on the search for effects of nuclear recoil in WIMP-nucleus collisions. However OHe-nucleus interaction leads to their binding and in OHe-Na system the energy of such level can be in the interval of energy 2-4 keV. The concentration of OHe in the matter of underground detectors is rapidly adjusted to the incoming flux of cosmic O-helium. Therefore the rate of energy release in radiative capture of Na by OHe should experience annual modulations. It explains the results of DAMA/NaI and DAMA/LIBRA experiments. The existence of low energy bound state in OHe-Na system follows from the solution of Schrodinger equation for relative motion of nucleus and OHe in a spherically symmetrical potential, formed by the Yukawa tail of nuclear scalar isoscalar attraction potential, acting on He beyond the nucleus, and its Coulomb repulsion at distances from nuclear surface, smaller than the size of OHe.

INTRODUCTION

According to the modern cosmology, 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 elementary weakly interacting particles. However it is not the only particle physics solution for the dark matter problem and more evolved models of self-interacting dark matter are possible. In particular, new stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms would look nonluminous, since they radiate invisible light of $U(1)$ photons. In the studies of new particles Primordial Black holes can play the role of important theoretical tool (see [4] for review and references), which in particular can provide constraints on particles with hidden gauge charges [5].

1 STRUCTURE OF O-HELIUM

Here we consider composite dark matter scenarios, in which new stable particles have ordinary electric charge, but escape experimental discovery, because they are hidden in atom-like states maintaining dark matter of the modern Universe. The main problem for these scenarios 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 together with positively charged particles stable particles $E^-$with charge -1, as it is the case for teraelectrons [6, 7]. As soon as primordial helium is formed in the Standard Big Bang Nucleosynthesis (SBBN) it captures all the free E^-in positively charged (HeE)$^+$ion, preventing any further suppression of positively charged species. Therefore, in order to avoid anomalous isotopes overproduction, stable particles with charge -1 should be absent, so that stable negatively charged particles should have charge -2 only.

Elementary particle frames for heavy stable -2 charged species are provided by: (a) stable "antibaryons" $\bar{U}\bar{U}\bar{U}$ formed by anti- U quark of fourth generation [8, 9, 10, 11] (b) AC-leptons [11, 12, 13], predicted in the extension [12] of standard model, based on the approach of almost-commutative geometry [14]. (c) Technileptons and antitechnibaryons [15] in the framework of walking technicolor models (WTC) [16]. (d) Finally, stable charged clusters $\bar{u}_5\bar{u}_5\bar{u}_5$ of (anti)quarks $\bar{u}_5$ of 5 th family can follow from the approach, unifying spins and charges [17]. Since all these models also predict corresponding $+2$ charge antiparticles, cosmological scenario should provide mechanism of their suppression, what can naturally take place in the asymmetric case, corresponding to excess of -2 charge species, X^{--}. Then their positively charged antiparticles can effectively annihilate in the early Universe.

In all the models, in which new stable species belong to non-trivial representations of electroweak SU(2) group sphaleron transitions at high temperatures provide the relationship between baryon asymmetry and excess of -2 charge stable species [15, 18, 19].

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN), ^{4}He screens the X^{--}charged particles in composite $\left(^4\mathrm{He}^{++}X^{--}\right)$O-helium "atoms" [9]. For different models of X^{--}these "atoms" are also called ANOhelium [10, 11], Ole-helium [11, 13] or techni-O-helium [15]. We'll call them all O-helium (OHe) in our further discussion, which follows the guidelines of [19].

2 O-HELIUM UNIVERSE

Following [9, 10, 11, 15, 19] consider charge asymmetric case, when excess of X^{--}provides effective suppression of positively charged species.

In the period $100 \mathrm{~s} \leq t \leq 300 \mathrm{~s}$ at $100\mathrm{keV} \geq T \geq T_o = I_o/27 \approx 60\mathrm{keV}$, ^{4}He has already been formed in the SBBN and virtually all free $X^{--}$are trapped by ^{4}He in O-helium "atoms" $\left(^4\mathrm{He}^{++}X^{--}\right)$. Here the O-helium ionization potential is [1]

$$I_o = Z_x^2 Z_{He}^2 \alpha^2 m_{He}/2 \approx 1.6\mathrm{MeV},$$

where α is the fine structure constant, $Z_{\mathrm{He}} = 2$ and $Z_X = 2$ stands for the absolute value of electric charge of X^{--}. The size of these "atoms" is [9, 13]

$$R_o \sim 1/\left(Z_X Z_{He} \alpha m_{He}\right) \approx 2 \cdot 10^{-13} \mathrm{~cm}$$

[1] The account for charge distribution in He nucleus leads to smaller value $I_o \approx 1.3\mathrm{MeV}$ [29]. Here and further, if not specified otherwise, we use the system of units $\bar{h} = c = k = 1$.

O-helium, being an α-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 [9, 13, 15, 19] indicate that this model does not lead to immediate contradictions with the observational data. The conclusions that follow from our first steps in the approach to OHe nuclear physics seem to support these arguments.

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 $T < T_{od} \approx 200 S_3^{2/3}\mathrm{eV}$ the energy and momentum transfer from baryons to O-helium is not effective [9, 15] because

$$n_B \langle\sigma v\rangle \left(m_p/m_o\right) t < 1$$

where m_o is the mass of the OHe atom and $S_3 = m_o/(1\mathrm{TeV})$. Here

$$\sigma \approx \sigma_o \sim \pi R_o^2 \approx 10^{-25} \mathrm{~cm}^2$$

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 $T \leq T_{RM} \approx 1\text{eV}$ 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 $\rho_d = (T_{RM}/T)\,\rho_{tot}$ is equal to

$$M = \frac{4\pi}{3}\rho_d t^3 = \frac{4\pi}{3}\frac{T_{RM}}{T} m_{Pl}\left(\frac{m_{Pl}}{T}\right)^2$$

within the cosmological horizon $l_h = t$. In the period of decoupling $T = T_{\rm od}$, this mass depends strongly on the Ohelium mass S_3 and is given by [15]

$$M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl}\left(\frac{m_{Pl}}{T_{od}}\right)^2 \approx 2 \cdot 10^{44} S_3^{-2}\ \text{g} = 10^{11} S_3^{-2} M_{\odot},$$

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 λ_J of the OHe gas was restricted from below by the propagation of sound waves in plasma with a relativistic equation of state $p = \varepsilon/3$, 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 CONCLUSIONS

Dark atom hypothesis can explain the puzzles of direct dark matter searches. In the next semester I will try to find out the effect of dark atom in galaxy formation and so on.

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