On the Trail of WIMPs

Direct Detection of Weakly Interacting Massive Particle Dark Matter

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The fundamental particle nature of the Dark Matter (DM) that constitutes more than 80% of the gravitating matter in the Universe is unknown. There is no suitable candidate for this DM in the Standard Model (SM) of particle physics. The so-called Weakly Interacting Massive Particles (WIMPs), predicted in many scenarios of possible new physics beyond the SM, are currently one of the most favoured candidates of the DM. A number of experiments worldwide are trying to directly detect these WIMPs in underground laboratories. Here we discuss the basic ideas behind the WIMP hypothesis and briefly discuss the latest results of such experiments and future prospects.

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In order for the light to shine so brightly, the darkness must be present.

– Francis Bacon

1. Introduction

A variety of astronomical observations made over the past several decades have indicated that more than 80% of the gravitating mass in the Universe is in a form that emits no detectable electromagnetic radiation at any wavelength. This invisible matter, commonly called the 'Dark Matter' (DM), reveals its presence only through its gravitational influence on the 'visible' matter such as stars, galaxies and so on. The composition of DM is unknown, and remains as one of the major unsolved problems in science. There are strong reasons to think that this DM is not made up of protons and neutrons – the baryons – that constitute all normal

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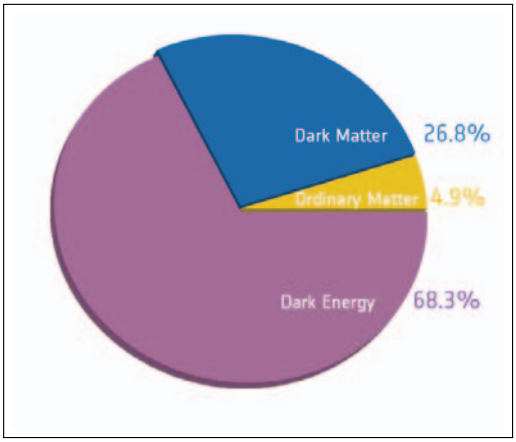

Figure 1. Composition of the Universe from Planck measurements (Source: http://sci.esa.int/planck/51557-planck-new-cosmic-recipe/).

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matter that we see around us including ourselves. Highly accurate measurements of the temperature fluctuations of the cosmic microwave background radiation (CMBR) on various angular scales on the sky by the Planck satellite mission [1] have allowed determination of the total average matter density as well as separately the average baryonic matter density in the Universe. These measurements show that the baryonic matter contributes only a fraction of about 4.9% to the total energy density of the Universe and that a non-baryonic DM component must be present comprising about 26.8% of the total energy density (see *Figure* 1). Indeed, without the additional attractive gravitational potential supplied by this DM component, it is difficult to explain in a natural way the formation of the structures like galaxies, clusters of galaxies, and even larger scale structures that we see in the Universe today.

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The evidence for the existence of DM comes not only from the observations of the CMBR. Historically, the first hints of the existence of DM came from the studies of the motion of stars and gas within galaxies, as well as those of galaxies within clusters of galaxies; see the article by Vera Rubin [2] reproduced in this issue of *Resonance* (pp.177–184) and the recent article by Bartone and Hooper [3]. In particular, measurements of the rotation curves – the circular speeds of stars as a function of the distance from the galactic centre of a large number of spiral galaxies, including our own Galaxy, the Milky Way, gave direct information on the total amount and spatial distribution of gravitating mass in the galaxies. These measurements showed that contrary to expectations, the rotation speeds remained approximately constant, instead of decreasing with distance, even at large distances well beyond the visible edges of the galaxies. In some cases, the rotation speeds even increased with distance out to the largest galactocentric distances at which measurements were made. Such behaviour of the rotation curves can be naturally explained if one assumes that in addition to the visible matter, there exists a large amount of invisible gravitating matter in the galaxies. This invisible matter could provide the additional gravitational potential needed to support a non-declining rotation curve in the outer regions of the galaxies, where the amount of visible matter is relatively low. These and other considerations have led to the now widely accepted general picture that large spiral galaxies are each surrounded by a large, roughly spherical, 'halo' of DM particles extending out, in many cases, to a radius of more than 100 kiloparsec (kpc)[1]. A typical picture of a DM halo surrounding a galaxy is schematically shown in *Figure* 2.

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[1] 1 kpc $\approx 3.26\times10^3$ light-year$\approx 3.1\times10^{21}$ cm

From the behaviour of the rotation curve as well as kinematics of the vertical motion of stars of the Milky way, the mass density of the DM in our neighbourhood (i.e., near the location of the Sun, which lies at a distance of about 8.5 kpc from the centre of the Galaxy) has been estimated to be about 0.3 GeV/ cm^3 (equivalent to roughly one-third of the mass of a proton every cubic centimeter) [3, 4].

Figure 2. Schematic picture of the dark matter halo (grey region) surrounding a spiral galaxy (white region) (From: https://www.cfa.harvard.edu/oir/mw/halo.html).

2. Weakly Interacting Massive Particles (WIMPs) as Possible Dark Matter Candidates

It is widely believed that at a fundamental level, the DM, the bulk of which must be non-baryonic in nature, is made of some new kind of particles, since there are no known particles within the Standard Model (SM) of particle physics that can satisfy all the properties required of the DM. Indeed, a large variety of possible new particle candidates for DM have been suggested [4]. One of the most favoured of these candidates, from theoretical as well as experimental points of view, are the so-called 'Weakly Interacting Massive Particles' (WIMPs), a general class of stable, massive particles that are predicted in many models of possible new physics beyond the SM which were actually proposed for reasons other than solving the DM problem. Such particles, with masses anywhere in the range of a few GeV to few hundred TeV,[2] depending on the model, can be present in the Universe today as relics surviving from the very early times in the history of the Universe.

[2]We use natural units defined by $c = \hbar = 1$ (where c is the speed of light and $\hbar = h/(2\pi)$, h being the Planck's constant). In these units, $1\,\text{GeV} \equiv 1.78 \times 10^{-24}$ gm. Also, $1\,\text{TeV} = 10^3\,\text{GeV} = 10^{12}\,\text{eV}$. Sometimes, we also set the Boltzmann constant k_B to unity, which makes temperature, mass and energy all having the same dimensions.

At sufficiently early times, when the Universe was much hotter and denser than it is today, and the temperature was high enough such that the average thermal energy of particles was higher than the rest mass-energy of the WIMPs, the WIMPs would be thermally produced from annihilations of other particle-antiparticle pairs in the Universe. Also, the rates of energy and momentum exchanging interactions of the WIMPs with other particles would be fast enough to maintain the WIMPs in thermal and chemical equilibrium with other particle species. However, the rates of such interactions generally fall as the temperature drops as a result of expansion of the Universe. Below a certain temperature, the relevant interaction rates may no longer be fast enough, compared to the expansion rate of the Universe, to maintain the WIMPs in thermal and chemical equilibrium with other particles. The WIMPs are then said to have 'frozen-out'.

For most weakly interacting particles with masses above a few GeV, this freezing out typically happens when the temperature of the Universe is well below the WIMP mass. At such temperatures, WIMPs cannot any more be thermally produced from collisions and/or annihilations of background particles. Thus, after the freeze-out, the WIMPs, if they are stable (or effectively stable, with decay lifetime at least as large as the age of the Universe), can survive down to the present-day Universe with an abundance fixed by their thermal abundance just prior to the freeze-out, and by the rate of any residual self-annihilations amongst the WIMPs. The latter is essentially fixed by the quantity $\langle\sigma_{\rm ann}v\rangle$, the thermal average of the product of WIMPs' annihilation cross section, $\sigma_{\rm ann}$, which is related to their weak interaction cross section, and the relative velocity v between annihilating pairs of WIMPs at around the time of freeze-out. Annihilations subsequent to freeze-out is negligible since the annihilation rate is proportional to the square of the WIMP number density, which falls off drastically at temperatures below the freeze-out due to expansion of the Universe. Thus, finally, the remaining relic abundance of the WIMPs turns out to be proportional to the thermal abundance of the WIMPs at the time of freeze-out and inversely proportional $\langle\sigma_{\rm ann}v\rangle$ at the freeze-out temperature.

The time or equivalently the temperature in the early Universe at which the WIMPs of a particular mass freeze out depends on the strength of their interactions with other particles. Weaker the interaction strength, earlier would be the freeze-out time, when

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the temperature was higher. Since the abundance of any massive particle species in thermal equilibrium falls exponentially with falling temperature (following the Maxwell–Boltzmann distribution), the earlier the WIMPs freeze-out, more would be their abundance at the time of freeze-out and so would be their relic abundance today. The wide interest in the WIMPs as possible DM candidates stems from the fact that, within a large class of particle physics model of WIMPs, the theoretically calculated relic abundance of WIMPs in the present day Universe naturally matches the required abundance of DM, for reasonable choices of parameters of the models. In other words, if WIMPs exist, they are a natural candidate for the DM.

In this article, we will not discuss any specific particle physics model of WIMPs, nor shall we discuss any of the various other possible particle candidates of DM. Rather, we shall now move on to the question of direct detectability of the WIMPs in general in laboratory experiments.

3. Direct Detection of WIMPs

If indeed WIMPs make up the DM in the Universe and, in particular, the DM halo of our Galaxy, then they should be present everywhere in the Galaxy, including our immediate neighbourhood. The question then arises if we can directly detect these WIMPs in the laboratory. This possibility was first investigated by two theoretical physicists, M Goodman and E Witten, in 1985, suggesting that WIMPs elastically scattering off nuclei of suitably chosen detector materials, may leave behind recoiling nuclei with large enough kinetic energies. The energy deposited by such recoiling nuclei in the detector medium may be detectable. In particular, Goodman and Witten suggested that possible coherent elastic scattering of WIMPs off nuclei, the cross section for which would be proportional to A^2 (A being the mass number of the nucleus), could give sufficiently large rate of scattering events so as to be detectable. Since then, a large number of experiments worldwide, employing a variety of different detection techniques with different target detector materials, and with larger and larger detector mass have been searching for the WIMPs.

Can WIMPs be directly detected in the laboratories?

3.1 *Signals and Backgrounds*

The energy deposited by the recoiling nuclei in the detector medium may manifest as signals of various forms such as a tiny rise in temperature in a cryogenic bolometric detector, ionization, as well as scintillation light signals in detectors made of scintillating crystals or liquids, phonon signals in crystalline materials, and so on. However, such signals can also be caused by various background particles such as cosmic rays, gamma rays and electrons passing through the detector. To reduce the cosmic ray background, WIMP DM search experiments are typically performed in deep underground laboratories. However, even at underground locations, backgrounds due to gamma (γ) rays and electrons (β) originating from the decay of radioactive contaminants within the detector material itself as well as in the air and other materials (including the rocks) surrounding the detector may remain. Proper purification of the detector material, and proper shielding of the detector from external radioactive sources are used to reduce these electromagnetic backgrounds.

The background γ/β particles interact predominantly with the electrons in the detector material and give rise to electron recoil (ER) events. On the other hand, the WIMPs, which move in the Galaxy with typical non-relativistic speeds of $\sim 300\,\text{km}\,\text{s}^{-1}$, are expected to interact predominantly with nuclei, thus causing nuclear recoil (NR) events. The kinetic energy of the recoiling nucleus can be anywhere in the range of a few keV to few hundred keV depending on the WIMP mass and the mass of the target nucleus. One of the major challenges in any WIMP DM search experiment is to be able to devise efficient detection schemes that can discriminate between the NR induced 'signal' events and the ER induced background events, and accept only the NR events as possible events attributable to WIMPs. However, any neutrons present around the detector, being electrically neutral, would also interact with the detector material primarily through NR. Sufficiently energetic

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background neutrons can thus mimic WIMPs in the sense that both produce NR events. The background neutrons arise mainly from two sources: (a) radiogenic neutrons from (α, n) reactions through decays of thorium, uranium and other radioactive isotopes in the rocks surrounding the detector, and (b) high energy neutrons from cosmic ray muon induced spallation process in the rocks surrounding the detector. Again, the neutron background can be controlled by using suitable shielding. However, any remaining neutrons would remain as an irreducible background for any WIMP DM search experiment.The only way to mitigate their effects is to estimate the remaining neutron background through direct measurements and then subtract the estimated NR events due to these neutrons from the final NR event counts in a detector.

A specific signal of WIMP induced events would be an annual modulation of the event rates caused by the periodic change in the relative velocity between the WIMPs in the Galactic halo and the detector on the Earth as the Earth goes around the Sun with a period of one year. This, however, is a small (approximately 3%) effect, and is generally hard to detect.

4. Present Status and Conclusion

None of the experiments have till date made any definite claim of detection of the WIMPs. The DAMA/ LIBRA experiment [5] has claimed detection of the expected annual modulation signal (mentioned above) in the event rates recorded by their detector, which they attribute to WIMPs. However, the WIMP mass and the WIMP-nucleon interaction cross section derived from their data are inconsistent with the null results of a large number of other experiments, including the most recent results from the Large Underground Xenon (LUX) experiment [6]– currently the most sensitive WIMP search experiment in the world. The LUX experiment uses ultrapure liquid Xenon (which is a liquid scintillator) as the target detector material. The null results of the LUX experiment have placed the most stringent upper limit of $\sim 1.1 \times 10^{-46}$ cm^2 on the coherent interaction cross section of WIMPs with nucleons (neutrons or protons) at a WIMP mass of about 50 GeV, ruling out a large region of the parameter space of particle physics models of WIMPs. Interestingly enough, with the steadily improving sensitivity and ability to probe even smaller cross sections, the planned future generation of WIMP search experiments will start becoming sensitive to the so-called 'neutrino floor', the irreducible background due to neutrinos from the sun as well as to the supernova neutrino background due to all the neutrinos emitted during all the supernova explosions in the Universe.

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Suggested Reading

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