Abstract

In this review of Dark Matter we review dark matter as sterile neutrinos, fermions, with their present and possibly future detection via neutrino Oscillations. We review the creation of Dark Matter via interactions with the Dark Energy (quintessence) field. We also review bosons as dark matter, discussing a proposed search for dark photons. Since photons are vector bosons, if dark photons exist at least part of dark matter are vector bosons. Ongoing experimental detection of Dark Matter is reviewed.

1 Introduction

The most important experiments which have estimated the amount of Dark Matter in the present universe are Cosmic Microwave Background Radiation (CMBR) experiments, discussed in the section 2.

There have been a number of theoretical models for the creation of Dark Matter, which is reviewed in section 3. It is almost certain that sterile neutrinos are part of Dark Matter.

Experiments detecting sterile neutrinos via neutrino oscillation and a theoretical study of neutrino oscillations with 3 active and 3 sterile neutrinos with the present results are discussed in section 4. Also a recent search for sub-Gev Dark Matter by the MiniBooNE-DM Collaboration is briefly discussed in section 4.

Neutrinos are fermions with quantum spin 1/2. It is possible that some Dark Matter particle are vector bosons with quantum spin 1, like the photon. A possible Dark Photon Search is discussed in section 5. Future experimental detection of Dark Matter is reviewed in section 6.

2 Cosmic Microwave Background Radiation (CMBR)

There have been many CMBR experiments, such as Refs[1, 2, 3, 4] which have estimated the total density of the present universe, Dark Matter density, dark energy density, etc.

With Ω the density of the Universe and Ω = 1.0 for a flat Universe, results from CMBR observations are:

$$\Omega = 1.0023^{+0.0056}_{-0.0054}$$

- Dark Energy Density (vacuum energy) ≈ 0.73
- Dark Matter Density ≈ 0.23
- Baryon(NormalMatter) Density ≈ 0.04
- Age of the Universe ≈ 1.37 billion years . (1)

Therefore about 23 % of the Universe is Dark Matter.

About 73 % of the universe is dark energy, which is anti-gravity. Dark Energy (Quintessence) is anti-gravity and produced inflation at a very early time, which is why we now have an almost homogeneous universe.

Only about 4 % of the universe is normal matter.
3 Creation of Dark Matter

There have been many studies of the origin of Dark Matter mass. In order to explain why the universe is highly homongeneous Guth previously introduced what is now called the dark energy or quintessence field to produce inflation. Peebles and Ratra studied the quintessence field. Farr ar and Peebles intersecting Dark Matter and the Dark Energy (quintessence) field.

A recent study estimated Dark Matter mass created via Dark Energy interaction during the Cosmological Electroweak Phase Transition (EWPT) at a time $t_{EWPT} = 10^{-11}$ s. Using the Dark Energy Lagrangian $L^{DE}$ and Dark Mass-Dark Energy Lagrangian $L^{DM-DE}$

$$L^{DE} = \frac{1}{2} \partial_\mu \Phi \partial^\mu \Phi - V(\Phi)$$

$$L^{DM-DE} = g_D \bar{\psi}^{DM} \Phi \psi^{DM},$$

with $\Phi$ the quintessence field and $V(\Phi)$ obtained from Refs. Depending on the choice of parameters Ref estimated Dark Matter mass $M_{DM}(EWPT)$ at the present time $t = t_{now}$ as

$$M_{DM}(EWPT) \approx \text{few GeV to 140 GeV}.$$ (3)

With this range of values Dark Matter particles might be detected in the near future.

More recently a study estimated Dark Matter mass created via Dark Energy interaction during the Cosmological Quantum Chromodynamics Phase Transition (QCDPT) using the Lagrangians in Eq(2) at a time $t_{QCDPT} = 10^{-4}$ s, with the result at $t = t_{now}$

$$M_{DM}(QCDPT) \approx 0.5 \text{ to 3.5 TeV},$$ (4)

which is more than an order of magnitude larger than $M_{DM}(EWPT)$ as $t_{QCDPT} \gg t_{EWPT}$.

4 Neutrino Oscillations and Sterile Neutrino Parameters

Sterile neutrinos are a well-known source of Dark Matter. For many years the MiniBooNE Collaboration has studied neutrino oscillations. The MiniBooNE Collaboration using $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations detected a sterile neutrino $\nu_4$ and estimated the mass difference between this sterile neutrino and a standard neutrino as

$$\Delta m^2 = m_4^2 - m_1^2 \approx 0.06(\text{eV})^2,$$ (5)

which is too small for sterile neutrino $\nu_4$ to be a WIMP (Weakly Interacting Massive Particle).

In a calculation with three active and three sterile neutrinos, an extension of work with six neutrinos, the transition probability for a muon neutrino to oscillate to an electron neutrino, was estimated. With the notation for the three active neutrinos $\nu_e = \nu_1, \nu_\mu = \nu_2, \nu_\tau = \nu_3$ and the three sterile neutrinos are $\nu_4, \nu_5, \nu_6$

$$P(\nu_\mu \rightarrow \nu_e) = \text{Re} \left[ \sum_{i=1}^{6} \sum_{j=1}^{6} U_{1i}^{*} U_{1j}^{*} U_{2i}^{*} U_{2j} e^{-i(\delta m_{ij}^2 / E)L} \right],$$ (6)

where neutrinos with flavors $\nu_e, \nu_\mu, \nu_\tau$ and three sterile neutrinos, $\nu_s_1, \nu_s_2, \nu_s_3$ are related to neutrinos with definite mass by

$$\nu_f = U \nu_m,$$ (7)

where $U$ is a 6x6 matrix. In Ref the sterile-active neutrino mixing angles were calculated, which should be useful for future searches for sterile neutrinos as Dark Matter particles.

Recently the MiniBooNE-DM Collaboration has carried out a search for sub-Gev Dark Matter at the Fermilab, but no excess from background predictions was observed.
5 Dark Photon Search

There is a worldwide race in the search for Dark Photons. A Dark Photon would be a vector boson (quantum spin=1), while a neutrino is fermion (quantum spin=1/2, so Dark Photons would be a very different kind of Dark Matter particle than a sterile neutrino. The Dark Photon Search is described in Ref[14]. The LANL (Los Alamos National Laboratory), P-25, PHENIX team is planning to search for Dark Photons at Fermilab. The Direct Search for Dark Photons at Fermilab is reviewed in Ref[15], which can be found by clicking on Ref[15] in “talks and presentations” in Ref[14]. Since the detection of Dark Photons is quite difficult the LANL-P-25 PHENIX team is carefully planning for the experiment. In Ref[14], using EmCal hardware, one finds a description of the hardware by Hubert van Hecke. Kun Liu, a co-PI, will plan for the P-25 PHENIX team at Fermilab.

6 Experimental Detection of Dark Matter

Since we do not know what dark matter is, we need a diverse pool of instruments and approaches to detect it[16,17]. Experiments LUX [18], PandaX-II[19], PICO[20,21], DAMA/LIBRA[22,23,24], SuperCDMS[25], CRESST-III[26], which use direct detection methods, are reviewed.

The LUX (Large Underground Experiment) [18] is a dark matter experiment that aims to detect the WIMPs (Weakly Interacting Massive Particles), a dark matter candidate. The experiment is carried out 1.5 km underground under SURF (Sanford Underground Research Facility). The LUX detector is a two-phase xenon time-projection chamber (TPC), containing 370 kg of xenon. The liquid xenon contains an array of photosensors which can sense a single photon of light.

The second phase of the PandaX (Particle and astrophysical Xenon) project [19] is located in the China Jinping Underground Laboratory (CJPL) and started it’s operation in early 2016. PandaX-II comprises of a 580 kg dual-phase xenon TPC along with a 60x60 cm cylindrical target containing 55 top and 55 bottom Hamamatsu R11410-20 3-inch photomultiplier tubes (PMTs). The data sets (Run 9 and Run 10) are now used to perform systematic studies using the PandaX-II detector.

The PICO project [20] is working towards the detection of dark matter particles with the bubble chamber technique. The experiments are installed at a depth of 2 km in the SNOLAB underground laboratory at Sudbury, Ontario, Canada. Searching WIMPs using superheated bubble chambers which are operated in thermodynamic conditions at which they are almost insensitive to gamma or beta radiation is the main detection principle of PICO experiment. A bigger version of the experiment with up to 500 kg of active mass is in progress.

The DAMA experiment at the Gran Sasso National Laboratories of the I.N.F.N. is an observatory for rare processes that use radiopure scintillator set-ups. The main activity field of DAMA/LIBRA[22,23,24] is the investigation on Dark Matter particles in the galactic halo. The second generation DAMA/LIBRA set-up (Large sodium Iodide Bulk for RAre processes) is continuing the investigations of DAMA/NaI.

The SuperCDMS (SCDMS) [25] is the next generation of the CDMS (Cryogenic Dark Matter Search) II experiment, which was located underground in the deep Soudan mine of Minnesota, USA. SCDMS wants to re-locate at SNOLAB (Vale Inco Mine, Sudbury, Canada) which is a much deeper facility. CDMS-II comprises of a cryostat surrounded by a passive shield and an outer muon veto situated beneath an overburden of 2090 meters water equivalent. The use of underground facilities provide the required shielding from the cosmic events and hence reduce the interference of known background particles.

The CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment [26], located at the Gran Sasso underground laboratory in Italy, has operated 13 detector modules in CRESST-III Phase 1 (2016-2018). CRESST searches for dark matter particles via their elastic scattering off the nuclei in a target material. The CRESST target comprises of scintillating CaWO₄ crystals. This experiment searches for dark matter masses below 1.7 GeV/c², extending the CRESST-II result in 2015. For CRESST-III, whose Phase 1 started in July 2016, detectors have been optomized to further probe the low-mass region.

The DINO Dark Matter experiment [27] will search for WIMPS using scintillation detectors for the detection of recoiling nuclei.

The presence of low mass WIMPs in the various ongoing experiments [28] have generated motivations to cross-check future proposals [29].
7 Conclusions

In this Review we have reviewed many aspects of experiments and theory related to Dark Matter.

Cosmic Microwave Background Radiation (CMBR) experiments have shown that about 23% of the Universe is Dark Matter and only about 4% of the universe is normal matter.

The creation of Dark Matter mass during the EWPT and QCDPT, two Cosmological Phase Transitions, via the dark matter field interacting with the dark energy (quintessence) field are reviewed. The Dark Matter mass $M_{DM}$ created during the QCDPT could be more than 1 TeV, more than an order of magnitude larger than $M_{DM}$ created during the EWPT.

Theoretical and experimental studies of neutrino oscillations producing sterile neutrinos are reviewed, with massive sterile neutrinos possibly being the Dark Matter detected by CMBR experiments. Also a Dark Photon search, with photons vector bosons rather than sterile neutrinos, which are fermions, is briefly reviewed.

Finally, six experiments for the experimental detection of Dark Matter are reviewed, with a detailed explanation of how these experiments can detect Dark Matter.

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