ABSTRACT

One of the most natural explanations for the dark matter which constitutes at least 90% of the universe, is that it is made of exotic particles, not yet seen at accelerators. The present density of dark matter constrains this rather general hypothesis enough for meaningful tests. The concentration of dark matter particles in the halo of our galaxy leads to potentially observable fluxes of $\bar{p}$, $e^+$, $\gamma$ rays and neutrinos. Elastic scattering rates of the order of a few events per kg and per day are also expected.

These two lectures will describe the present searches for such dark matter particles and the developments which are being undertaken to improve these searches.
Experimental searches for dark matter particles

Bernard SADOUL ET
UC Berkeley

OUTLINE

1. **Dark matter**
   - A Fundamental problem
   - Controversy on nature

2. **The hypothesis that dark matter = particle**
   - Fairly defined
   - Hunts from particle physics
   - Hunts from cosmology

3. **Indirect searches for WIMPs**
   - Cosmic rays $\gamma$'s
   - High energy $\nu$'s from the sun

4. **Direct searches for WIMPs**
   - Rates / energy deposition
   - Background
   - Signatures
OUTLINE (2)

1. Direct detection of WIMPS

2. Conventional technologies
   - Present limits
   - New developments

3. Cryogenic detectors
   - Superconducting
     - Granules
     - Tunnel junction films
   - Phonons detectors

4. Conclusion
# The Dark Matter Problem

Summary of astrophysical evidences

Determination of \( \mathcal{N} = \frac{g}{g_c} \sqrt{\frac{\Delta H^2}{8\pi G}} \)

\[ = 1.3 \times 10^{-29} \text{ g/cm}^3 \]

\[ \frac{H}{100 \text{ km/s/Mpc}} \]

<table>
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<tr>
<th>Scalar ((k^{-1} \text{ Mpc}))</th>
<th>(\mathcal{N})</th>
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<tr>
<td>Visible part of galaxies</td>
<td>0.01</td>
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<tr>
<td>Halos of galaxies</td>
<td>0.1</td>
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<tr>
<td>Clusters</td>
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<tr>
<td>Virgo infall</td>
<td>10</td>
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<tr>
<td>Large scale infall</td>
<td>30</td>
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<tr>
<td>Geometry</td>
<td>3000</td>
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> 90\% of mass is dark!
Figure 2.10:
The velocity in the plane of the galaxy plotted as a function of the distance to the galactic center.

a) 21 cm line [Bosma, 1981]
b) HII regions [Rubin, et. al.1980]
Controversy on the nature of dark matter

\[ \text{Baryonic } \neq \text{ Non baryonic} \]

\[ \Rightarrow \text{ Occam Razor} \]

- Non baryonic
  - Primordial nucleosynthesis
  
  \[ 5 \times 10^{-3} \leq \Omega_b h^2 \leq 2 \times 10^{-2} \]

\[ \log \Omega \]

\[ \begin{array}{c|c|c|c}
0.03 & 0.15 & 0.2 & 1 \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow \\
\end{array} \]

\[ \log \Omega > 0.2 \]

- Value of \( \Omega \)
  
  \[ (1 - \Omega^{-1}) = \frac{(1 - \Omega_0^{-1})}{1 + z} \]

\[ \Omega_0 = 1 \text{ only stable for } \Omega < 2 \]

\[ \text{Inflation} \]

- Difficult to hide
  - Absorption
  - Jupiters
  - Radiation
  - Contamination

- Galaxy Formation \( \leftrightarrow 30 \text{ K} \)

Need additional component
Hypothesis that dark matter = particles

Hints from particle physics

- Zoo of particles
  - Heavy vs (GUT)
  - Supersymmetry (hierarchy)
  - Axion (CP problem)

=> quite natural

- Experimental limits

\[ v_e < 20 \text{eV} \]
\[ v_\mu < 250 \text{eV} \]
\[ v_\tau < 70 \text{MeV} \]
\[ e^+ > 54 \text{GeV} \]
\[ f > 70 \text{GeV} \]
\[ \bar{p}p \]
axion = "invisible"

Hints from cosmology

- Axions

\[ \text{Red giants} \]
\[ \text{SN} 1987a \]
\[ m_a \leq 9 \times 10^{-5} \text{eV} \]
\[ m_a \geq 2 \times 10^{-5} \text{eV} \]
Species in thermodynamical equilibrium

\[ \bar{s}s \leftrightarrow q\bar{q} \quad \text{+ axions} \]

\[ \mu, \delta \]

Freeze out

\[ \langle \sigma v \rangle \gtrsim 10^{-26} \text{ cm}^3/\text{s} \]

\[ \text{Asymmetry} \quad N_s h^2 \]

- Current density \( \leftrightarrow \) Interaction rate
- \( N_s \sim 1 \) \( \Rightarrow \) Weak interaction \( \sigma v \) !!!

Nowhere W.I. Scale put in Hint or numerical coincidence?

Crossing

\[ M (s\bar{s} \leftrightarrow q\bar{q}) \sim M (q\bar{q} \rightarrow q\bar{q}) \]

\[ \Rightarrow \quad \sigma_{el} \gtrsim 10^{-38} \text{ cm}^2 \]

\( N_s \)

\( \Rightarrow \quad M_r < 30 \text{ eV} \)

Light neutralinos

WIMPs

\[ m_s > 2 \text{ GeV/c}^2 \]

\( e^+e^- \rightarrow \gamma + \text{nothing} \)

\( \text{ASP, CECCO, MAC} \)

\( \nabla \)

Light dark matter insufficient

- Galaxy Formation
- Dwarf spheroidals

\[ M_r > 500 \text{ eV} \]

\[ V + \text{Cosmic Strings} \]
New field of investigation

Detection schemes for light dark matter

Axions

\[ a + \chi \rightarrow \chi \]

200 times expected density

Light neutrinos

- No good idea for cosmological \( \nu \)
  - Accelerator
    - Mass measurement
    - Oscillation measurement
Figure 4.1: The Cosmic Axion Search [DePristo et al. 1987]
Indirect searches for WIMPS

1. Cosmic rays
   \( s\bar{s} \rightarrow \gamma \gamma, \bar{p} \)
   - \( \gamma \)'s diffuse
   \( s\bar{s} \rightarrow c\bar{c} + \gamma \)
   \( \gamma \leftarrow \frac{1}{\chi} \)
   ≠ Buffetton
   (weak limit)

2. High energy \( \nu \)'s from the sun
   - Fuyug
   - Kamiokande
   - IMB
   \( m_\nu < 4 \text{ GeV/c}^2 \) or \( m_{\nu_H} > 25 \text{ GeV/c}^2 \)
   \( m_{\nu_H} < 4 \text{ GeV/c}^2 \) \( m_{\nu_H} > 65 \text{ GeV/c}^2 \)
   \( m_\nu \rightarrow \) weak bound
   \( \leftarrow \) Uncertainty on axial vectorial couplings
   (EMC measurement)
   \( m_\nu \sim m_\nu \)
Present Dark Matter Density

\[ \delta \delta \]
Annihilation in the halo of our galaxy

\[ \gamma \ \bar{p} \]
Cosmic Rays

\[ \langle \sigma v \rangle \]
Elastic Cross section

\[ \text{Low energy} \quad \text{High energy} \]

\[ \text{Crossing} \]

Trapping in sun and planets

\[ \delta \delta \rightarrow \gamma e^+ e^- \]

Cooling of solar core?

High energy neutrinos

Present Dark matter density

\[ m_\chi > 2 \cdot 5 \, \text{GeV} \]
Accelerator Constraints
\[ e^+ e^- \rightarrow \gamma + \text{nothing} \]
\[ \bar{p} p \rightarrow \text{missing } E_T \]
\[ 3^\circ \text{ width} \]

Lee Weinberg
Direct detection

- The challenges of searching for elastic interactions.

- Rates

  3 archetypes

  a) No cosmic asymmetry - minimal coherence factor

     (e.g. axial vectorial coupling: couples to spin only ⇒ need a target with nuclear spin.

     Unfortunately case for photinos and higgsinos)

  b) No cosmic asymmetry - charge coherence factor

     (e.g. vectorial coupling to neutron number for heavy neutrinos with small hypercharge)

  c) Cosmic asymmetry ⇒ large cross sections

     (e.g. Dirac neutrinos with normal hypercharge)

- Deposited energy

  Small!

  ~ \( \text{KeV} \)

- Signatures

  + [Yearly modulation] (+ directanility?)

  + Spectrum

  + Dependence on target atomic mass

  + [Interaction on nucleus (cryogenic detectors)]

- Radioactive background

  + State of the art: \( 0.5 \text{ evt/kg/day}/\text{keV} \)

  + Most: interaction on electrons. (Neutrons can be degraded)

  + Mainly Compton ⇒ flat

\[ \Rightarrow \]

\[ 1 - 10 \text{ kg of material} \]

\[ \text{Low thresholds: } 100 \text{eV} \]

\[ \text{Extremely low background} \]
Photinos
Normalised to Lee-Weinberg

Figure 1a

Heavy Neutrino
Normalised to Lee-Weinberg

Figure 1b

Heavy Neutrino

Z\textsuperscript{0} exchange
$Y=1/2$

Figure 1c

Non muon asymmetry

Spin coherence

Ellis - Flow somewhat lower

No muon asymmetry

Charge rate

Heavy asymmetry
\[ \langle E \rangle = \frac{m_s^2 \, M}{(m_s + M)^2} \langle \nu^2 \rangle \]
Incompatible with flat background

Events/keV/kg/day vs Deposited Energy (keV)

- MASS = 12 GeV/c^2
- MASS = 20 GeV/c^2

Mass = 12 GeV/c^2

Mass = 20 GeV/c^2

\( ^{3}H \)
NGP

NEP

Sun

Dec 4

Jun 2

230.4 km/s

CG
Mine
(Power plant
Orozuela)

Active Veto
Shield

Detector
(e.g. 0.3 kg Ge)

\[
\frac{dN}{d\varepsilon_d}
\]

GENERIC DARK MATTER
DETECTOR.
Direct detection

"Conventional" ionization

- Proportional counters
- Solid state detectors

Cryogenic detectors

- Cooper pairs
  - ~ 1 meV
- Phonons
  - 100 mk ~ 10 keV

Breaking of superconductors
- Granules
- SC films

Tunnel junctions

Calorimetry

As an example: Berkeley effort
Conventional
ionization detectors

- Exist!
- Basic problem: very little ionization

\[ \Rightarrow \text{RESULTS} \quad \text{high mass} \]
\[ \text{high rate} \]

F. Goulding
A. Smith
D. Cardwell
R. Eisberg
H. Withen
B. Sadoulet

\[ \Rightarrow \text{FUTURE} \]

- Ge \[ \rightarrow 10 \text{ GeV/c}^2 \]
- Si \[ \rightarrow 3 \text{ GeV/c}^2 \]

Important: Check CDM Ions (WIMPs)

Explanation of deficit of solar \(\nu\)

\[ 4 < m < 10 \text{ GeV/c}^2, \quad \Omega \approx 10^{-36} \]

- Still a lot to gain
  - Lower background
  - Spatial segmentation
  - Smaller 2 thresholds
1.5 OCR Output

Kiretic energy (keV) 0.0 20.0 40.0 60.0 0.0 100.0

<table>
<thead>
<tr>
<th>Ratio of ionisation deposition</th>
<th>Germanium</th>
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<tbody>
<tr>
<td>0.0</td>
<td>Figure 1a</td>
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Ratio of ionisation deposition

Germanium

Figure 1a

40 keV nucleus = 12 keV electron

Ratio of ionisation deposition

Silicon

Figure 1b

Kiretic energy (keV) 0.0 20.0 40.0 60.0 80.0 100.0

n/e 1.0

0.8

0.6

0.4

0.2

0.0
Glycolic Detectors

Motivations

2 Frontiers:

- Threshold
- Low mass

Real → Background

Justification

- Spectrum
- Position sensitivity

Important

- Materials
- Interactions on nucleus
- Directionality ?

Existence proof

$(10^{-5} g !)$

Other potential applications

- Coherent scattering
- Double $\beta$
- $X$ mass
- X-ray spectroscopy

Large number of (subcritical) qio
Basic concepts

Historical evolution

- Proportional chamber electrons $\sim 10$ ev
- Scintillation excitation $\sim 5$ ev
- Semiconductor holes $\sim 1$ ev
- Superconductors quasiparticles $\sim 10^{-2}$ ev
- Phonons at 100 mK $\sim 10^{-5}$ ev

Basic idea: if detection of these quanta can be efficient

$\Rightarrow$ Low threshold
$\Rightarrow$ High Accuracy $\frac{sN}{N} \sim \frac{1}{\sqrt{N}}$

PIONEERS: Infrared Astronomers

Particles: Orsay 1967
Niinikoski-Udo 1974
Applications

- Particle physics
  - Coherent scattering
  - Double $\beta$
  - Ne mass position resolution
  - Partially radiative

- Nuclear physics
  - X ray spectrscopy
  - $\gamma$ ray Doppler Shift
  - $n$ detection
  - Recoil of nuclei

- Astrophysics
  - X rays Imaging
  - Dark matter

- Others
  - X ray diffraction
  - Ultracold neutron
  - Industrial Non Destructive Q.C.
  - Medical imaging
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Cryogenic Detectors

Quasi particles

- Breaking of superconductivity
  - Granules
  - Films

- Tunnel junctions

Phonons

- Thermalized
  - Thermistors
  - Supercond. Films

- Ballistic
  - Breaking Tunnel Junct.

By B. Sadoulet
"Cryogenic Detectors: hopes and challenges"
IEEE Sept 87
Superconductivity

Cooper pairs $2\Delta \approx 3.5 \, kT$

- Quasiparticles $e^*$
- Complete breaking of Superconductivity
- Tunnel junctions
- (Superheated) Superconducting Granules

Ozsay 1967 (Valette)
Waysand Drückier
(Superheated) Superconducting Granules

Marker = 10K
40 - 65K

Magnetic field
Cryostat

Sensing Loop

Adaptation

Amplifier
Granules

Osay group 1967

Advantages
- Fast position resolution 0.5 mm
- Radiation & and High sensitivity

Technical problems
- Manufacturing of regular enough spheres
- Quantum efficiency
- High sensitivity amplifiers

Threshold detector

Films

Advantages
- Simple
- Photolithographic

Drawback
- Threshold
- Low mass
- Coupled to planes

Cabina 1.5 μ 490 Å
Tunnel junctions

Potentially much more precise \( \sim 10^6 \) quasiparticles/keV

### Principle of Josephson junction

Small B suppresses Cooper tunelling

![Graph](attachment:image.png)

- I
- V
- Bias

### Best result so far

Rehder

\((50\mu)^2\) Sn: 6 eV: 41 eV FWHM

0.6\% Importance of decreasing diffuse

Mossbauer
(a) Increase in tunneling current (Process a)

Excess

Ionizing particle

$E_{F1}$

$eV_B$

Tunnel junction

$E_{F2}$

(b) Increase in tunneling current (process b)

Excess

$eV_B$

Ionizing particle

$\Delta$

$\Delta$
Challenges

Manufacturing of good junctions

"Black magic"
Low leakage current (shot noise limitation)
Niaoshorts

Robust (should resist many cool-downs)

Detection in large volume

Tunnelling probability $\leq 10^{-6}$

$\Rightarrow$ large junctions : too much noise

Trapping: Booth Cabrera

First experimental verification Zehnder

(But no lines !)
TRAPPING

(a) Stimulus

(b) Stimulus

Energy

E_F

Δ₁

Δ₂

S₁

S₂

S₃

Tunnel barrier

High gap superconductor

S₁, vol. V

Lower gap material

Stimulus

Δ₁

Δ₂

S₁

S₂

S₃

Tunnel barrier
Phonon Detectors

Basic idea $<E> \sim kT = 10^{-6}$ eV at 10mK

Existence proof

Bolometry (I.R. Astronomy)
Calorimetry
Niinikoski
McCann
et al

\[ \text{Thermalized phonons} \quad \text{Ballistic phonons} \]
An existence proof

CALORIMETRY

Oldest method: Joule

Extension of bolomtery (Infrared Astronomy)

\[ \Delta V = \frac{\partial V}{\partial T} \left( \frac{\Delta E}{C_M} \right) \]

\[ \text{Noise} \quad SE = \frac{\delta}{\sqrt{kT^2c_M}} \]

Works!

\[ > 100 \text{ mk} \]

McComman, Fossey

\[ > 20 \text{ mk} \]

Berkeley, Coton (France)

Assumes Debye law

\[ \xi \text{ constant (Thermistor)} \]

\[ SE \sim T^{\xi/2} M^{1/2} \]

Extrapolation: Constant $\xi$: 100 g Ge 300 g B $\Rightarrow 100 \text{ eV}$

$\xi$ Measured $\frac{dV}{dT}$ (Berkeley) 50 g B

threshold
Fig. 1

1. BOLOMETER
2. THERMISTOR
3. COLLIMATOR
4. $\alpha$ - SOURCE

Fig. 1
Fig. 3a

Counts

Energy (MeV)

5  6  7  8  9  10

FWHM 100 keV

0.7 g 40 mK

\( E_d, E_\alpha + E_{\text{ recoil}} \)
**Physics of phonons**

**Thermalization mechanisms.**

- Solid state physicists: High energy interaction
  - Optical Phonons
  - Transverse phonons
  - Down conversion

- Lattice defects: e-holes
  - Recombination

- Unimportant for dark matter
- No need for recombination

- Maxwell 200k (expanded for clarity)

- "Ballistic" phonon: \[ \gamma \propto \frac{1}{\text{cm}} \]

- Crystal rings forever! "Acoustic"
Naive description \( G, T \) wrong

=> At best qualitative

- Evidences with particles
  - Fast rise time
  - Fraction of phonons > 1 meV
    (Tunnel Junction Sn)
  - Focussing

- Is it bad?
  - Not Necessarily (Cabrera)
    - Crystal heat capacity irrelevant

Naive

\[ \Delta E \]

- Localization
  - Timing
  - Focussing

- Superconductors detectors
  - Threshold \( \sim 3.5\,\text{kT} \)
  - Films
  - Tunnel junctions

- Rotons
  - R. Lanou, H. Nevis, C. Seidel
    (Brown University)
The sensors

II Thermistors

- Highly doped semiconductors
- NTD
- Parasitic effects
- Difficult physics
- Sensitive to "ballistic" phonons?
- Fast rise time
  ≠ lattice heating
  No real proof yet

Superconducting film (Cabreira)

= 4μm x 400Å
Local breaking of superconductivity
Simple (Photolithography)
Threshold?
Quite linear

Superconducting film + tunnel junction

Cooper pairs trapped above
Labrea
Neuhauser

Elegant

but

Junctions + low leakage
+ resist cool down
+ Trapping
Challenges

- Solid State Physics
  - Phonons: not "real" particles
  - Thermalisation
  - Propagation
    - Bulk
    - Surfaces
    - Interfaces
  - Physics of sensors
    - Thermistors = dirty
  - Coupling e- - phonons - materials
    $\Rightarrow$ complex physics
  - Trapping - Tunnel junction

- Fabrication problems
  - Reproducibility.
Conclusion

Emergence of a new field
- Dark matter complementarity of Accelerators
- Cosmic Rays
- Direct detection

Good example of particle astrophysics

Very fundamental
- Nature of 90% of mass in universe

Already some progress

Future
- "Conventional" ionization detectors
  - Static, lots of improvement
  - Understand background
- Cryogenic detectors
  - Difficult
    - Danger: Subcriticality!
  - Frontier problems of Solid state physics

Interdisciplinary effort (FUN!)