Is Dark Matter Made out of Particles?

Current searches and detector developments.

Bernard Sadoulet
University of California
Berkeley

The hypothesis that Dark Matter is made out of exotic particles is definite enough to be testable in a variety of ways. We review the first generation experiments looking for dark matter particles, using conventional techniques. They may find those particles and in any case will provide powerful constraints. We argue that in the long run, cryogenic detectors will have to be used for that type of physics, and since the European effort is covered by other speakers, we review the present developments in this area in the USA.

1. Introduction

One of the most fundamental question in Astrophysics and in Cosmology is the nature of the Dark Matter which pervades the universe [e.g.1a]. At least 90% of the mass in the universe does not emit electromagnetic radiation and is inferred only through its gravitational interactions. It is difficult to prevent ordinary matter to radiate in an astrophysical environment and primordial nucleosynthesis limits the density of the baryons to a fraction of what seems necessary to account the dark matter. Although not yet convincing for a part of the community, these are rather strong arguments to doubt that dark matter is made out of ordinary matter. Among the other possibilities (primordial black holes, exotic objects), the idea that it could be made out of the lowest stable member of another (unknown) family of particles is fairly attractive. Many current Particle Physics theories need such a family in order to be singularity-free; the most familiar example is Supersymmetry. So a fundamental cosmological problem may have its solution in Particle Physics!

Many groups are getting interested in testing this hypothesis[1b,c]. In section 2 we describe the many complementary ways in which this can be done. Section 3 attempts to delimit the region which will be explored by first generation experiments using existing technologies. They may be able to find dark matter particles if they have favorable properties and they will at least place interesting limits.

These current searches should be kept in mind when designing second generation experiments using cryogenic detectors. We review in section 4 the justifications for their development. Section 5 summarizes the various development going on in the USA.

2. The many complementary ways to look for dark matter

The hypothesis that dark matter is made out of particles is much more constrained than it looks by the known current density of dark matter[2]. The fundamental observation made for instance by Lee and Weinberg[3] is that, if these particles that we will call δ, have been in thermodynamical equilibrium with quarks and leptons in the early universe, their annihilation rate at the time when they drop out of equilibrium is bounded from below. Above a mass of 1 GeV/c^2

$$\langle \sigma v \rangle_{\text{annihilation}} \geq \frac{10^{-26}\ \text{cm}^3/\text{s}}{\Omega_\delta\ h^2}$$

where Ω_δ is the ratio of the current density of the δ's to the critical density and h the Hubble constant in units of 100 km/s/Mpc.

By crossing this is related to the elastic scattering of δ on ordinary matter.

Fig 1 shows how then these particles can be searched for. The annihilation cross section at freeze out given by the Lee-Weinberg argument can be extrapolated to high energy and current and future accelerator experiments will provide interesting limits[2b]. Extrapolated down to very low energy, it predicts a minimum rate of annihilation of the δ's in the present universe and the annihilation rate products could be observable in the cosmic rays (gamma lines[4,5], low energy antiprotons[4]).

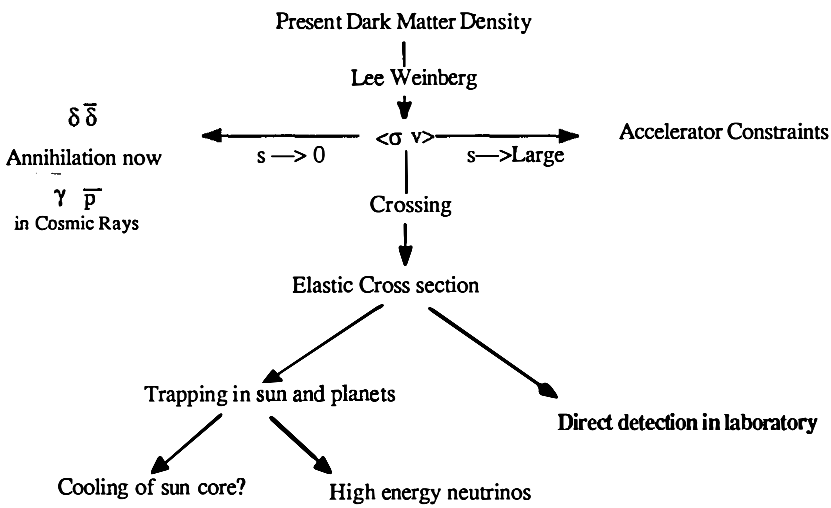

Figure 1 Schematical relationships between the various dark matter searches

The elastic scattering cross section obtained by crossing leads both to the possibility of detecting the particles directly in the laboratory (or in a mine)[7] and to the fact that they should be trapped in the sun and in the planets. Their density may then be large enough to enhance the annihilation rate sufficiently for the generation of a detectable flux of high energy neutrinos (> 1.5 Gev) [8] or alternatively to cool effectively the core of the sun [9]: this may explain the deficit of solar neutrinos observed by Ray Davis [10].

3. What may be learned from the first generation experiments?

Most of these consequences of the hypothesis that dark matter is made out of particles are already being tested.

3.1 The antiproton flux in the cosmic ray is being remeasured by a Berkeley,Boston and Indiana group.

3.2 Proton decay experiments are looking for high energy neutrons coming from the sun. The most interesting result may come soon from Frejus which has a very good angular resolution. For instance if they are able to exclude a flux above 1.5 Gev/c of 1.5 events/ton/day, and if the calculations of Gaisser et al. are realistic [8], the mass of dark matter Majorana particles (e.g. photinos) may be constrained to be above 20 Gev/c^2 or below 4 Gev/c^2. Heavy Dirac or scalar neutrinos will also be constrained. If their hypercharge is small and their interaction cross section at the Lee-Weinberg level, a similar mass region will be excluded. Note however that if those neutrinos interact with the full Z^0 strength (hypercharge $\approx 1/2$) , and are indeed the major component of dark matter, proton decay experiments will not provide any limits. This occurs because an initial asymmetry is required for the large cross section to be compatible with the present density,and no annihilation is expected, because one of the components (δ or $\bar{\delta}$) has disappeared at freeze-out. We should remark also that these limits are quite sensitive to the details of the neutrino spectrum calculations, and that they should be checked with the e^+e^- data.

3.2 Present ionization detector are already providing limits in the favorable cases of large masses and large cross sections. Spiro [11] summarizes in this workshop present constraints for high cross section scenarios. The PNL-USC [12] and UCSB-LBL[13] groups are using their double beta apparatus to put an upper limit of 20 Gev/c^2 on heavy neutrino interacting with full Z^0 strength. And they both are decreasing their threshold from 4 to 1.5 keV equivalent electron energy. In the Z^0 model, the upper limits may then be brought down to 8 or 10 Gev/c^2. In discussions during the workshop we realized [14] that similar experiments with silicon ionization detectors which have lower threshold and are better matched to the mass of the projectile, could bring these limits down to 4 Gev/c^2. This is particularly important in relation with the hypothesis that trapping of dark matter particles may be responsible for the cooling of the sun core. In that case elastic cross sections have to be large and initial asymmetry is likely [15] so the proton decay experiments cannot provide any limit. This experiment is being proposed in Berkeley. Let us remark finally that in the intermediate mass range, (4 to 10 Gev/c^2), the ionization detectors may be sensitive to vectorially coupled particles interacting at the Lee Weinberg level[14].

We are therefore witnessing quite a number of searches for dark matter using many different techniques. Of course, these complementary efforts may be able to provide some evidence for dark matter particles. They will at least severely constrain the available phase space.

4. Justification for cryogenic detector development

It is however, likely that an unambiguous confirmation or rejection of the hypothesis that dark matter is made out of particle, will require better detectors, sensitive to very small quanta of energy deposition. These detectors usually known as cryogenic detectors[16], are based on the detection of quasi particles or phonons.

4.1 In the case of a prior detection by conventional methods, cryogenic detectors would be required for confirmation and detailed studies. They could bring in two interesting properties:

-- They should allow to use a mix of materials for the target. This would be important to confirm the signal, measure the mass of the incident particle and study its coupling mechanism.

-- Phonon detectors should have localisation capability which would help to reduce the background by checking for instance that the claimed signal is not coming from edges or close to dead regions of the detector.

4.2 In the case where no detection is achieved in the first generation experiments, cryogenic detectors will be essential to explore the three cases inaccessible to conventional techniques:the Majorana candidates which a target with nuclear spin, the low mass region which requires lower thresholds and the very large masses for cross sections on the Lee Weinberg bound, where it is crucial to decrease the background, because of the very low rates.

-- Cryogenic detectors will allow relatively easily to have targets with nuclear spin. This is necessary to be able to detect any Majorana spin 1/2 dark matter particle[2b], such as the photino, one of the most likely candidates.

-- Phonon detectors should allow very low thresholds (100 eV) for reasonable masses (at least a few hundred grams) at temperature of 15 or 20 mK. This will permit the exploration of the low mass region down to present limit from accelerator experiments (≈2 Gev/c^2).

-- Schemes coupling phonon and ionisation detection may moreover give a signature that the interaction occured on the nucleus and not on an electron: a nucleus deposit a much larger fraction of its energy in heat than an electron of the same kinetic energy. This would be extremely important [2a] if accelerator experiments or the absence of high energy neutrino from the sun indicate that the interesting mass region is above 20 Gev/c^2. For cross sections on the Lee Weinberg bound, it can be shown that the signal to background ratio goes as the inverse of the cube of the mass[2a]! At large masses the above signature would be crucial to decrease the background sufficiently.

5. Development efforts

Because of these potential advantages for dark matter searches as well as for other experiments such as the detection of coherent scattering of neutrinos on nuclei, solar neutrinos and double beta decay [1b and 16], many groups are starting development of cryogenic detectors.

The European effort have been described by other speakers at this workshop. Table I gives a list of the teams working in the USA on the development of large mass cryogenic detectors. In addition, there is a large number of groups working on small bolometers for X-ray applications and their experience is quite valuable.

Table I
Cryogenic detector development in the USA

Group	Technique	Dilution Refrig?	Funding
NRL,UBC,PNL/USC BU Druikier et al	Granules,Squid	UBC	Operating funds
Stanford Cabrera,Neurhauser Martoff	Ballistic Phonons Tunnel Junctions +trapping	Yes +He^3	Operating funds
UC Santa Barbara Caldwell,Witherell	Quasiparticles?	No low temper.	ββ Decay
UC Berkeley/LBL Sadoulet,Haller,Lange Steiner,Wang,Park	Phonons. Semiconductor Thermistors	Parasiting now 20mK on order	UCB +LBL
Brown Univ. Maris,Seidel,Lanou	Rotons in He^4 Bolometers		Operating funds

So far, most of the groups in the USA are setting up and learning to master the technology they chose to try. Among notable achievements let us quote

a) The first successful readout of granules with a RF Squid at the University of Brittish Columbia[17] by Druikier and collaborators.

b) An encouraging detection of phonons from α particles on a superconducting film after travel of 275 μm in a silicon substrate by the Stanford group.

c) A detection of α particles with a NTD bolometer of 0.6 10^{-2}gram with a signal to rms noise ratio of 20,at 1.4K by the Berkeley team and more interestingly, their first attempt to run bolometers at 20 mK. A thermal bottle-neck with an unusually small heat conductivity seems to set in at low temperature and tests are currently being performed to understand its origin.

The reader interested in more technical details is referred to our review [18] at the Munich Workshop on Cryogenic Detectors.

6. Conclusions

We are witnessing the birth of a new research field: the hypothesis that dark matter is made out of particles is **specific enough** to be tested in many different ways. Both conventional techniques and new technologies which have yet to be developed, are put to work. It will very likely take time but the question of the nature of dark matter is fundamental enough to warrant these efforts and the enthusiasm of the teams involved!

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