Problems of OHe dark matter

Steve Branchu

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1 Introduction

The dark matter, which corresponds to 25 % of total cosmological density, makes it possible to understand the creation of the large scale structures in the Big Bang. This matter is named like this because it is nonluminous. The existence of dark matter was confirmed by the astronomical observations. There are more accurate methods to calculate the mass of matter in the Universe. Two of them permit to discover the dark matter for the first time : the speed of rotations of the galaxies, which come from the Newton's laws, and the luminosity of the galaxies, which relates the mass of the galaxy to its luminosity. The data obtained by this 2 methods have not the same value that means there is missing matter, i.e dark matter. The non baryonic nature of the dark matter comes from analysis of the nucleosynthesis of the Big Bang and the cosmic microwave background anisotropies. The results obtained indicate the dark matter should be stable, saturate matter density and decouple from the plasma just before matter dominance era ([1]).

Today we don't know the nature of the dark matter, i.e its physical composition, the mass of its constituents and the interaction with other particles. For every model of dark matter, simulations of the large scale structures formation have been done. The results are different according for the model of the dark matter. Some searches use the astroparticles and the LHC data and other experiments to study the physical composition of the dark matter. There are several types of dark matter, but the simpliest variant of dark matter is the Weakly Interactive Massives Particles (WIMP). This is not the unique solution for the dark matter scenario, and more elaborate models of composite dark matter are possible.

It is presented here one of the propositions for the cosmological dark matter, which is the simpliest model of dark atoms, the O-Helium dark matter, abbreviated in OHe, which corresponds to the composite dark matter model. I will explain in this referat the research about OHe, the advantages of this model and finally the problems of this model.

2 The origin of the model

The particles in the composite dark matter model can be electrically charged, but they are hidden in atom-like states maintaining dark matter of the modern Universe. This is the origin of the name of this model : the electrically charged constituents of dark atoms may be not only elementary particles, but can be composite objects.

This idea was proposed by Sheldon Glashow in his model ([2]) : it is based on million times heavier partners of normal quarks and leptons related by a strict simmetry. The lightest of these partners are the tera-electrons and tera-U-quark, they could form a stable tera-helium atom (UUU)EE, in which +2 charged quark cluster (UUU) was bound by ordinary Coulomb force with two tera-electrons. It was proposed that in the early Universe, the excessive U-quarks first bind in (UUU) cluster, which recombines then with excessive tera-electrons to form tera-helium atom. As revealed in [3], there is an unrecoverable problem : binding of U-quarks and tera-electrons is incomplete, that implies an overproduction +1 and +2 charged like (Uud), (UUu) hadrons or (UUU)E ions, which bind with ordinary electrons. It makes impossible to realize the dark atom scenario not only in Glashow's sinister model, but also in any other model predicting stable +1 and −1 charged species.

Since 2006, different solutions for dark atom scenario were proposed ([4, 5, 6, 7, 8]), in which the important role of stable −2 charged species was revealed. The OHe dark atoms scenario was first proposed in 2005 ([4]) : in this model, dark atoms are composed by stable −2 charge particles, which should be heavy ($\sim 1TeV$) called O^{--}, which are bound by the Coulomb interaction with primordial helium. The candidates for O^{--} are : (a) stable clusters of heavy quarks formed by 3 anti-U quarks of fourth generation ([9, 10, 11]), (b) AC-leptons predicted in the extension of standard model ([12]) in the case of the almost-commutative geometry, (c) Technileptons and technibaryons in the framework of walking technicolor models (WTC) ([13]), and finally (d) the stable charged clusters, composed by 3 anti-quarks of fifth family ([14]).

Creation of OHe dark matter following the scenario below : after its formation in the Standard Big Bang Nucleosynthesis (SBBN), ^4He screens the excessive O^{--} charged particles in composite O-Helium. In all the considered forms of OHe, O^{--} behaves either as a lepton or as a heavy quark cluster with strongly suppressed hadronic interaction. Thus the OHe interaction with matter is determined by the Coulomb barrier of He nucleus.

3 The atomic structure of OHe

An OHe atom is composed by a helium nucleus and a heavy double charged particle O^{--} ([15]), which is a particle with strongly suppressed hadronic interaction. There are the mass M_O and M_{H_e}, and the charge $Z_O = 2e$. The potential interaction follows the laws below :

$$V(r \geq R_{H_e}) = -\frac{Z_O Z_{H_e} \alpha}{r} \tag{1}$$

$$V(r \leq R_{H_e}) = -\frac{Z_O Z_{H_e} \alpha}{r} \left(3 - \frac{r^2}{R_{H_e}^2}\right) \tag{2}$$

where $\alpha = e^2/4\pi$ is the fine structure constant and r the distance bewteen O^{--} and the center of the nucleus. The potential is represented in Figure 1. Then, we put the expression of potential (1) in the radial time-independent Schrödinger equation, to obtain the eigenvalues of an OHe atom. At angular momentum $l = 0$, the non-modified WKB approximation was used in ([16]) as potential V is regular at the origin ($\lim_{r\to 0} rV(r) = 0$).

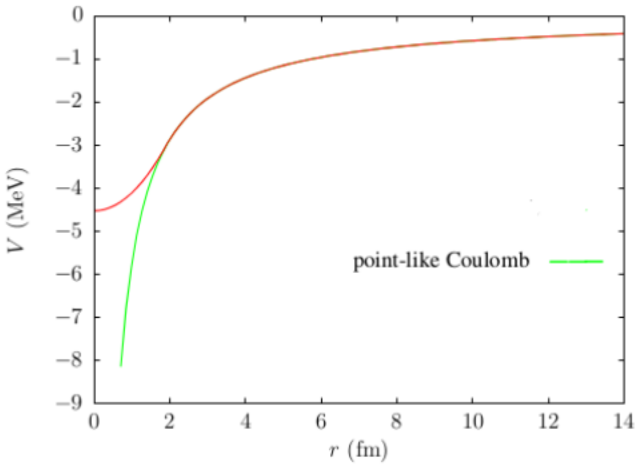

Figure 1 – The O-helium interaction potential (red) and the elementary Coulomb potential (green) obtained for a point-like helium nucleus, as a function of the distance r between O^{--} and the center of the helium nucleus.

For states at $l \neq 0$, we replace $l(l+1)$ by $(l+\frac{1}{2})^2$ in the centrifugal term of the effective potential. For the first ten values of the quantum numbers n and l, the formula looks like pure hydrogen :

$$E_n^H = -\frac{1}{2} M_{He} \frac{(Z_O Z_{He} \alpha)^2}{n^2}$$

For the fundamental level, $E_1^H = 1.5879 MeV$. In fact the potential is no longer $\propto 1/r$, so energy depends on both n and l, the energy of ground state increases with E_1^H, when we take into account the charge distribution of the helium nucleus. The eigenvalues $E_{n,l}$ are shown in Table 1. In general, at fixed n, the pure hydrogen-like energy levels constitue a lower limit to which the levels $E_{n,l}$ tend as l increases, i.e. as the states are excited and thus as O^{--} and He lie further apart from each other, making the helium nucleus increasingly point-like. As it is well known that the WKB approximation is less accurate for the deeper bound states, the energy of the ground state was computed by a variational method using up to 11 hydrogen-like s-orbitals and found the result −1.1771 MeV, which shows that the error on the values given in Table 1 is less than 0.1% ([15]).

4 The OHe model of the Universe

During the radiation dominance (RD) era, O-Helium, plasma and radiation are in thermal equilibrium, while the plasma transfers the energy and momentum to OHe ([1]). The radiation pressure in the plasma is transferred to density fluctuations to the OHe gas and transforms them in acoustic waves at scales up to the size of the horizon. To explain the

n	$l=0$	$l=1$	$l=2$	$l=3$	$l=4$	E_n^H
1	-1.1760	-	-	-	-	-1.5879
2	-0.3446	-0.3969	-	-	-	-0.3970
3	-0.1607	-0.1764	-0.1764	-	-	-0.1764
4	-9.2538^{-2}	-9.9230^{-2}	-9.9240^{-2}	-9.9239^{-2}	-	-9.9244^{-2}
5	-6.0057^{-2}	-6.3511^{-2}	-6.3511^{-2}	-6.3511^{-2}	-6.3510^{-2}	-6.3516^{-2}
6	-4.2097^{-2}	-4.4106^{-2}	-4.4106^{-2}	-4.4106^{-2}	-4.4106^{-2}	-4.4108^{-2}
7	-3.1136^{-2}	-3.2404^{-2}	-3.2404^{-2}	-3.2404^{-2}	-3.2404^{-2}	-3.2406^{-2}
8	-2.3957^{-2}	-2.4808^{-2}	-2.4811^{-2}	-2.4810^{-2}	-2.4810^{-2}	-2.4811^{-2}
9	-1.9002^{-2}	-1.9602^{-2}	-1.9602^{-2}	-1.9602^{-2}	-1.9602^{-2}	-1.9604^{-2}
10	-1.5439^{-2}	-1.5878^{-2}	-1.5878^{-2}	-1.5878^{-2}	-1.5878^{-2}	-1.5879^{-2}

n	$l=5$	$l=6$	$l=7$	$l=8$	$l=9$	E_n^H
1	-	-	-	-	-	-1.5879
2	-	-	-	-	-	-0.3970
3	-	-	-	-	-	-0.1764
4	-	-	-	-	-	-9.9244^{-2}
5	-	-	-	-	-	-6.3516^{-2}
6	-4.4105^{-2}	-	-	-	-	-4.4108^{-2}
7	-3.2403^{-2}	-3.2406^{-2}	-	-	-	-3.2406^{-2}
8	-2.4810^{-2}	-2.4810^{-2}	-2.4810^{-2}	-	-	-2.4811^{-2}
9	-1.9604^{-2}	-1.9602^{-2}	-1.9602^{-2}	-1.9602^{-2}	-	-1.9604^{-2}
10	-1.5878^{-2}	-1.5878^{-2}	-1.5878^{-2}	-1.5878^{-2}	-1.5879^{-2}	-1.5879^{-2}

Table 1 – Energy levels $E_{n,l}$ (MeV) of the OHe atom, for the first ten values of the principal quantum number n and the corresponding angular momenta $l = 0, ..., n-1$. In the last column are also shown the pure hydrogen-like solutions E_n^H n (MeV) obtained when the helium nucleus is assumed to be point-like. The exponents indicate the power of 10 by which the numbers have to be multiplied to obtain the energy in MeV ([15]).

next step of the scenario, we use the following relations :

$$v = \sqrt{\frac{2T}{m_p}} \tag{3}$$

$$\sigma \approx \sigma_0 \sim \pi R_0^2 \approx 10^{-25} cm^2 \tag{4}$$

The formula (3) is the baryon thermal velocity, with T the temperature of the plasma and m_p the mass of the proton and the relation (4) is the cross section of OHe. At temperature $T \leq T_{od} \approx 200 S_3^{2/3} eV$ the energy and momentum transfer from baryons to O-Helium is not effective because :

$$n_B \langle \sigma v \rangle (m_p/m_0) t \leq 1$$

where $S_3 = m_0/(1TeV)$, and m_0 the mass of the OHe atom. In this formula $\sigma(m_p/m_0)$ is the transport cross section per nucleon. This relation means at this temperature the baryon thermal velocity is too weak and the transport cross section per nucleon is too small to make possible the transfer of energy to OHe atoms ([4]). After OHe gas decoupled from plasma, it started to become dominant after $t \sim 10^{12}s$ at $T \approx 1eV$ and OHe atoms have the main role in the development of gravitationnal perturbations, and the formation of large scale structure. The nature of OHe determines the features of the composite dark matter scenario. At $T \geq T_{RM}$, the density of OHe gas is $\rho_d = (T_{RM}/T)\rho_{tot}$. After we obtain the total mass of OHe gas within the cosmological horizon $t = l_h$:

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

During the period of decoupling $T = T_{od}$ this mass depends strongly on the OHe mass S_3 and is given by :

$$M_{od} = \frac{T_R M}{T_{od}}m_{Pl}(\frac{m_{Pl}}{T_{od}})^2 \approx 2 \times 10^{44} S_3^{-2} g$$

At $T = T_0$ the OHe forms and within the cosmological horizon the total mass is $M_0 = M_{od}(T_{od}/T_0)^3 = 10^{37}g$.

During the radiation dominance era, just before the decoupling, the propagation of the sound waves in the plasma is limited the Jeans length λ_J of the OHe gas. The relativistic equation of state is $p = \epsilon/3$, at the cosmological horizon the Jeans length is at the same order $\lambda_J = l_h/\sqrt{3} = t/\sqrt{3}$. After decoupling it decreases to $\lambda_J \sim v_0 t$, with $v_0 = \sqrt{2T_{od}/m_0}$, and the Jeans mass decreases to :

$$M_J \sim v_0^3 M_{od} \sim 3 \times 10^{-14} M_{od}$$

we expect, at scales $M \leq M_0$ a strong suppression of fluctuations, and an adiabatic damping of sound waves in the plasma at the radiation dominance era for scales $M_0 \leq M \leq M_{od}$. This suppression has not the same effect as the free streaming suppression in the Warm Dark Matter model, and its impact on the structure formation needs a special study in detailed numerical simulations. In WDM, the free-streaming scale corresponds to the mode that enters the horizon at the time when WDM particles become non-relativistic ([17]). In the case of O-Helium, its composite nature makes the large scale structure formation more close to CDM, but a bit Warmer. Due to the slight suppression of small scale fluctuations, the OHe model is called the Warmer than Cold Dark Matter model.

After the decoupling from the baryonic matter, the OHe gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms the dark matter halos of galaxies, the problem is OHe has too small interaction to follow baryonic matter, but sufficiently large interaction to make baryonic objects opaque for it.

5 Signatures of OHe

5.1 The solution for puzzles of direct dark matter searches

Dark atom interpretation of the puzzles of direct dark matter search is based on the interactions between OHe nucleus and the baryonic matter. If dark matter can bind to normal matter, the observations from DAMA/LIBRA experiments ([18]) could be interpreted like come from the radiative capture of thermalized OHe and could depend on the detector composition and temperature ([19]). The concentration of OHe in the underground detector is determined by the equilibrium between the infalling cosmic OHe flux and its diffusion to the center of Earth. The infalling flux experiences annual changes due to Earth's rotation around Sun and modifies the OHe concentration, so this local OHe concentration possess annual modulations.

Many experiments have been done but only one gave a positive result ([19]) : DAMA/NaI and DAMA/LIBRA. The interpretation of the experiments in terms of OHe model are based on the idea that OHe slowed down in the terrestrial matter, can form a few keV bound state with sodium nucleus, if OHe is situated beyond the nucleus. The positive result of these experiments is explained by annual modulation in reaction of radiative capture in the detector :

$$A + ({}^4He^{++}O^{--}) \rightarrow [A({}^4He^{++}O^{--})] + \gamma$$

The low energy OHe-nucleus bound states is possible only for intermediate-mass nuclei : this explain the negative results of LUX experiments and all heavy nuclei detectors (XENON 100, XENON 1T etc...). To calculate the rate of this capture, [20] use an analogy with the radiative capture of neutron by proton, without the M1 transition from conservation of orbital momentum and suppression of E1 transition in the case of OHe. The rate of OHe radiative capture according to atomic numbers A and Z, the energy level E in the medium and the temperature T is given by the relation below :

$$\sigma v = \frac{f\pi\alpha 3T}{m_p^2\sqrt{2Am_pE}}\left(\frac{Z}{A}\right)^2 \tag{5}$$

with the factor $f = (m_n - m_p)/m_N \approx 1.4 \times 10^{-3}$, corresponding to the difference of mass of neutron m_n and proton m_p, relative to the mass of nucleon m_N. The capture rate is proportional to the temperature at the thermal equilibrium : this leads to a suppression of this effect in cryogenic detectors. Since OHe capture rate is proportional to the temperature, it looks like it is suppressed in cryogenic detectors by a factor of order 10^{-4}. However, for the size of cryogenic devices less, than few tens meters, OHe gas in them has the thermal velocity of the surrounding matter and the suppression relative to room temperature is only $\sim m_A/m_O$ (m_O is the mass of OHe). Then the rate of

OHe radiative capture in cryogenic detectors is given by equation (5), in which room temperature T is multiplied by factor m_A/m_O, and the equation becomes :

$$\sigma v = \frac{f\pi\alpha 3T}{m_p^2\sqrt{2Am_pE}}\left(\frac{Z}{A}\right)^2 \times \frac{m_A}{m_O} \tag{6}$$

5.2 Positron annihilation in the galactic bulge

The composite nature of O-helium dark matter results in a number of observable effects. The satellite INTEGRAL observed a positron-annihilation line excess in the galactic bulge. This observation can be explained by the presence of OHe ([15, 19]). The O-helium collisions excite the 2S level, after OHe de-excites by electron-positron pair-production. The rate of collisions between OHe particles can take place everywhere in the Galaxy. It is nonzero and grows in the regions of higher OHe density, particularly in the central part of the Galaxy because these collisions are enhanced. The collision rate is estimated to ([21]) :

$$\frac{dN}{dt} = n^2\sigma v_h \frac{4\pi}{3} r_b^3 \approx 3\times 10^{42} S_3^{-2} s^{-1}$$

At a velocity $v_h \sim 3\times 10^7 cm/s$, the energy transfered in the collisions is $\Delta E \sim 1MeVS_3$. The collisions excite the OHe gas, which de-excites by pair production, then the de-excitation in E0 transitions had been observed by excess of positron-annihilation line. However, measurement of the collisions rate depends of the density of OHe, but the theoretical estimations for dark matter are uncertain because in the bulge OHe gas density doesn't lead to strong gravitationnal effect and can vary by several orders of magnitude. The last analysis indicates a lower value of dark matter density, which makes it possible to explain the observed effect if the mass of O^{--} near 1.0 TeV.

The collisions excite the OHe gas at the first level with non-zero angular momentum, the E1 transition create gamma lines with principal quantum numbers n and m, when n is higher than m, at the energies :

$$E_{nm} = \left(\frac{1}{m^2} - \frac{1}{n^2}\right) \times 1.5879MeV$$

The interest of this predictions is to analyze and compare the unidentified lines from the center of the Milky Way. In all line emissions from the Galaxy ([15]), there are some X-Ray and gamma ray, probably produced by OHe. The important line for INTEGRAL data have an energy around 20 keV, and the X-Ray lines have a lower energy. XMM-Newton can check the observations between $0.1 - 12$keV.

Taking into account all the possible electric dipole transitions (E1) between the states of OHe between 3 and 4 keV, several hundreds of allowed lines were found in ([15]), with energies from the eV to the MeV range. The comparison between the predictions and the observations provides an effective tool to test OHe dark matter model.

5.3 Composite dark matter solution for high energy positron excess

PAMELA and AMS02 experiments ([22, 23, 24]) found an excess of high-energy cosmic-ray positrons. This can be explained by the decay of doubly positive charged techniparticles to pairs of same-sign leptons. This is the two-component dark atom model, based on Walking Technicolor sparse WIMP-like component of atom-like state, made of positive and negative doubly charged techniparticles. This is possible for the mass of decaying +2 charged particle below 1 TeV and depends on the branching ratios of leptonic channels ([19]). Since even pure lepton decay channels are inevitably accompanied by gamma radiation the important constraint on this model follows from the measurement of cosmic gamma ray background in FERMI/LAT experiment. The multi-parameter analysis of decaying dark atom constituent model is under way in order to determine the maximal model independent value of the mass of decaying +2 charge particle, at which this explanation is possible.

5.4 The LHC probes

One of the propositions to understand the constitution OHe atom, is to do searches for stable doubly charged lepton-like particles at the LHC ([19]). The objective is to compare the results with astroparticle data. The ATLAS and CMS experiments give the lower value for double charged particle around 700 GeV ([25]), this result will permit to test OHe explanation when the future data can approach 1 TeV range in this searches. Recently, a Yu S Smirnov's studies improved this result, he found a value for double charged particle around 685 GeV ([26]).

6 Some potential problems

6.1 Inelastic process

It was first assumed that the effective potential between OHe and a normal nucleus would have a barrier, preventing He and/or O^{--} from falling into the nucleus, allowing only one bound state, and decreases rapidly the interactions of OHe. Under these conditions elastic collisions dominate in OHe interactions with matter, and lead to a successful OHe scenario. The cosmological and astrophysical effects of such composite dark matter (dark atoms of OHe) are dominantly related to the helium shell of OHe and involve only one parameter of new physics, the mass of O^{--}. In this section, I want to explore another scenario ([4, 7]), in which OHe dark matter interacts strongly with normal matter : OHe is neutral, but a priori it has an unshielded nuclear attraction to matter nuclei. I explain in this section the consequences of this effect.

At the beginning of the Universe, inelastic scattering between particles of OHe and between OHe and primordial He decreased the quantity of OHe ([27]). The nuclear reactions are :

$$OHe + OHe \rightarrow O_2Be \tag{7}$$

$$OHe + He \rightarrow OBe \tag{8}$$

where Be is the beryllium. The OHe forms at a temperature T_0 which depends of it binding energy, which is 1.175 MeV, that corresponds to $T_0 = 50$keV, i.e the energy absorbed during the formation of OHe. The cosmological time is calculated with the temperature, the inelastic process start at a time :

$$t(s) \simeq \frac{1}{T^2(MeV)} \simeq \frac{1}{0.05^2} = 400s$$

after the Big Bang and continue until helium freezes out at $t_* \simeq 600s$.

During these 200 s, the rate of the quantity of OHe decreases like this :

$$\frac{dn_{OHe}}{dt} = -3Hn_{OHe} - n_{OHe}^2\sigma_1 v_1 - n_{OHe}n_{He}\sigma_2 v_2 \tag{9}$$

with n_{OHe} and n_{He} are the number densities of OHe and He, $H = 1/2t$ the expansion rate of the Universe during the radiation dominance era, σ_1, σ_2, v_1 and v_2 are respectivly the cross section and the relative velocity of the reaction (7) and (8). The only factor which affect n_{He} is the expansion :

$$\frac{dn_{He}}{dt} = -3Hn_{He} \iff n_{He}(t) = n_{He}^0\left(\frac{t_0}{t}\right)^{3/2} \tag{10}$$

where n_{He}^0 is the number density of He at $t = t_0$. We calculate the fraction of free OHe atoms due to their inelastic reactions, with the ratio f of the number density of OHe and He nuclei, $f = \frac{n_{OHe}}{n_{He}}$. The expressions (9) and (10) give the relation of evolution :

$$\frac{df}{dt} = -n_{He}f(\sigma_1 v_1 f + \sigma_2 v_2) \tag{11}$$

The cross sections σ_1 and σ_2 depend of the size of the nucleus :

$$\sigma_1 \approx 4\pi(2r_{OHe})^2 \tag{12}$$

$$\sigma_2 \approx 4\pi(r_{OHe} + r_{He})^2 \tag{13}$$

where r are the radius of respectively the OHe nucleus and the He nucleus. The both are approximately equal to 2 fm, $\sigma_1 \approx \sigma_2 \approx 64\pi 10^{-26} cm^2$. The mean relative velocities v_1 and v_2 are obtained by the Maxwell-Boltzmann velocity distributions, because the species are in thermal equilibrium with the plasma :

$$v_1 = \sqrt{\frac{8T}{\pi \mu_1}} \tag{14}$$

$$v_2 = \sqrt{\frac{8T}{\pi \mu_2}} \tag{15}$$

with $\mu_1 = \frac{m_{OHe}}{2}$ the reduced mass of OHe-OHe and $\mu_2 \simeq m_{He}$ the reduced mass of OHe-He. During the radiation-dominated era, the relation between time and temperature is : $Tt^{1/2} = T_0 t_0^{1/2}$, we insert it in the expression of velocities, and use the relation (11) to obtain :

$$\frac{df}{dt} = -\gamma \frac{1}{t^{7/4}} f(\alpha f + \beta) \tag{16}$$

with

$$\alpha = \frac{\sigma_1}{\sqrt{\mu_1}} \tag{17}$$

$$\beta = \frac{\sigma_2}{\sqrt{\mu_2}} \tag{18}$$

$$\gamma = n_{He}^0 t_0^{7/4} \sqrt{\frac{8T_0}{\pi}} \tag{19}$$

The initial condition is $f(t_0) = f_0$, the solution of (16) is :

$$f(t) = \frac{\beta f_0}{exp(\frac{4}{3}\beta\gamma(t_0^{-3/4} - t^{-3/4}))(\alpha f_0 + \beta) - \alpha} \tag{20}$$

We can calculate the number density of He at the biginning of the baryon nucleosynthesis from its actual value. It corresponds today about 10% of all baryons, and the current critical density :

$$\rho_c^1 = 5.67 \times 10^{-6} m_p/cm^3 \iff n_{He}^1 \simeq 2.8 \times 10^{-8} cm^{-3} \tag{21}$$

Then, it is necessary to add the effect of the expansion, which is proportionnal at the temperature of the CMB $n_{He}^0 = n_{He}^1 \left(\frac{T_0}{T_1}\right)^3 \simeq 2.8 \times 10^{-17} cm^{-3}$. At the early Universe the number of O^{--} particles was equal to OHe particles. Between t_0 and today, O^{--} particles may have been bound in different structures, but they have not been created or destroyed, so that their number density has only been diluted by the expansion in the same way as that of He nuclei, so that the ratio of the number density of O^{--} particles to the number density of He nuclei remains unchanged : $\frac{n_O^0}{n_{He}^0} = \frac{n_O^1}{n_{He}^1}$. The fraction of OHe hasn't been change, almost 25% of the critical density, so we can calculate the parameter $f_0 \simeq 0.05$. Now it is possible to insert this value in the equation (20) and calculate the fraction at the freeze-out time :

$$f(t_*) \simeq 5 \times 10^{-6133} \ll f_0 \tag{22}$$

this results means the OBe creation by the reaction 1 decreases rapidly. To be more clearly, the reaction (8) is prevalent, so the dark matter is now in form of OBe. The suppression of f comes when the exponential term in (20) is evaluated to be e^{14127}. This value represents the number N_2 of reactions that happened between t_0 and t_* :

$$\begin{aligned}
N_2 &= \int_{t_0}^{t_*} n_{He}(t)\sigma_2 v_2(t)dt \\
&= n_{He}^0 t_0^{3/2} \sigma_2 \sqrt{\frac{8T_0 t_0^{1/2}}{\pi\mu_2}} \int_{t_0}^{t_*} \frac{1}{t^{7/4}} dt \\
&= n_{He}^0 t_0^{7/4} \sqrt{\frac{8T_0}{\pi}} \frac{\sigma_2}{\sqrt{\mu_2}} \left(-\frac{4}{3}\right) \left(\frac{1}{t_*^{3/4}} - \frac{1}{t_0^{3/4}}\right) \\
&= \frac{4}{3}\beta\gamma \left(\frac{1}{t_0^{3/4}} - \frac{1}{t_*^{3/4}}\right)
\end{aligned}$$

This relation means the realization of the OHe dark matter model implies a very strong suppression of the reaction (8), which corresponding to $N_2 \ll 1$. This particular case needs the development of a strong dipole Coulomb barrier in OHe-He interaction.

6.2 Problems of OBe dark matter

Due to the Coulomb barrier, OBe can't capture helium nucleus, and it recombines with electrons during the radiation dominante era ([27]) at the temperature $T_{od} = 2eV$. Without this barrier there will be no suppression of inelastic reactions, in which O^{--} binds with nuclei. It makes anomalous helium the dominant form of dark matter in this scenario. After recombination the OBe gas will undergo a decoupling from the plasma and the radiation, after that there is an adiabatic damping slightly suppresses density fluctuation at scales smaller than the scale of the horizon in the period of He recombination.

This dark matter is mixed with ordinary matter in the process of galaxy formation, and become collisional on the scale of the galaxies. So there is some OBe in the stars, but the thermonuclear reaction in the stars interacts with it and create anomalous isotopes. OBe can be ionized, but the dominant part is neutral. In the atmosphere, OBe atoms are the prevalent part of the dark matter, in the ionosphere the particles are ionized by the radiation and neutralized by electron capture. When OBe fall down on the Earth there are many collisions which decrease the velocity of OBe. The cross section of OBe is in the order of $\sigma \approx 10^{-15} - 10^{-14} cm^{-2}$, with the number density of terrestrial matter $n = 0.27 \times 10^{23}$molecules/cm we calculate the OBe atoms velocity inside the Earth at :

$$V = \frac{g}{n\sigma v} \leq 2.7 \times 10^{-11} cm/s \approx 270 fm/s \tag{23}$$

To determine the OBe abundance in the Earth we need to know the equilibrium between the in-falling and down-drifting fluxes. The flux of OBe in-falling from dark matter halo is given by :

$$F = \frac{n_0}{8\pi} \times \mid \bar{V_h} + \bar{V_E} \mid \tag{24}$$

with $V_h = 220 km/s$ the speed of the Solar System, $V_E = 29.5 km/s$ the speed of the Earth and $n_0 = 3 \times 10^{-4} cm^{-3}$ is the assumed local density of OBe dark matter. To simplify the calculation, Cudell et al ([27]) didn't take into account the annual modualtion of the incoming flux and take $\mid \bar{V_h} + \bar{V_E} \mid = u \approx 300 km/s$. The equilibrium concentration of OBe is obtained by :

$$n_{0E} = \frac{2\pi \times F}{V} \tag{25}$$

and the ratio of anomalous isotopes to the total amount of the Earth matter is given by :

$$r_{0E} = \frac{n_{0E}}{n} = \frac{2\pi \times F\sigma v}{g} \geq 3.1 \times 10^{-9} \tag{26}$$

The upper limits on the anomalous helium abundance are very stringent ([28]) $r_{0E} \leq 10^{-19}$, and the rough estimate is ten orders of magnitude too large. Together with the other problems of OBe Universe stipulated above, this rules out the OBe scenario.

6.3 Problem of seasonal variation for OHe model

O-Helium fall down to the terrestrial surface with the same velocity as OBe (23). At a depth L below the Earth's surface, the drift timescale is $t_{dr} \sim L/V$ where V is given by equation (23). It means the motion of the Earth around the Sun cause a change of the incoming flux, should lead at the at the depth $L \sim 10^5$cm ([7]) to the corresponding change in the equilibrium underground concentration of OHe on the timescale $t_{dr} \approx 2.5 \times 10^2 S_3^{-1}$s ($S_3$ is defined in the section 4). In underground detectors, OHe dark atoms are slowed down to thermal energies and give rise to energy transfer $\sim 2.5 \times 10^{-4}$eVA/S_3, where $A \sim 30$ is the average atomic weight in terrestrial surface matter. OHe slowed down far below the threshold for direct dark matter detection. The equilibrium concentration of

OHe is obtained by :

$$n_{0E} = \frac{2\pi \times F}{V} = n_{0E}^{(1)} + n_{0E}^{(2)} \times \sin(\omega(t - t_0)) \quad (27)$$

where $\omega = 2\pi/T$, $T = 1year$ and t_0 is the phase. This parameters are a consequences of the rotation of the Earth. The 2 other variables are the average concentration

$$n_{0E}^{(1)} = \frac{n_0}{320 S_3 A^{1/2}} V_h \quad (28)$$

and the annual modulation of concentration

$$n_{0E}^{(2)} = \frac{n_0}{640 S_3 A^{1/2}} V_E \quad (29)$$

The rate of nuclear reactions of OHe with nuclei is proportional to the local concentration and the energy release in these reactions should lead to observable signal. There are two parts of the signal : the one determined by the constant part and the second determined by annual modulation, which is concerned by the strategy of dark matter search in DAMA experiment ([29, 30, 31, 32, 33]).

The terrestrial matter is opaque for OHe, what should inevitably lead to an effect of Earth matter shadowing for the OHe flux and corresponding diurnal modulation. This effect needs special study in the confrontation with the constraints, recently obtained in DAMA/LIBRA experiment ([19, 18]).

7 Conclusion

The O-Helium dark atom, composed by helium nuclei and a double charged O^{--} particle, is a serious candidate for the dark matter. The physical nature of OHe is at the center of the experimental astroparticles searches.

The warmer than cold dark matter scenario has the advantage to have a few parameters for explain the Universe, and the scenario is not very different from the cold dark matter scenario. The advantage is there is only one parameter in OHe scenario : the mass of OHe. The OHe dark matter can explain the observations from the center of the galaxies, especially the positron line excess due to OHe de-excitation. ATLAS experiments at LHC gave lower limits of the particles which compose OHe, but didn't rule it out yet.

The existence of heavy stable particles is one of the popular solutions for the dark matter problem. These particles are usually considered to be electrically neutral, but dark matter can also be formed by stable heavy charged particles bound in neutral atom-like states by the ordinary Coulomb attraction. The OHe dark matter model needs a deeply study about OHe-nucleus interaction and taking account the existence of the strong Coulomb barrier.

8 References

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