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Article

Measuring the effect of early universe dark matter on the primordial values of helium-4 and deuterium

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SUMMARY

Recent observations of helium-4 and deuterium abundances by the "Extremely Metal-Poor Representatives Explored by the Subaru Survey" (EMPRESS) collaboration may be evidence for an astronomical anomaly. Though the deuterium abundance matched previous observations, the helium-4 abundance was found to be lower than before, conflicting with existing scientific theories. What type of dark matter must have existed in the early universe in order to match observed deuterium and helium-4 abundance values with the theoretical predictions? In our study, we used a customized script of the Python package "PRyMordial" to investigate the effect of the presence of dark matter in the early universe on the primordial abundance values of helium-4 and deuterium to propose a solution to the tension between the theoretical and observed values of helium-4. We used a computer simulation to determine the effect of dark matter particles with varying masses on the primordial abundances of helium-4 and deuterium. We hypothesized that, through computational modeling, adding dark matter particles that are coupled to neutrinos in the early universe could create a match between the observed and theoretical abundance values of deuterium and helium-4, suggesting that this type and mass of dark matter particles could have existed in the early universe during Big Bang Nucleosynthesis. Our proposed model could not match the observed values of helium-4, indicating that inclusion of dark matter coupled to neutrinos is not sufficient to explain the lower levels of helium-4 observed by EMPRESS. To solve the helium-4 tension, further factors in the model of the early universe must be tweaked and explored.

INTRODUCTION

The current leading theory for the origin of the universe is the Big Bang theory, which has been well tested and is heavily supported. A crucial part of this theory includes the formation of the first elements starting a mere one second after the Big Bang; the first nuclei were formed in a process known as Big Bang Nucleosynthesis (BBN) (1). BBN is the first cosmic event that we have definitively observed by noticing close matches in theoretical predictions of most light element abundances from the BBN model to their observed abundances in the current universe, and through its study, the circumstances of the primordial universe can also be studied (1). During BBN, the universe was nearly homogeneous and isotropic with a neutron-to-proton ratio of one to seven (2). Neutrons, protons, electrons, photons, and other particles existed in a hot plasma, the density and temperature of which prevented the formation of any heavier particles (2). However, as the seconds went by, the universe became less dense as a result of expansion, which also led to the cooling of the universe (2). This provided adequate conditions for protons and neutrons to fuse, forming the first atomic nuclei (2). Some of the earliest nuclei formed were helium-4, isotopes of hydrogen, and lithium-7 (2).

The elements considered in this study are deuterium, an isotope of hydrogen consisting of one proton and one neutron, and helium-4, an isotope of helium consisting of two protons and two neutrons. Deuterium was the first nucleus to be formed, and its formation paved the way for the synthesis of other elements such as helium-4 (2). At the end of BBN, the universe was composed of approximately 75% hydrogen and 24% helium by mass, with less than 1% consisting of all other nuclei (2). This study focuses solely on deuterium and helium-4 as they are the only nuclei that have reliable primordial abundance data (3).

BBN successfully explains the formation of baryonic matter, or matter composed primarily of baryons such as protons and neutrons, including the previously mentioned elements that evolved over cosmic history to form the rest of the visible cosmos (4). However, this only accounts for a small fraction of the mass in the universe, as the majority of the mass is made up of dark matter (5). Dark matter is a hypothetical form of matter that interacts gravitationally with other forms of matter but does not interact with photons (5). Although dark matter cannot be observed directly through electromagnetic radiation, its existence is supported through many pieces of indirect scientific evidence. Through its interaction with gravity, the presence of dark matter can explain a variety of gravitational anomalies that cannot be explained by the theory of general relativity. Measurements of galaxy rotation curves show that gravitational activity near the edge of galaxies does not adhere to what is scientifically expected based on the mass of visible matter observed in those locations (6). The most popular explanation for this is the existence of dark matter, which we now believe makes up the majority of the mass in the universe as we know it.

Studying dark matter in the context of BBN is important because changing the particle content of the early universe alters the final abundances of helium-4 and deuterium, which are well known from observation of the current universe. Recent observations from the Extremely Metal-Poor Representatives Explored by the Subaru Survey (EMPRESS) collaboration have found the helium-4 abundance to be lower than previously found while the deuterium abundance was normal, creating an anomaly needing to be solved (7). The study used deep Subaru NIR spectroscopy to observe helium-4 and deuterium abundances with high accuracy in 64 galaxies, including 13 candidate extremely metal-poor galaxies (EMPGs), which have helium-4 abundance values that are closer to primordial values (7). After narrowing the sample down to 10 EMPGs, the results revealed that the helium-4 abundance was 0.2370 with an uncertainty of +0.0034 and -0.0033, and the deuterium abundance was (2.527 ± 0.030) × 10^{-5} (7). The EMPRESS study is reliable due to its notable difference in its galaxy sample, which includes more EMPGs than previous studies (7). Many other studies have attempted to relieve the tension between the EMPRESS results and the theoretical helium-4 values. Hypotheses range from lepton asymmetries to non-standard neutrino interactions, both of which involve new theories about neutrinos. Lepton asymmetry considers the ratio of neutrinos to antineutrinos, while non-standard neutrino interactions address extra interactions and three-neutrino mixing (8,9). Both hypotheses propose a reason for the decrease in the neutron abundance in the universe that would lead to a decrease in helium-4 abundance, which hypothetically solves the tension between theoretical values and the values observed by EMPRESS. While these are the prevailing hypotheses, current research cannot rule out other reasons for the helium-4 tension between theoretical values and the values observed by EMPRESS.

In our study, we wanted to test the effect of adding in dark matter particles of various masses to primordial abundances of helium-4 and deuterium by using their respective experimental values as standard markers. We hypothesized that, through computational modeling, adding dark matter particles coupled to neutrinos in the early universe could create a match for the observed and theoretical deuterium and helium-4 abundance values. This would solve the helium tension while also suggesting that this type and mass of dark matter particles could have been existent in the early universe during BBN. This study focused on dark matter particles coupled to neutrinos because neutrinos interact more weakly with the standard model of the universe than other particles, implying that altering the dark matter and neutrinos would likely not ruin other cosmological predictions as much as other subatomic particles would (10). Other subatomic particles interact with the standard model through the strong force, meaning the presence of dark matter and these particles would alter cosmological predictions by a larger amount than neutrinos would, making it harder to reconcile with existing understandings in the field (10). We found that this specific type of dark matter coupled to neutrinos created a match for deuterium abundances but could not resolve the helium-4 tensions, as the simulated values of helium-4 were greater than the observed values. These findings suggest that according to the parameters that we tested, this type of dark matter, which was coupled to neutrinos, was likely not present in the early universe. We acknowledge that there can likely be other parameters of the BBN model that need to be concurrently changed in order to resolve the abundance tensions and account for the presence of neutrino-coupled dark matter. Future experiments are needed to determine which type of dark matter may have been present in the early universe by either ruling out the dark matter that is coupled to neutrinos, or by manipulating other parameters of the computer simulations.

RESULTS

To determine whether dark matter coupled to neutrinos could relieve the tension caused by the EMPRESS data, we adapted the PRyMordial code to introduce a dark matter particle coupled to neutrinos (11). Using this code, we modeled deuterium and helium-4 abundance under conditions where dark matter particles coupled to neutrinos were present at BBN.

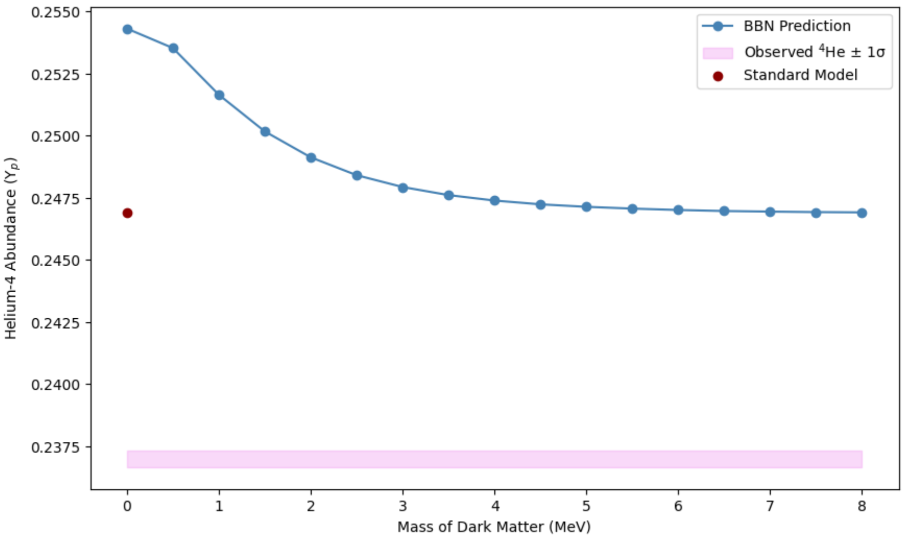

Figure 1: Helium-4 abundance vs. dark matter mass. Line graph (blue) showing theoretical values of helium-4 abundance in the universe for dark matter masses ranging from 0.0 MeV to 8.0 MeV. The dark matter introduced in this model is coupled to neutrinos. The outlier point (red) indicates the standard model value for helium-4 abundance without any added dark matter. The standard model is a leading theory that explains most fundamental particles and forces of the universe. The pink bar represents the observed EMPRESS data for helium-4 with a margin of error of +/- 1 standard deviation. BBN represents Big Bang Nucleosynthesis while EMPRESS represents Extremely Metal-Poor Representatives Explored by the Subaru Survey.

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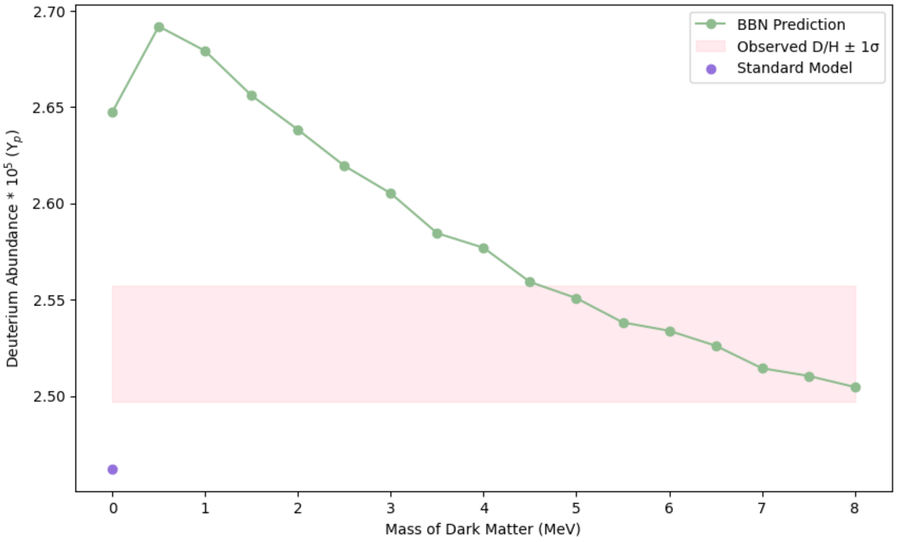

Figure 2: Deuterium abundance × 10^5 vs. dark matter mass. Line graph (green) showing theoretical values of deuterium abundance in the universe for dark matter masses from 0.0 MeV to 8.0 MeV. The dark matter introduced in this model is coupled to neutrinos. The outlier point (purple) indicates the standard model value for deuterium abundance without any added dark matter. The standard model is a leading theory that explains most fundamental particles and forces of the universe. The pink bar represents the observed EMPRESS data for deuterium with a margin of error of +/- 1 standard deviation.

We found that, as the mass of dark matter increased, the helium-4 abundance decreased (**Figure 1**). When the mass of dark matter was 1.0 MeV, the helium-4 abundance value was 0.252 by mass fraction; whereas helium-4 abundance was only 0.247 when the mass of dark matter was 8.0 MeV (**Figure 1**). The abundance value for helium-4 from EMPRESS was 0.2370 with an uncertainty of +0.0034 and -0.0033, which is lower than the values predicted by our model (**Figure 1**). The standard model value for helium-4 is 0.24689, which is depicted on the graph as a singular point at 0.0 MeV. This value is not the same as having a dark matter mass of 0.0 MeV, but rather it represents a value for conditions involving no dark matter at all, as the standard model is a leading theory in physics that explains most fundamental particles and forces of the universe but does not include dark matter (10).
A decrease in abundance of deuterium was observed with increasing mass of dark matter (**Figure 2)**. As the mass of dark matter increased from 1.0 MeV to 8.0 MeV, the abundance of deuterium decreased from 2.679 × 10^{-5} to 2.505 × 10^{-5} (**Figure 2**). The deuterium abundance value obtained from EMPRESS was (2.527 ± 0.030) × 10^{-5}. For neutrino-coupled dark matter particle mass between 4.5 MeV and 8.0 MeV, the theoretical values for deuterium matched the experimental values (**Figure 2**). The standard model value for deuterium is 2.46225 × 10^{-5} and is depicted on the graph as a singular point at 0.0 MeV.

As the dark matter mass approaches 0.0 MeV, the predicted curve for helium-4 would not contain a local maximum but rather experience a decrease in the rate of change of the helium-4 abundance values. The predicted graph for deuterium, on the other hand, would contain a maximum of around 2.692 at 0.5 MeV before decreasing. The values for both helium-4 and deuterium do not approach the standard model values because a dark matter particle with a mass of 0.0 MeV is a different type of particle than the dark matter particles investigated in this study. Anything massless travels at the speed of light, which means the massless dark matter would be traveling too fast to get trapped in gravitational wells around galaxies and therefore cannot explain the dark matter that we observe in our universe.

DISCUSSION

We found that dark matter coupled to neutrinos created a match between the theoretical and experimental values for deuterium within a certain range of dark matter masses but could not match the theoretical and experimental values of helium-4.

The dark matter studied in this paper was theorized to be coupled exclusively to neutrinos. It is quite common to look at simple dark matter models as opposed to complicated ones in which dark matter particles are coupled to many types of particles (12). In addition, neutrinos interact with the rest of the standard model, including other leptons, quarks, and bosons, only through the weak force, so it is generally easier to administer changes with dark matter coupling in the neutrino sector without altering any cosmological predictions (10). However, by focusing on a single dark matter model (i.e. a scalar particle coupled to neutrinos) rather than a broader class of models, this study had a narrow scope. Additionally, the EMPRESS study is limited in that it assumed that all hydrogen atoms are ionized, and despite targeting the same region of each galaxy for observation, the use of different instruments and setups may have caused the datasets to sample slightly different portions of each galaxy's region (7).

The theoretical values for helium-4 were high compared to the experimental values, likely due to the effect of dark matter particles on universe expansion and neutron decay. At the time of BBN, neutrons and protons interconverted, and the neutron-to-proton ratio was about one to six (2). As the universe naturally began to expand and cool down, this interconversion could no longer occur; however, the process of neutron decay was then able to occur (2). In about 15 seconds, a neutron decays into a proton, electron, and neutrino (13). Because of this, the neutron-to-proton ratio became one to seven due to a decreasing amount of neutrons and increasing amount of protons (13). Adding in a new particle, such as dark matter particles, to this model of the universe would increase the universe's energy density, or the total amount of energy within a given volume of space in the universe (14). An increase in energy density such as this would have caused the universe to expand more quickly (14). As the expansion rate increased, neutron decay would have become increasingly unable to account for the adequate decrease in the neutron-to-proton ratio, as neutrons had less time to decay and therefore had a greater chance of surviving (14). As a result, there would have been more neutrons available for synthesis (14). First, deuterium would have been created when one neutron and one proton combined. The production of deuterium then would allow for more nuclear reactions to occur. Deuterium nuclei would fuse with more neutrons and protons, resulting in stable helium-4 nuclei, each consisting of two neutrons and two protons (14). In other words, there were more neutrons due to less decay, the majority of which were incorporated into helium-4. This is why, when the dark matter was added to the model, the theoretical helium-4 abundance was higher than what was observed.

In summary, after varying the dark matter particle masses (mX) in intervals of 0.5 from 0.0 to 8.0 MeV in the PRyMordial code, the deuterium abundance was able to match the EMPRESS observed values within a certain range, whereas the helium-4 abundances did not reach the EMPRESS values. Since the helium-4 tension was left unresolved, our hypothesis was disproved. The type of dark matter coupled to neutrinos that was used in this study cannot provide the solution to this anomaly; however, other types of dark matter, perhaps coupled to other types of particles, may solve the tensions in both helium-4 and deuterium. This can be tested by modifying the PRyMordial code to couple the particles to electrons rather than neutrinos in the PRyM_thermo.py section (11). Another possible solution could be adjusting another parameter in the BBN simulation that affects the production of atomic nuclei, such as the expansion rate of the universe. Ideally, multiple studies could be conducted in the future using the BBN simulation and changing parameters of the primordial universe until a dark matter particle match between the observed and theoretical helium-4 and deuterium abundance values is found. Overall, this study used computational simulations to demonstrate that dark matter particles coupled to neutrinos cannot solve the helium-4 tension, but can solve the tension in the deuterium. Further studies or work in the field may therefore assume that this type of dark matter most likely did not exist in the early universe, potentially ruling them out as a candidate in the search for a solution to the helium-4 abundance anomaly.

MATERIALS AND METHODS

In the publicly available code PRyMordial, we added a section of code in PRyM_thermo.py, where the thermodynamics of BBN are computed, to introduce a dark matter particle, (a scalar particle in thermal equilibrium coupled to neutrinos) (11). The dark matter mass (mX) and the neutrino mass (gX) were both adjustable. The code not only outputs helium-4 and deuterium abundances at BBN, but also other numerical values including the effective number of neutrino species (Neff), helium-4 abundance by mass fraction (YP) from the Cosmic Microwave Background (YP(CMB)), helium-3 abundance as a ratio to hydrogen (He3/H x 10^5), and lithium-7 abundance as a ratio to hydrogen (Li7/H × 10^{10}). By changing the dark matter particle mass, or mX, the resulting YP(BBN), or helium-4, and D/H × 10^5, or deuterium, values were also changed and were recorded.

In order to study how the presence of dark matter coupled to neutrinos with different masses influences the primordial abundances of helium-4 and deuterium, we used the publicly available PRyMordial code (11). PRyMordial follows an isotropic, homogenous universe at local thermodynamic equilibrium, allowing the laws of thermodynamics to be applied (11). The code allows the user to adjust both the dark matter mass (mX) and the neutrino mass (gX). The code then outputs helium-4 and deuterium abundances at BBN, as well as other important values including the effective number of neutrino species (Neff), helium-4 abundance from the Cosmic Microwave Background (YP(CMB)), helium-3 abundance as a ratio to hydrogen (He3/H × 10^5), and lithium-7 abundance as a ratio to hydrogen (Li7/H × 10^{10}).

In the section of the code in which the thermodynamics of the plasma are computed, PRyM_thermo.py, we implemented a specific code in order to modify the model to include a scalar dark matter particle coupled to neutrinos in thermal equilibrium (**Appendix**) (11)

We then ran the code for a range of dark matter masses from 0.0 MeV to 8.0 MeV in intervals of 0.5 MeV. After each change, the values of the helium-4 abundance, reported as YP (BBN), and the values of the deuterium abundance, reported as D/H × 10^5, were recorded and compiled into two separate tables, one for each variable. We included a singular point at 0.0 MeV to represent the abundance of each element according to the standard model. The standard model is a leading theory that explains most fundamental particles and forces of the universe, but it does not include dark matter. This point was plotted to display the effect of dark matter on the abundance values of both elements. We also added the EMPRESS abundance values for each element in their respective tables with an error margin of +/- 1 standard deviation. We then compared the simulated values for each variable with the EMPRESS values by looking for an overlap in the two datasets in each table and took note of which dark matter masses produced an overlap.

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APPENDIX

Code used to modify PryM_thermo.py to include a scalar dark matter particle coupled to neutrinos in thermal equilibrium (11).

```
import PRyM.PRyM_init as PRyMini
PRyMini.NP_nu_flag = True
import numpy as np
from scipy.integrate import quad
# Scalar with mass mX = 5 MeV
gX = 1; mX = 5;
def rho_NP(T_NP):
    if T_NP < mX/30.: return 0.
    else:
        res_int = quad(lambda E: E**2*(E**2-(mX/T_NP)**2)**0.5
        /(np.exp(E)-1.) ,mX/T_NP,100.,epsrel=1e-9,epsabs=1e-12)[0]
        return gX/(2*np.pi**2)*T_NP**4*res_int
    def p_NP(T_NP):
        if T_NP < mX/30.: return 0.
        else:
            res_int = quad(lambda E: (E**2-(mX/T_NP)**2)**1.5
            /(np.exp(E)-1.) ,mX/T_NP,100.,epsabs=1e-9,epsrel=1e-12)[0]
            return gX/(6*np.pi**2)*T_NP**4*res_int
    def drho_NP_dT(T_NP):
        if T_NP < mX/30.: return 0.
        else:
            res_int = quad(lambda E: 0.25*E**3*(E**2-(mX/T_NP)**2)**0.5*
            np.sinh(E/2.0)**-2 ,mX/T_NP,100,epsabs=1e-9,epsrel=1e-12)[0]
            return gX/(2*np.pi**2)*T_NP**3*res_int
    import PRyM.PRyM_main as PRyMmain
    res = PRyMmain.PRyMclass(rho_NP,p_NP,drho_NP_dT).PRyMresults()
```