

Dark Matter – Possible Candidates and Direct Detection

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Abstract

The cosmological observations coupled with theoretical calculations suggest the existence of enormous amount of unseen and unknown matter or dark matter in the universe. The evidence of their existence, the possible candidates and their possible direct detections are discussed.

1 Introduction

The observations by Wilkinson Microwave Anisotropy Probe or WMAP [1] for studying the fluctuations in cosmic microwave background radiation reveal that the universe contains 27% matter and the rest 73% is an unknown energy known as Dark Energy. Out of this 27%, only 4% accounts for the ordinary matter like leptons and baryons, stars and galaxies etc. The rest 23% is completely unknown. Moreover, there are strong indirect evidence (gravitational) from various observations like velocity curves of spiral galaxies, gravitational lensing etc. in favour of the existence of enormous amount of invisible, non-luminous matter in the universe. The measurement of mass-luminosity ratio which can be used to determine the cosmological density parameter also estimates a very low value for luminous matter. This huge amount of unknown and “unseen” matter (which in fact constitutes more than 90% of the total matter content of the universe) is known as “Dark Matter”.

Although the nature and identity of dark matter still remain a mystery, indirect evidence suggests that they are stable and probably heavy, non relativistic (Cold Dark Matter or CDM) and are weakly interacting. Therefore they are often known as Weakly Interacting Massive Particles or WIMPs.

In this article, the properties, types and the possible candidates of dark matter are discussed. The possibilities of their direct detection and theoretical detection rates are also given.

2 Cosmological Density Parameter

The space-time metric consistent with the homogeneity and isotropy of the universe – on large scales – can be given by the Robertson-Walker (RW) metric

$$ds^2 = -dt^2 + a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right] \quad (1)$$

Here $a(t)$ is a scale factor and k denotes the spatial curvature. Thus, $k = +1$ means the spatial section is positively curved, i.e. the space is locally isometric to 3-D spheres; $k = -1$ signifies that the space is locally hyperbolic (spatial section is negatively curved); and finally $k = 0$ signifies no spatial curvature, i.e. a flat geometry for the local space.

The RW metric follows from the kinematic consequences. The dynamics, i.e. the time evolution of the scale factor $a(t)$ follows by applying Einstein's equation (with the cosmological constant Λ)

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi GT_{\mu\nu} + \Lambda \quad (2)$$

to the RW metric. In the above, $R_{\mu\nu}$ are Ricci Tensors, R is the Ricci scalar, $g_{\mu\nu}$ is the spatial metric, $T_{\mu\nu} = (\rho + p)U_\mu U_\nu + pg_{\mu\nu}$ is the energy-momentum tensor contains the density ρ and pressure p . The Einstein's equation relates the geometry with the energy-momentum.

Applying Einstein's equation to cosmology, one gets the Friedmann's equation

$$\left(\frac{1}{a} \frac{da}{dt} \right)^2 = \frac{8\pi G}{3} \rho + \frac{\Lambda}{3} - \frac{k}{a^2} \quad (3)$$

Defining $\frac{1}{a} \frac{da}{dt} = H$, the expansion rate of the universe or formally Hubble constant, the above equation can be written as

$$\frac{k}{H^2 a^2} = \frac{8\pi G}{3H^2} \rho + \frac{\Lambda}{3H^2} - 1 \quad (4)$$

Defining $\frac{3H^2}{8\pi G} = \rho_c$ – the critical density of the universe, the above equation takes the form

$$\begin{aligned} \frac{k}{H^2 a^2} &= \frac{\rho}{\rho_c} + \frac{\rho_\Lambda}{\rho_c} - 1 \\ &= \Omega_m + \Omega_\Lambda - 1 \end{aligned} \quad (5)$$

where $\Omega_m = \frac{\rho}{\rho_c}$ and $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$ are the cosmological density parameters for matter and energy respectively. For a flat universe ($k = 0$) we have therefore

$$\Omega = \Omega_m + \Omega_\Lambda = 1 \tag{6}$$

The analysis of WMAP probe predicts curvature parameter $k = 0$ (the universe is spatially flat)¹ and therefore the matter density of the universe

$$\Omega_m = \Omega_{\text{visible}} + \Omega_{\text{DM}} = 0.27$$

out of which

$$\Omega_{\text{visible}} = 0.4 \quad \text{and} \quad \Omega_{\text{DM}} = 0.23$$

where ‘DM’ stands for the dark matter and the energy density (unknown dark energy) Ω_Λ is

$$\Omega_\Lambda = 0.73$$

3 Evidence of the existence of Dark Matter

The evidence of dark matter was first envisaged by the observation of motion of galaxies in cluster of galaxies like Virgo and Coma. A galaxy cluster is a gravitationally-bound group of galaxies². Assuming the dynamical equilibrium of the cluster, it obeys the Virial theorem, $K + U/2 = 0$, where K is the kinetic term and U the potential. The kinetic term K was estimated by measuring the velocities of individual galaxies and is found to be much larger than the potential term U which was calculated by assuming that the mass of the cluster is the sum of the individual mass of the galaxies. This discrepancy indicates the existence of unseen and unknown mass in the cluster.

Stronger observational evidence exists by studying the rotational velocities of the stars inside a galaxy (rather than observing the galaxy itself inside a cluster). For a star in a spiral galaxy – which can be considered as a rotating disc with a central bulge where most of the galactic mass is concentrated – describing a circular orbit at a radial distance r from the centre of the galaxy,

¹A stringent limit is however put for $\frac{k}{H^2 a^2} = \Omega_k = -0.003 \pm 0.010$ [2].

²A cluster can be rich with thousand(s) of galaxies or can be poor with $\sim 30 - 40$ galaxies. The cluster, Local Group, to which our galaxy – Milky Way – belongs contains only about 30 galaxies.

with a rotational velocity v_r , one has

$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2} \quad (7)$$

where m is the mass of the star and M_r is the mass inside the orbit of radius r . If the object is inside the central concentrated mass region, the mass M_r can be estimated as

$$M_r = \frac{4}{3}\pi r^3 \rho \quad (8)$$

where ρ is the average density of the central region. From Eq. (7) therefore we readily see

$$v_r \sim r \quad (9)$$

Now, for a star outside the central bulge, one can approximate $M_r = M$ (a constant, neglecting the mass outside the central bulge) and in this case the nature of rotational velocity v_r becomes (from Eq. (7))

$$v_r \sim \frac{1}{r^{1/2}} \quad (\text{Keplerian Decline}) \quad (10)$$

Hence normally, for rotational velocities $v_r(r)$, one would expect an initial rise with increase of radial distance r from the galactic centre (Eq. (7)) and then a Keplerian decline for radial distance r outside the central bulge.

Instead, the observation of rotation curves (variation of v_r with r) reveal the initial rise of v_r with r as expected but then $v_r(r)$ becomes a constant with the increase of r instead of suffering the $r^{-1/2}$ decline. Hence from Eq. (7), with v_r constant

$$M_r \sim r \quad (11)$$

which suggests the existence of enormous unknown mass.

The evidence of dark matter is indicated from other observations like measurement of temperature and density of hot X-ray emitting gases from elliptical galaxies like M87.

The other evidence comes from the observance of the phenomenon of gravitational lensing. This occurs due to the bending of light in presence of gravitational potential. The mass of a cluster and hence Ω_m can be estimated by exploring the multiple lense effects of background galaxies produced by the cluster. These observations also point to $\Omega_m \sim 0.3$.

4 Types of Dark Matter

On the basis of the nature of the constituents, the dark matter can be divided into two types namely a) baryonic and b) non-baryonic. Different cosmic microwave anisotropy (CMB) measurements predict a value of baryon density to be $\Omega_b \sim 0.04$ which is far less than the total dark matter density $\Omega_{\text{DM}} = 0.23$. This is indicative of the fact that the most of the dark matter in the universe is non-baryonic in nature.

Again, on the basis of their velocities, the dark matter can be broadly classified as a) Hot Dark Matter (HDM) and b) Cold Dark Matter (CDM). For HDM, the particle candidates are light and hence move with relativistic velocity while the CDM candidates are heavy and move with non-relativistic velocities. If a candidate falls in between the two categories they are sometimes referred to as Warm Dark Matter.

Neutrinos can be a possible candidate for Hot Dark Matter, but their relic density falls far short of the total dark matter density, 0.23, if the neutrinos are indeed light ($\sim \text{eV}$). It is general wisdom that, most of the dark matter of the universe is Cold type (CDM) and non-baryonic in nature.

5 Candidates for Dark Matter

The dark matter candidates still remain an enigma. But the fact that they constitute more than 90% of the matter content of the universe and their little or no interaction with any Standard Model particles indicate that they are made up of stable, neutral and very weakly (or almost non-) interacting particles. Also most of their constituents are massive (heavy) to account for that large mass.

The known particles like baryons are proposed but as is discussed earlier baryons alone cannot explain the total dark matter of the universe. But some of the dark matter may need to be baryonic as $\Omega \lesssim 0.01$ in the galactic disk.

There are other candidates (baryonic) for dark matter like jupiter-like objects, dead massive stars etc. But they fail to account for the density $\Omega_{\text{DM}} = 0.23$.

Recently there has been experimental evidence of at least one form of dark matter namely Massive Astrophysical Compact Halo Objects or MACHOs in the halo of Milky Way galaxy. The light from a distant star, passing by

a MACHO, bends due to the large gravitational field of the MACHO. The bending of light is a consequence of Einstein's General Theory of Relativity and as discussed above, is known as gravitational lensing. In the present case, since the lens is relatively small (compared to galaxy), multiple images are not observed. On the other hand, due to relative motion between the stars and MACHOs the lensing effect causes an increase in the brightness of that distant object. Using this phenomenon, known as gravitational microlensing, around 13-17 MACHOs have been detected in the Milky Way Halo.

A candidate for MACHOs has been proposed in Ref. [3]. It is suggested that MACHOs have evolved out of the strange quark nuggets (SQNs) formed during the first order phase transition of the early universe from quark phase to hadronic phase at a temperature around 100 MeV ($\sim 10^{-5}$ second after Big Bang). During this phase transition, hadronic matter starts to appear as individual bubbles in quark-gluon phase [4, 5]. With the progress of time more bubbles appear and they expand to form a network of such bubbles (percolation) in which the quark matter gets trapped. With further cooling of the universe, these trapped domains of quark matter shrink very rapidly without significant change of baryon number and eventually evolves to SQNs through weak interactions with almost nuclear density [6]. These objects are stable and calculation shows that to explain all the CDM, the baryon number of an SQN should be $\sim 10^{42-44}$ [7] assuming all SQNs to be of same size. These SQNs with masses $\sim 10^{44}$ GeV and size ~ 1 metre, would have very small kinetic energy compared to their mutual Gravitational potential.

Among the possible candidates of light non baryonic dark matter, come the relic neutrinos. But as briefly discussed earlier, the light neutrinos cannot account for the dark matter relic density obtained from, say, WMAP observation.

Another viable light dark matter candidate is axion. Axion is a pseudo-Goldstone boson and is introduced to solve the strong CP problem [8] (conservation of CP symmetry in Quantum chromodynamics or QCD). It arises as a consequence of a global $U(1)$ symmetry (Peccei-Quinn symmetry). The axions gets a small mass due to the breaking of this global $U(1)$ symmetry. Axions can also be produced in supernova. But the QCD consideration alongwith the production process of axions in supernova [9] (through nucleon-nucleon Bremsstrahlung), it is estimated that axion can be a dark matter candidate within a very limited window [10].

For the particle candidates of Cold Dark Matter or CDM that are non-baryonic in nature, there are various proposals. These candidates are not Standard Model (SM) particles and follow from the theories beyond SM like Supersymmetric theories or theories with extra dimensions. These particles if existed would have manifested themselves at higher energy scales during the very early phase of the universe. With the expansion of the universe, when the annihilation rate of these particles fall below the expansion rate of the universe, these particles get decoupled from the universe fluid and remain as they were. This phenomenon is known as “freeze out”. After the freeze out takes place those particles float around as relics.

The popular and favourite candidate for non-baryonic CDM is proposed from theory of Supersymmetry or SUSY. Supersymmetry is the symmetry between fermions and bosons or rather more precisely the symmetry between the fermionic and bosonic degrees of freedom. This is introduced to address the so called “hierarchy problem” or “Weak scale instability problem”. The hierarchy such as W-boson mass $m_W \ll M_p$ or the SM Higgs Boson mass $m_H \ll M_p$, where M_p is the Planck Mass ($1/\sqrt{G_N} \sim 10^{19}$ GeV) tends to be destroyed as a consequence of the higher order correction to the mass. The correction suffers a quadratic divergence. A fine tune of large orders of magnitude is required to restore the physical SM Higgs mass. This fine tuning in turn affects the masses of other SM fermions and gauge bosons and thus hierarchy. SUSY stabilises this hierarchy and peeps to the possibility of new physics beyond the electroweak energy scale of ~ 250 GeV.

In minimal supersymmetric standard model or MSSM (see e.g. [11]), each SM fermion has their bosonic SUSY partner and the gauge bosons have their fermionic SUSY partners. Thus in the MSSM framework, one generation in SM is to be represented by five left handed chiral superfields Q , U^c , D^c , L , E^c where the superfield Q contains quarks and their bosonic superpartner, squark $SU(2)$ doublets; U^c and D^c are the quark and squark singlets; L contains leptons and their bosonic superpartner slepton $SU(2)$ doublets and E^c contains lepton and slepton singlets. In the gauge sector however, in MSSM framework, in addition to the SM gauge bosons, we have eight gluinos, the fermionic superpartners of QCD gluons; three winos (\tilde{W}) the fermionic partner of $SU(2)$ gauge bosons and a bino (\tilde{B}), the fermionic partner of $U(1)_Y$ gauge boson. In the Higgs sector, one needs to introduce two Higgs superpartners \tilde{H}_1 and \tilde{H}_2 in order to break the $SU(2) \times U(1)_Y$. Without going into details,

due to space constraints it is only mentioned that the two Higgsino doublet with hypercharge $Y = +1/2$ and $Y = -1/2$ make the model anomaly free (cancellation due to opposite hypercharge).

It is a general practice in MSSM (to ensure protection against rapid proton decay), to introduce a parity called R parity and it is assumed to be conserved. The R parity is defined as $R = (-1)^{3B+L+2S}$, where, B is the baryon number, L , the lepton number and S the spin. This ensures that the Lightest Supersymmetric Particle or LSP is stable and if it is neutral then can be a candidate for dark matter.

One such dark matter candidate is neutralino (χ) [12] which is the linear superposition of the fermionic superpartners of neutral SM gauge bosons and Higgs bosons and can be written as

$$\chi = \alpha\tilde{B} + \beta\tilde{W}^0 + \gamma\tilde{H}_1 + \delta\tilde{H}_2 \quad (12)$$

The coefficients can be obtained by diagonalizing the mass matrix (in the basis $\{ \tilde{B}, \tilde{W}^0, \tilde{H}_1, \tilde{H}_2 \}$)

$$\begin{pmatrix} M_2 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_1 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \cos \theta_W & 0 & -\mu \\ M_Z \sin \beta \sin \theta_W & M_Z \sin \beta \cos \theta_W & -\mu & 0 \end{pmatrix}. \quad (13)$$

In the above, the parameters M_1 and M_2 are soft SUSY breaking terms, μ is the so called “ μ term” in the superpotential (associated with two Higgs supermultiplets), $\tan \beta = \frac{v_2}{v_1}$, the ratio of the vev’s of two Higgs.

The lightest neutralino eigenstate (LSP) of the mass matrix above (Eq. (13)) is considered to be a candidate for dark matter.

Another important proposal for dark matter candidates comes from the theories of extra higher dimensions. Although we live in a four dimensional world, there is apparently no reason to believe that extra dimensions do not exist. If dimensions > 4 do at all exist they must be so compactified that the effect due to them is not manifested in our 4-D world. The ideas and theories of extra dimensions have been proposed to look for new physics beyond standard model and to address the hierarchy problem mentioned earlier as also to explain the non SM particles like gravitons (unification of gravity and gauge interactions), cosmological constant problem etc.

The effect of compactification of one extra space dimension can be demonstrated by considering a Lagrangian density \mathcal{L} for a massless 5 dimensional scalar field Φ , where one extra spatial dimension is included [13]. Thus (following [13])

$$\begin{aligned}\Phi &\equiv \Phi(x_\mu, y), & \mu = 0, 1, 2, 3; & \text{ } y \text{ is the extra spatial coordinate} \\ \mathcal{L} &= -\frac{1}{2}\partial_A\Phi\partial^A\Phi & A = 0, 1, 2, 3, 4\end{aligned}\quad (14)$$

The extra 5th dimension is compactified over a circle of radius R so that at distance scales $\gg R$, the radius of compactification, the effect of extra dimension is not manifested. It is to be noted that the field is periodic in $y \rightarrow y + 2\pi R$ ($\Phi(x, y) = \Phi(x, y + 2\pi R)$). Thus, expanding $\Phi(x, y)$ in y as

$$\Phi(x, y) = \sum_{n=-\infty}^{\infty} \phi_n(x)e^{iny/R} \quad (15)$$

(with $\phi_n^*(x) = \phi_{-n}(x)$) and substituting in the expression for \mathcal{L} in Eq. (14) we have

$$\mathcal{L} = \frac{1}{2} \sum_{n,m=-\infty}^{\infty} \left(\partial_\mu\phi_n\partial^\mu\phi_m + \frac{nm}{R^2}\phi_n\phi_m \right) e^{i(n+m)y/R} \quad (16)$$

The action S is given by

$$S = \int d^4x \int_0^{2\pi R} dy \mathcal{L} \quad (17)$$

Replacing \mathcal{L} (using Eq. (16)) and integrating out the 5th dimension to obtain the equivalent four dimensional result, the action S becomes

$$S = \int d^4x \left(-\frac{1}{2}\partial_\mu\psi_0\partial^\mu\psi_0 \right) - \int d^4x \sum_{k=1}^{\infty} \left(\partial_\mu\psi_k\partial^\mu\psi_k^* + \frac{k^2}{R^2}\psi_k\psi_k^* \right) \quad (18)$$

where $\psi_n = \sqrt{2\pi R}\phi_n$. Thus, from Eq. (18) we see that for a massless scalar field in 5-dimension, compactification over a circle yields, in equivalent 4-dimensional theory, a zero mode (ψ_0) as real scalar field and an infinite number (tower) of massive complex scalar fields with tree level masses given by $m_k = k/R$. These modes are known as Kaluza-Klein modes (or Kaluza-Klein tower) and the integer k becomes a quantum number called Kaluza-Klein (KK)

number which corresponds to the quantized momentum p_5 in the compactified dimension. The 5-D Lorentz invariance (local) of the tree level Lagrangian allows us to write the dispersion relation as

$$E^2 = \mathbf{p}^2 + p_5^2 = \mathbf{p}^2 + m_k^2 \quad (19)$$

where \mathbf{p} is the usual 3-D momentum. The conservation of this KK number apparently seems to indicate that the Lightest Kaluza-Klein Particle or LKP is stable and can be a possible candidate for dark matter.

An LKP dark matter candidate is proposed by Cheng et al [14] in the model of universal extra dimension (UED) [15, 16]. According to UED model the extra dimension is accessible to all standard model fields. In other words all SM particles can propagate into the extra dimensional space. Therefore every SM particle has a KK tower. The proposed LKP candidate for dark matter in UED model is the first KK partner B^1 , of the hypercharge gauge boson.

But in order to obtain chiral fermions in equivalent 4-D theory, the compactification over a circle (S^1) does not suffice. The simplest possibility for the purpose is to compactify the extra dimension over an orbifold S^1/Z_2 [17] where S^1 is the circle of compactification radius R and Z_2 is the reflection symmetry under which the 5th coordinate $y \rightarrow -y$. The fields can be even or odd under Z_2 symmetry. This orbifold can be looked as a line segment of length πR such that $0 \leq y \leq \pi R$ with the orbifold fixed points (boundary points) at $0, \pi R$ with two boundary conditions (Neumann and Dirichlet) for even and odd fields given by,

$$\begin{aligned} \partial_5 \phi &= 0 \text{ For even fields} \\ \phi &= 0 \text{ For odd fields} \end{aligned} \quad (20)$$

A consistent assignment for chiral fermion ψ would be; (ψ_L even, ψ_R odd) or vice versa, for gauge field A ; A_μ even ($\mu = 0, 1, 2, 3$), A_5 odd and the scalars can be either even or odd.

Now from Eq. (15) and using the orbifold compactification discussed above, the KK decomposition of Φ in even or odd fields looks as

$$\begin{aligned} \Phi_+(x, y) &= \sqrt{\frac{1}{\pi R}} \phi_+^0 + \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} \cos \frac{ny}{R} \phi_+^n(x) \\ \Phi_-(x, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} \sin \frac{ny}{R} \phi_-^n(x) . \end{aligned} \quad (21)$$

Thus, Φ_- (odd field) lacks a zero mode due to the effect of Z_2 symmetry and Eq. (21) satisfies the boundary conditions in Eq. (20). Thus we clearly see only left chiral or right chiral fermionic fields (by assigning $\psi_L(\psi_R)$ to even(odd) fields or vice versa) will have zero mode and chiral fermions can thus be identified in equivalent 4-D theory.

But this leads to problem as the boundary points $(0, \pi R)$ breaks the translational symmetry along the y direction. Thus under S^1/Z_2 orbifold compactification, the momentum p_5 is no more conserved and hence the KK number is also not conserved. This means that the stability of LKP is no more protected by the conservation of KK number.

However, it can be seen from Eq. (21) that, under a transformation πR in the y direction, the KK-modes remain invariant when the KK number n is even while the KK-modes with n odd change sign. Therefore, we readily have a quantity, $(-1)^{KK}$ which is a good symmetry and is conserved. This is called KK-parity. The conservation of this KK-parity ensures that the LKP is stable and therefore is a possible candidate for dark matter. In this context, the KK-parity serves the same purpose as the R -parity in supersymmetric models in terms of assuring stability to the dark matter candidate.

Note that the proposed dark matter candidate B^1 (as mentioned before) in universal extra dimension model is a bosonic neutral particle whereas the candidate (neutralino (χ)) in supersymmetric theory is a fermionic neutral particle. This dark matter candidate B^1 has been explored in several works (see e.g. [18, 19, 20, 21]).

There are other possible dark matter candidates proposed from other models too. One such recently proposed candidate is lightest inert particle or LIP from the so called ‘Inert Doublet’ model [22]. This LIP dark matter has also been explored (see e.g. [23]).

6 Detection of Dark Matter

As the dark matter has no or very minimal interaction, it is extremely difficult to detect them. There are two types of detection processes, namely direct detection and indirect detection. In direct detection, the scattering of dark matter off the nucleus of the detecting material is utilised. As this cross-section is very small, the energy deposited by a dark matter candidate on the detector nucleus is also very small. In order to measure this small recoil

energy (\sim keV or less) of the nucleus, a very low threshold detector condition is required. In the indirect detection, the annihilation product of dark matter is detected. If the dark matter is entrapped by the solar gravitational field, they may annihilate with each other to produce a standard model particle such as neutrino. Such neutrino signal, if detected, is the signature of dark matter in the indirect process of their detection. In what follows, we will discuss the direct detection.

Differential detection rate of dark matter per unit detector mass can be written as

$$\frac{dR}{d|\mathbf{q}|^2} = N_T \Phi \frac{d\sigma}{d|\mathbf{q}|^2} \int f(v) dv \quad (22)$$

where N_T denotes the number of target nuclei per unit mass of the detector, Φ - the dark matter flux, v - the dark matter velocity in the reference frame of earth with $f(v)$ - its distribution. The integration is over all possible kinematic configurations in the scattering process. In the above, $|\mathbf{q}|$ is the momentum transferred to the nucleus in dark matter-nucleus scattering. Nuclear recoil energy E_R is

$$\begin{aligned} E_R &= |\mathbf{q}|^2 / 2m_{\text{nuc}} \\ &= m_{\text{red}}^2 v^2 (1 - \cos \theta) / m_{\text{nuc}} \end{aligned} \quad (23)$$

$$m_{\text{red}} = \frac{m_\chi m_{\text{nuc}}}{m_\chi + m_{\text{nuc}}} \quad (24)$$

where θ is the scattering angle in dark matter-nucleus centre of momentum frame, m_{nuc} is the nuclear mass and m_χ is the mass of the dark matter.

Now expressing Φ in terms of local dark matter density ρ_χ , velocity v and mass m_χ and writing $|\mathbf{q}|^2$ in terms of nuclear recoil energy E_R with noting that $N_T = 1/m_{\text{nuc}}$, Eq. (22) takes the form

$$\begin{aligned} \frac{dR}{dE_R} &= 2 \frac{\rho_\chi}{m_\chi} \frac{d\sigma}{d|\mathbf{q}|^2} \int_{v_{\text{min}}}^{\infty} v f(v) dv, \\ v_{\text{min}} &= \left[\frac{m_{\text{nuc}} E_R}{2m_{\text{red}}^2} \right]^{1/2} \end{aligned} \quad (25)$$

Following Ref. [12] the dark matter-nucleus differential cross-section for the scalar interaction can be written as

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{\sigma_{\text{scalar}}}{4m_{\text{red}}^2 v^2} F^2(E_R) . \quad (26)$$

In the above σ_{scalar} is dark matter-nucleus scalar cross-section and $F(E_R)$ is nuclear form factor given by [24, 25]

$$\begin{aligned} F(E_R) &= \left[\frac{3j_1(qR_1)}{qR_1} \right] \exp\left(\frac{q^2 s^2}{2}\right) \\ R_1 &= (r^2 - 5s^2)^{1/2} \\ r &= 1.2A^{1/3} \end{aligned} \quad (27)$$

where thickness parameter of the nuclear surface is given by $s \simeq 1$ fm, A is the mass number of the nucleus and $j_1(qR_1)$ is the spherical Bessel function of index 1.

The distribution $f(v_{\text{gal}})$ of dark matter velocity v_{gal} with respect to galactic rest frame, is considered to be of Maxwellian form. The velocity v (and $f(v)$) with respect to earth rest frame can then be obtained by making the transformation

$$\mathbf{v} = \mathbf{v}_{\text{gal}} - \mathbf{v}_{\oplus} \quad (28)$$

where v_{\oplus} is the velocity of earth with respect to galactic rest frame and is given by

$$v_{\oplus} = v_{\odot} + v_{\text{orb}} \cos \gamma \cos\left(\frac{2\pi(t - t_0)}{T}\right) \quad (29)$$

In Eq. (29), $T = 1$ year, the time period of earth motion around the sun, $t_0 \equiv 2^{\text{nd}}$ June, v_{orb} is earth orbital speed and $\gamma \simeq 60^\circ$ is the angle subtended by earth orbital plane at galactic plane. The speed of solar system v_{\odot} in the galactic rest frame is given by,

$$v_{\odot} = v_0 + v_{\text{pec}} \quad (30)$$

where v_0 is the circular velocity of the Local System at the position of Solar System and v_{pec} is speed of Solar System with respect to the Local System. The latter is also called peculiar velocity and its value is 12 km/sec. The physical range of v_0 is given by [26, 27] $170 \text{ km/sec} \leq v_0 \leq 270 \text{ km/sec}$ (90 % C.L.). Eq. (29) gives rise to annual modulation of dark matter signal reported by DAMA/NaI experiment [28]. This phenomenon of annual modulation can be elaborated a little more. Due to the earth's motion around the sun, the directionality of the earth's motion changes over the year. This in turn induces an annual variation of the WIMP dark matter speed relative to the earth

(maximum when the earth's rotational velocity adds up to the velocity of the Solar System and minimum when these velocities are in opposite directions). This phenomenon imparts an annual variation of dark matter detection rates at terrestrial detectors. Therefore investigation of annual variation of WIMP detection rate is a useful method to confirm the WIMP dark matter detection.

Defining a dimensionless quantity $T(E_R)$ as,

$$T(E_R) = \frac{\sqrt{\pi}}{2} v_0 \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv \quad (31)$$

and noting that $T(E_R)$ can be expressed as [12]

$$T(E_R) = \frac{\sqrt{\pi}}{4v_{\oplus}} v_0 \left[\operatorname{erf} \left(\frac{v_{\min} + v_{\oplus}}{v_0} \right) - \operatorname{erf} \left(\frac{v_{\min} - v_{\oplus}}{v_0} \right) \right] \quad (32)$$

we obtain from Eqs. (25) and (26)

$$\begin{aligned} \frac{dR}{dE_R} &= \frac{\sigma_{\text{scalar}} \rho_{\chi}}{4v_{\oplus} m_{\chi} m_{\text{red}}^2} F^2(E_R) \left[\operatorname{erf} \left(\frac{v_{\min} + v_{\oplus}}{v_0} \right) \right. \\ &\quad \left. - \operatorname{erf} \left(\frac{v_{\min} - v_{\oplus}}{v_0} \right) \right] \end{aligned} \quad (33)$$

The total local dark matter density ρ_{χ} is generally taken to be 0.3 GeV/cm^3 . The above expression for differential rate is for a monoatomic detector like Ge but it can be easily extended for a diatomic detector like NaI as well.

The measured response of the detector by the scattering of dark matter off detector nucleus is in fact a fraction of the actual recoil energy. Thus, the actual recoil energy E_R is quenched by a factor qn_X (different for different nucleus X) and we should express differential rate in Eq. (33) in terms of $E = qn_X E_R$.

Thus the differential rate in terms of the observed recoil energy E for a monoatomic detector like Ge detector can be expressed as

$$\frac{\Delta R}{\Delta E}(E) = \int_{E/qn_{\text{Ge}}}^{(E+\Delta E)/qn_{\text{Ge}}} \frac{dR_{\text{Ge}}}{dE_R}(E_R) \frac{dE_R}{\Delta E} \quad (34)$$

and for a diatomic detector like NaI, the above expression takes the form

$$\begin{aligned} \frac{\Delta R}{\Delta E}(E) &= a_{\text{Na}} \int_{E/qn_{\text{Na}}}^{(E+\Delta E)/qn_{\text{Na}}} \frac{dR_{\text{Na}}}{dE_R}(E_R) \frac{dE_R}{\Delta E} \\ &+ a_{\text{I}} \int_{E/qn_{\text{I}}}^{(E+\Delta E)/qn_{\text{I}}} \frac{dR_{\text{I}}}{dE_R}(E_R) \frac{dE_R}{\Delta E} \end{aligned} \quad (35)$$

where a_{Na} and a_{I} are the mass fractions of Na and I respectively in a NaI detector.

$$a_{\text{Na}} = \frac{m_{\text{Na}}}{m_{\text{Na}} + m_{\text{I}}} = 0.153 \quad a_{\text{I}} = \frac{m_{\text{I}}}{m_{\text{Na}} + m_{\text{I}}} = 0.847$$

The differential detection rates $\Delta R/\Delta E$ (/kg/day/keV) can thus be calculated for the case of a particular detector material.

There are certain ongoing experiments and proposed experiments for WIMP direct search. The target materials generally used are NaI, Ge, Si, Xe etc. NaI (100 kg) is used for DAMA experiment and near future LIBRA (Large sodium Iodine Bulk for RAre processes) experiment (250 kg of NaI) [28]. These set ups are at Gran Sasso tunnel in Italy. The DAMA collaboration claimed to have detected this annual modulation of WIMP through their direct WIMP detection experiments. Their analysis suggests possible presence of dark matter with mass around 50 GeV. This result is far below the range of LKP mass. The Cryogenic Dark Matter Search or CDMS detector employs low temperature Ge and Si as detector materials to detect WIMP's via their elastic scattering off these nuclei [29]. This is housed in a 10.6 m tunnel (~ 16 m.w.e) at Stanford Underground Facility beneath the University of Stanford. Although their direct search results are compatible with $3\text{-}\sigma$ allowed regions for DAMA analysis, it excludes DAMA results if standard WIMP interaction and a standard dark matter halo is assumed. CDMS II experiment [30] is located at the Soudan underground laboratory at a depth of 780 metres (2090 metre water equivalent). The EDELWEISS dark matter search experiment which also uses cryogenic Ge detector at Frejus tunnel, 4800 m.w.e under French-Italian Alps observed no nuclear recoils in the fiducial volume [31]. This experiment excludes DAMA results at more than 99.8% C.L. The lower bound of recoil energy in this experiment was 20 keV. The second stage of EDELWEISS experiment is EDELWEISS II [32] where a higher detection mass is to be used with low radioactive background. The Heidelberg Dark Matter Search (HDMS) uses in their inner detector, highly pure ^{73}Ge crystals [33] and with a very low energy threshold. They have made available their 26.5 kg day analysis. The recent low threshold experiment GENIUS (Germanium in liquid Nitrogen Underground Setup) [34] at Gran Sasso tunnel in Italy has started its operation. Although a project for $\beta\beta$ -decay search, due to its very low threshold (and expected to be reduced further) GENIUS is a potential detector for WIMP direct detection experiments and for detection

of low energy solar neutrinos like pp-neutrinos or ${}^7\text{Be}$ neutrinos. In GENIUS experiment highly pure ${}^{76}\text{Ge}$ is used as detector material. For dark matter search, 100 kg. of the detector material is suspended in a tank of liquid nitrogen. The threshold for Germanium detectors is around 11 keV. But for GENIUS, this threshold will be reduced to 500 eV. The proposed XENON detector [35] consists of 1000 kg of ${}^{131}\text{Xe}$ with 4 keV threshold.

7 Discussions

The possible nature of the still unknown and overwhelming dark matter is discussed. Different theories predict different possibilities of dark matter candidates. Due to space constraints, the calculation of relic densities of such candidates could not be addressed. The theoretical calculation for direct detection rates in case of a detector material is also outlined. The experimental detection, if conclusively confirmed, will not only help us understand the nature and the particle constituents of dark matter, also it will open new vistas in understanding the fundamental laws of nature.

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