International Journal of Theoretical and Applied Science **3**(2): 103-106(2011) **ISSN No. (Print) : 0975-1718**
ISSN No. (Online) : 2249-3247

On Certain Properties and Detection of Dark Matter: A Critical Analysis

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(Received 17 August, 2011, Accepted 14 September, 2011)

ABSTRACT : In this paper we analyse critically, the cryogenic dark matter which is designed to detect weakly. Interacting Massive particals in the Milky way halo. Astronomical and cosmological observations on a huge range of scales from single galaxies up to entire visible universe, indicate that the majority of the matter in the universe is not composed of any known particle. We will usually use the expression dark matter as shorthand of majority non-baryonic component.

Keywords: CDMS, WIMPs, Shielding, BBN, DAMA Cold Dark Matter.

I. INTRODUCTION

Dark matter is a fundamental part of the picture for the astronomers and cosmologists as a part of a very active area of study. With the help of these studies a large number of properties can be deduced or inferred both as microscopic and macroscopic properties. There properties can be summarized as under:

- The orbital velocities of material outside of the visible disk of galaxies imply the existence of an invisible massive halo extending far past the disk.
- The total mass of clusters of galaxies as inferred by the velocities of the constituent galaxies, the temperature of the x-ray-emitting intergalactic gas and gravitational lensing far exceeds the mass of the visible matter [2].
- Cosmological measures of the matter density of the universe, utilizing such probes as the cosmic microwave background anisotropy and baryon acoustic oscillation studies, indicate that the total mass density is approximately five times that of the mass density of baryonic matter (i.e., matter whose mass is primarily protons and neutrons).

II. PROPERTIES OF DARK MATTER

The following are the microscopic and macroscopic properties of dark matter:

A. Microscopic Properties

First, dark matter is, indeed, matter. The particles have mass and interact gravitationally. So far, all that is known about dark matter (apart from inferences from non-observations) is derived from its gravitational effects). Secondly, dark matter is dark. This term is meant both to evoke our lack of knowledge and more specifically, to indicate that dark matter does not interact in the ways that make baryonic matter visible. Not only does dark matter not emit, absorb, or scatter light; it also travels through matter unimpeded as dramatically demonstrated by gravitational lensing maps of dark matter distributions in *e.g.* the Bullet Cluster.

A third property of dark matter is that it is cold. This qualifier is related dark matter's role in structure formation. The very small density fluctuations of the universe as seen in the cosmic microwave background must have grown to produce the large-scale structures seen today. This growth must be primarily due to dark matter particles that were moving at speeds much slower than the speed of light. If dark matter particles were moving at relativistic speeds at the time that structure formation was beginning, density fluctuations would tend to shrink rather than grow and the large-scale structure seen today could never have developed. The term cold defines particles moving at non-relativistic speeds at the onset of structure formation [3].

B. Macroscopic Properties [*4*]

The body of knowledge on the macroscopic properties of dark mater namely its density and velocity distributions - is growing at a steady rate. Of particular relevance to terrestrial direct detection experiments are the details of these distributions in our astronomical neighborhood. Through modeling of structure formation and measurements of velocities of nearby visible matter, it is known that the dark matter halo of the Milky Way galaxy has the following features:

- It is nearly spherically symmetric with an approximate radial density distribution proportional to $1/r^2$.
- The velocity of its constituent particles has an approximate isotropic Maxwellian distribution.
- At the galactic radius of our solar system:

(*i*) the dark matter mass density is approximately 0.3 $GeV/c^2/cm^3$.

(*ii*) the characteristic dark matter spend relative to Earth is approximately 220 km/s (*iii*) the galactic escape speed is approximately 544 km/s. (Whatever the specific dark matter velocity distribution, this represents a maximum cutoff).

III. THEORIZED DARK MATTER

The expression Weakly-Interacting Massive Particle (WIMP) is used to refer to the class of proposed dark matter particles that interact via the weak nuclear force and with mass on the order of 100 GeV/c^2 (within a couple of orders of magnitude). What is particularly compelling about WIMPs as dark matter candidates is that the existence of a stable WIMP is predicted by particle theory quite independently of dark matter considerations.

If dark matter particles are created in this well-understood way we should be able to draw conclusions about their interaction properties through our knowledge of their relic density. For example, if we assume that dark matter particles interact at the characteristic strength of the weak interaction, their relic density itself can be used to set the scale of the mass of an individual dark matter particle. The result is on the order of $m \approx$ GeV/c^2 *i.e.* about 100 times as massive as the proton. The result is intriguing because this is the same mass scale as the gauge bosons that carry the weak interaction.

A compelling class of theories predicting WIMPs are those involving supersymmetry, a conceptually natural extension to the Standard Model that predicts the existence of a suspersymmetric partner to every known particle. None of these superpartners has yet been detected (indicating that they should have high enough masses to have escape detectable production in collider experiments). Many theories with supersymmetry naturally predict a stable WIMP (usually the neutralino, a superpartner to the neutral electroweak gauge bosons).

The most obvious way to detect halo WIMPs is to look for the recoil of an ordinary matter target after an elastic collision with a WIMP. The characteristic fraction of the WIMPs kinetic energy that is transferred in the collision, from simple kinetic arguments, is

$$\left\langle \frac{E_{recoil}}{E_{kinetic}} \right\rangle = \frac{4M_W M_T}{(M_W + M_T)^2} \quad \text{... (1.1)}$$

with M_W and M_T the respective masses of the incident WIMP and the target particle. This is maximum when WIMP and target have the same mass falling off the greater the mismatch in their masses. Therefore the signal is maximized by choosing a target with the same mass as a WIMP. Considering the range of possible WIMP masses (50 GeV/c^2 or greater) this suggests a heavy atomic nucleus as an appropriate target. Since the de Broglie wavelength of an incident WIMP is on the order of a fm, to first approximation a nucleus serves as a single target.

In the general interaction Lagrangian expression

$$L \times N \approx 4X^{\circ}X(f_p\eta_p{}^{\circ}\eta_p + f_n\eta_n{}^{\circ}\eta_n)$$

$$16\sqrt{2}G_{Fx^{\circ}}\frac{\vec{\sigma}}{2}\times\left(a_p\eta_p{}^{\circ}\frac{\vec{\sigma}}{2}\eta_p + a_n\eta_n{}^{\circ}\frac{\vec{\sigma}}{2}\eta_n\right) \quad \text{... (1.2)}$$

This represents the fundamental interactions between WIMPs and nucleons (protons and neutrons). In this expression, Ξ is the WIMP wave function, η_p and η_n are the proton and neutron Weyl spinors and $\vec{\sigma}$ is the spin operator. The first term represents so-called spin-independent (*S*) interactions, while the second indicates the possibility of coupling of the spins of the WIMP and the target, so-called spin-dependent (*SD*) interactions.

In the *SI* case, the collision cross section can be calculated from (1.2) to be

$$\sigma_0{}^{SI} = \frac{4}{\pi}\mu^2{}_{WT}[Zf_p + (A-Z)f_n]^2 \quad \text{... (1.3)}$$

where the subscripted 0 indicates that this holds in the extreme nonrelativistic limit. *A* and *Z* are the mass number and atomic number of the target nucleus, μ_{WT} is the reduced mass of the WIMP and the target nucleus.

$$\mu_{WT} = \frac{M_W M_T}{M_W + M_T} \quad \text{... (1.4)}$$

All of this holds true for a generic WIMP. But we can simplify further if we assume $f_p \approx f_n$ as is true in supersymmetric models. We then find [7].

$$\sigma_0{}^{SI} = \frac{4}{\pi}\left(\frac{M_W M_T}{M_W + M_T}\right)^2 (Af_{p,n})^2 \quad \text{... (1.5)}$$

Considering that M_T is proportional to *A*, σ_0^{SI} increases very strongly with increasing *A*: at least as strongly as A^3 (A^4 in the limit $M_W \pi M_T$).

The *SD* cross section can also be derived from (1.2). Some of the features of *SD* cross sections are:

- The strong mass number enhancement is not present.
- Nuclei with large spins are favored.
- Nuclei with an odd number of protons or an odd number of neutrons are favored.

IV. DIRECT DETECTION EXPERIMENTAL TERMINOLOGY [9]

The following terms are used frequently in direct detection WIMP searches. Usage can vary; the definitions given here are the sense in which I will use these terms in this thesis.

Event: Information from all detectors in an experiment collected simultaneously over a restricted time interval. Coincidence is evidence of simultaneous signals in two separate detector volumes.

Live Time: The total amount of time in which the detectors are ready to detect a new signal. For a period of data taking this is real time minus the intervals over which events are being recorded. If periods of data taking are later rejected due to high noise or other problems, the live time is adjusted accordingly.

Raw Exposure: The live time multiplied by the detector mass, typically expressed in kg days or kg years. This is the basis for characterizing the rate of the WIMP signal, which is the primary aim of a direct detection experiment. The greater the exposure, the more sensitive the experiment is a low-rate signal.

Background: Signals from ordinary radiation that satisfy all WIMP identification criteria. Different background categories exist for different types of ordinary radiation. For a given experimental exposure, background is expressed in units of events. for low-background experiments the expected background is often less than one (an expectation value). Typically the background of an experiment falls between two extremes:

- **Zero-background:** A total background that is much less than one event for a given exposure. In a zero-background experiment the sensitivity is directly proportional to the exposure.
- **Background-limited:** A total background that is proportional to the exposure, and which cannot be efficiently separated from the WIMP signal by global features. In a background-limited experiment the sensitivity cannot be increased by increasing the exposure.

Discrimination: Identification of potential background that distinguishes it from a WIMP signal. Any events thus identified are eliminated as background.

Leakage: Potential background that is not eliminated by some discrimination criterion. Leakage is expressed in units of events. The leakage fraction is the fraction of some set of potential background that is not eliminated by a discrimination criterion.

Efficiency: The fraction of potential WIMP signal events that satisfy one or more WIMP selection criteria, including background discrimination criteria. The exposure is the product of the raw exposure and the combined efficiency of all WIMP selection criteria.

Blind Analysis: A procedure to avoid unconscious bias in which the researchers finalize all WIMP selection criteria before examining any data that could contain an identifiable WIMP signal. Any conclusion drawn in a rare event search is much stronger if a blind analysis is performed. Data files from which potential WIMP signal events have been automatically removed are often referred to as "blinded" "Unblinding" is the opening of a complete data set for analysis.

WIMP Candidate: An event satisfying all WIMP selection criteria. Any WIMP candidate is considered to be either background or a WIMP interaction. If the number WIMP candidates is significantly larger than the expected background this constitutes evidence of a WIMP signal.

V. ANALYTICAL RESULTS

Armed with the information above we can predict the expected interaction rate and recoil energy spectrum for SI collisions of halo WIMPs with target nuclei. The details depend on the two least-known parameters (WIMP mass and fp.n, the latter usually expressed in terms of the SI cross section between a WIMP and a single will nucleon). However regardless of the specific values, the recoil energy spectrum will be approximately a decreasing exponential with characteristic energy in the tens of keV, and the overall rate will be small because WIMPs interact weakly. The WIMP signal will therefore face competition from familiar forms of radiation that interact much more strongly. Most of the effort in experimental design goes into dealing with potential background signals from collisions between known particles and the matter in the detector. One class of strategies to extract a WIMP signal in the presence of background exploits differences between the global features of the background signal and the expected WIMP signal. If the background spectrum is understood well enough, it can be subtracted from the total spectrum, leaving any residual WIMP signal. This strategy has been employed by CoGeNT. Alternatively one ca look for a feature of the WIMP signal that is not expected in any background signal. As mentioned above, the expected WIMP spectrum is essentially free of distinguishing features such as peaks. However an additional expected feature of a WIMP signal is a spectrum that changes over the course of a year due to the earth' velocity relative to the sun. This motion will alternately enhance and diminish the average relative velocity of the WIMP wind which will in turn modify the WIMP signal spectrum and overall rate. A (WIMP + background) signal could be studied over time for signs of annual modulation, which would serve as a WIMP signal signature (assuming an annual modulation in any background source can be ruled out) [10]. This strategy is used by DAMA/LIBRA.

VI. CONCLUSIONS

In contrast to global approaches, a different strategy for extracting a WIMP signal is to exploit the differences between WIMP interactions and background particle interactions. The most prevalent background is typically photons from radioactivity inside the shielding. When a photon of the relevant energy collides with an atom, it collides with one of its electrons, rather than the nucleus. In a sense the atom's electrons serve as shielding for the true WIMP target: the nucleus of the atom. (WIMP-electron collisions are not impossible, but the cross section is much smaller and the deposited energy typically unmeasurable.) Generally the type of particle detectors used in WIMP search experiments produce a collision signal whose strength is proportional to the recoil energy. However most such detectors respond to electron recoils and nuclear recoils differently. We seek collisions between WIMPs and atomic nuclei in disk-shaped germanium and silicon detectors. A key design feature is to keep the rate of collisions from known particles producing WIMP-like signals very small. The largest category of such background is interactions with electrons in the detectors that occur very close to one of the faces of the detector. The next largest category is collisions between energetic neutrons that bypass the experimental shielding and nuclei in the detectors. Analytical efforts to discriminate these backgrounds and to estimate the rate at which such discrimination have been refined and improved throughout each phase of CDMS.

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