Profiling the Invisible

Quantum Mechanics and the Unseen Universe

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Public Lecture by:
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Stanford Linear Accelerator Center

February 22nd
7:30–9:30 pm
SLAC Conference/Panofsky Auditorium
2575 Sand Hill Road
Menlo Park, CA

Free Admission
For scientific knowledge
needed to attend!

Following the event,
may be refreshments
NEXT LECTURES

March 22  (at Stanford U):  David Gross (Nobel Laureate, UCSB)

April 26: Clyde Smith (SSRL)
Smarter Drugs: How Protein Crystallography Revolutionizes Drug Design

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In this lecture, I will discuss matter that is invisible in three different ways:

It is composed of incredibly tiny particles.

It cannot register a signal in very sensitive particle detectors.

It fills the universe, surrounding every star and galaxy.

What is it? How could we ever find out?
Outline:

Elementary particles
Quantum Mechanics
“Spin Transfer Patterns”
Dark Matter
Dark Matter at Accelerators
Tiny elementary particles live in a world remote from human experience.

To create exotic particles, we need very high energies.

To study them, we need specialized detectors.
To probe to distances $R$, we need

$$E = \frac{(200 \text{ MeV-fm})}{R}$$

To study the $W$ and radioactivity we need about **100 Billion Volts**.

Speeding up, SLAC gives

**17 Million Volts / m**

Slowing down, a block of lead gives

**1200 Million Volts / m**
To interpret the data, we need to understand the new and unfamiliar laws of physics at very small distances.

"Quantum Mechanics"
The predictions of quantum mechanics are **probabilities**.

We cannot predict when any individual nucleus will undergo radioactive decay.

But, the decay of many nuclei display a pattern, which can be revealed by experiment.
pause for Java Program #1
Richer and more interesting patterns come from studying Angular Momentum
Especially, the internal angular momentum ("spin") of elementary particles
Stern-Gerlach experiment 1922
Here is a modern version of the experiment.
Here is the result of the experiment:
The electron has spin $= \frac{1}{2} \hbar$

in one of two orientations

spin down

spin up
The spin of a particle is the key to its identity:

- electron (spin 1/2)
- quark (spin 1/2)
- gluon (spin 1)
- W boson (spin 1)
- graviton (spin 2)
What happens when we do two sequential Stern-Gerlach selections?
The probability of being in the top beam is a simple mathematical function of $\cos \theta$.

For spin $1/2$

$$P(\theta) = \frac{1 + \cos \theta}{2}$$

This is the “spin transfer pattern”. 
There is a characteristic pattern for each value of the spin.

\[
\text{spin } \frac{1}{2} : \quad P(\theta) = \frac{1 + \cos \theta}{2}
\]
\[
\text{spin } 1 : \quad P(\theta) = \frac{(1 + \cos \theta)^2}{4}
\]
Spin transfer patterns are part of the territory of “Bell’s inequality”, the proof that quantum mechanics is not governed by hidden variables with classical probabilities.
We will use spin transfer as a tool to understand elementary particles

the torsion wrench of Quantum Mechanics
The probability of this collision is proportional to

\[
\frac{(1 + \cos \theta)^2}{4} + \frac{(1 - \cos \theta)^2}{4} = \frac{1 + \cos^2 \theta}{2}
\]
$e^+ e^- \rightarrow Z^0 \rightarrow \tau^+ \tau^-$
pause for Java Program #2
$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q}$
$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q}$
$e^+ e^- \rightarrow Z^0 \rightarrow b \bar{b}$
So much for things we know.

Now use these tools to explore things we don’t know.
Kepler’s law of planetary motion:

\[ T^2 \sim R^3 \quad \text{or} \quad v \sim \frac{1}{\sqrt{R}} \]

Mercury: 46 km/sec
Earth: 30 km/sec
Jupiter: 13 km/sec
Neptune: 5 km/sec
This law must also work for galaxies, if the mass is concentrated at the center.
Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio $M/L_B$ greater than 100.
The Coma cluster of galaxies

O. Lopez-Cruz and I. K. Sheldon -- Kitt Peak
F. Zwicky  (Phys. Rev., 1937)

"The mass of an average nebula until recently was thought to be of the order of $M_N = 10^9 M_\odot$ … Some time ago, however, I showed that a straightforward application of the virial theorem to the great cluster of nebulae in Coma leads to an average nebular mass four hundred times greater… This result has recently been verified by an investigation of the Virgo cluster. Observations on the deflection of light around nebulae may provide the most direct determination of nebular mass and clear up the abovementioned discrepancy."
Gravitational Lens in a Galaxy Cluster  0024+1654

W. N. Colley, E. Turner, J. A. Tyson  -- Hubble Space Telescope
Galaxies and even clusters are small islands in a sea of unseen matter.

By mass, there is roughly 5 times more “dark matter” than ordinary matter!
Imagine that, in the early universe, there were additional particles, including one that is

neutral, heavy, and absolutely stable

created and annihilated in pairs.

Astrophysicists call this a Weakly Interacting Massive Particle.
the universe expands and cools ...
until today ...
The left-over density of N is

$$\text{density} \sim m_N^2$$

We obtain the observed density for

$$m_N \approx 200 \text{ Billion eV}$$

So it makes sense to look for the N particle at high-energy accelerators.
the International Linear Collider (ILC)
Hypotheses for the $N$:

Supersymmetry/Superstrings

spin 1  photon

--> photino  spin 1/2

spin 1/2  electron

--> selectron  spin 0
5th Dimension

spin 1 photon

--> KK photon  spin 1

spin 1/2 electron

--> KK electron  spin 1/2
Two spin transfer patterns come into play:

production angle $\theta$

decay angle $\chi$

infer these from:
pause for Java Programs #3, #4
This experiment measures spin directly. It gives important information irrespective of the model.

It gives us a powerful way to deduce the profile of the invisible dark matter that fills the universe.
Thanks to (among others):

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Ray Cowan, Lance Dixon, Gabriella Sciolla
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