What is the Universe Made of?

Professor David Cinabro
Wayne State University
3 November 2001
A Fundamental Answer: Atoms
How do we know? Mendeleyev (1869)

<table>
<thead>
<tr>
<th>Periodic Table</th>
</tr>
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<tbody>
<tr>
<td>1a</td>
</tr>
<tr>
<td>1  H</td>
</tr>
<tr>
<td>2a</td>
</tr>
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</tr>
<tr>
<td>4  Be</td>
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<tr>
<td>5  B</td>
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<tr>
<td>6  C</td>
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<tr>
<td>7  N</td>
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<tr>
<td>8  O</td>
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<tr>
<td>9  F</td>
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<tr>
<td>10  Ne</td>
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<tr>
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<td>12  Mg</td>
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<tr>
<td>13  Al</td>
</tr>
<tr>
<td>14  Si</td>
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<tr>
<td>15  P</td>
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<tr>
<td>16  S</td>
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<tr>
<td>21  Sc</td>
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<tr>
<td>22  Ti</td>
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<tr>
<td>23  V</td>
</tr>
<tr>
<td>24  Cr</td>
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<tr>
<td>27  Co</td>
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<td>29  Cu</td>
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<td>35  Br</td>
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<tr>
<td>37  Rb</td>
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<tr>
<td>38  Sr</td>
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<td>39  Y</td>
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<td>44  Ru</td>
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<td>54  Xe</td>
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<tr>
<td>56  Ba</td>
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<td>57  La</td>
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<tr>
<td>58  Ce</td>
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<tr>
<td>59  Pr</td>
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<tr>
<td>60  Nd</td>
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<td>62  Sm</td>
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<td>63  Eu</td>
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<td>64  Gd</td>
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<td>65  Tb</td>
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<td>66  Dy</td>
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<tr>
<td>67  Ho</td>
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<tr>
<td>68  Er</td>
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<tr>
<td>69  Tm</td>
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<td>74  W</td>
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<tr>
<td>75  Re</td>
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<td>76  Os</td>
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<tr>
<td>77  Ir</td>
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<tr>
<td>78  Pt</td>
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<tr>
<td>79  Au</td>
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<tr>
<td>80  Hg</td>
</tr>
<tr>
<td>81  Tl</td>
</tr>
<tr>
<td>82  Pb</td>
</tr>
<tr>
<td>83  Bi</td>
</tr>
<tr>
<td>84  Po</td>
</tr>
<tr>
<td>85  At</td>
</tr>
<tr>
<td>86  Rn</td>
</tr>
</tbody>
</table>

Lanthanides

| 58  Ce          |
| 59  Pr          |
| 60  Nd          |
| 61  Pm          |
| 62  Sm          |
| 63  Eu          |
| 64  Gd          |
| 65  Tb          |
| 66  Dy          |
| 67  Ho          |
| 68  Er          |
| 69  Tm          |
| 70  Yb          |
| 71  Lu          |

Actinides

| 90  Th          |
| 91  Pa          |
| 92  U            |
| 93  Np          |
| 94  Pu          |
| 95  Am          |
| 96  Cm          |
| 97  Bk          |
| 98  Cf          |
| 99  Es          |
| 100  Fm         |
| 101  Md         |
| 102  No         |
| 103  Lr         |

Legend:

- Alkali Metal
- Metal
- Alkali Earth
- Non-Metal
- Rare Earth
- Trans. Met.
- Noble Gas
- Halogen
How do we know? Rutherford (1909)
How do we know? Rutherford (1909)

The Predicted Result:

Expected Path

Expected Marks on screen
How do we know? Rutherford (1909)

Extrapolation of Result:

Mark on Screen

Likely Alpha Particle Path
How do we know? Rutherford (1909)

A Positive Nucleus Reflects Alpha Particles

Gold Foil Atoms, magnified
## Standard Model: 1920

<table>
<thead>
<tr>
<th>Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear</strong></td>
</tr>
<tr>
<td><strong>Non-Nuclear</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravity</strong></td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
</tr>
<tr>
<td><strong>Strong</strong></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Mysteries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atomic Structure</strong></td>
</tr>
<tr>
<td><strong>Radioactivity</strong></td>
</tr>
</tbody>
</table>
Experiments: 1920-1950

**Beam:** Cosmic Rays

**Target:** Atmosphere, Metal Plates

**Detector:** Cloud Chamber, Geiger Tube
Anderson (1933) Discovery of Antimatter

Predicted by Quantum Theory (Heisenberg, Pauli, Schrodinger in 1920’s) which explained structure of atoms.
Radioactivity = Weak Force

Decay does not conserve energy. A new particle proposed (Pauli and Fermi in 1930’s), non-nuclear and no charge. Neutrino (little neutral guy in Italian).
Who ordered this? (Pais 1937)

Found a new particle in cosmic rays. Charged and heavy like proton and neutron, but does not feel the strong force. A heavy cousin of the electron called the muon.

This is a big puzzle. The entire visible universe can be explained by protons, neutrons, and electrons. Add in the as yet unobserved neutrino to explain the Weak force and it is a simple picture. Why is there a muon?
# Standard Model: 1950

## Matter

<table>
<thead>
<tr>
<th></th>
<th>Nuclear</th>
<th>Non-Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>proton, neutron</td>
<td>electron, muon</td>
</tr>
</tbody>
</table>

## Forces

<table>
<thead>
<tr>
<th>Force</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>Particles with mass</td>
</tr>
<tr>
<td>Weak</td>
<td>Connects Nuclear and Non-Nuclear</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Particles with charge</td>
</tr>
<tr>
<td>Strong</td>
<td>Particles in nucleus</td>
</tr>
</tbody>
</table>

## Mysteries

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Force</td>
<td>How does it work? Is there a neutrino?</td>
</tr>
<tr>
<td>Muon</td>
<td>What does this do? Why is it here?</td>
</tr>
</tbody>
</table>
Experiments: 1950-1970

**Beam:** Cosmic Rays, First Accelerators

**Target:** Atmosphere, Metal Plates, Liquid H

**Detector:** Much more complex

Control and high rate of accelerators leads to direct observation of the neutrino. Electron-type (Cowan and Reines: 1959) and muon-type (Lederman, Steinberger, and Schwartz: 1962) confirming the theory of the Weak Force formulated by Fermi (1937).
Charged Particle Tracking

When a charged particle passes through matter it interacts with the atoms of the material. It has a chance to “free” some of the electrons normally bound to the atom leaving a free electron and an ion. This is called ionization.
Now add some wires to set up an electric field to get the light electrons to “drift” towards the $+V$ wires.

The electrons are light, thus they start moving fast, so as they move through the drift medium they cause more ionization. Eventually a large pulse of charge crashes into the $+V$ wires.
Now add a magnetic field. The charged particle will bend in the field with a radius of curvature proportional to its momentum.

Thus by measuring the position of the wires with charge, “hits”, and the radius of curvature of the hit pattern we measure the position and momentum of the track.
The Particle Zoo

Clear patterns lead to proposal (Gell-Mann and Zweig 1963) that there is an underlying structure. Quarks are the building blocks of all the Nuclear particles.
Observation of Quarks (Friedman, Kendal, Taylor: 1969)

Experiment was much like the Rutherford experiment. Beam was high energy electrons. The target was liquid hydrogen. The detector measured the electron scattering as a function of angle. Found small, hard things inside the proton. Gell-Mann and Zweig’s quarks.
Modern Experiments: Beam
Matter

<table>
<thead>
<tr>
<th>Generation</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Particles</strong> (Mass (GeV))</td>
<td><strong>Particles</strong> (Mass (GeV))</td>
<td><strong>Particles</strong> (Mass (GeV))</td>
</tr>
<tr>
<td>Quarks</td>
<td>( \begin{pmatrix} up(0.001) \ down(0.003) \end{pmatrix} )</td>
<td>( \begin{pmatrix} charm(1.3) \ strange(0.015) \end{pmatrix} )</td>
<td>( \begin{pmatrix} top(175) \ bottom(5) \end{pmatrix} )</td>
</tr>
<tr>
<td>Leptons</td>
<td>( \begin{pmatrix} e^- (0.0005) \ \nu_e(&lt; 1 \times 10^{-8}) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \mu^- (0.1) \ \nu_\mu(&lt; 0.00017) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \tau^- (1.8) \ \nu_\tau(&lt; 0.018) \end{pmatrix} )</td>
</tr>
<tr>
<td>Antiquarks</td>
<td>( \begin{pmatrix} \bar{up}(0.001) \ \bar{down}(0.003) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \bar{charm}(1.3) \ \bar{strange}(0.015) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \bar{top}(175) \ \bar{bottom}(5) \end{pmatrix} )</td>
</tr>
<tr>
<td>Antileptons</td>
<td>( \begin{pmatrix} e^+ (0.0005) \ \bar{\nu}_e(&lt; 1 \times 10^{-8}) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \mu^+ (0.1) \ \bar{\nu}_\mu(&lt; 0.00017) \end{pmatrix} )</td>
<td>( \begin{pmatrix} \tau^+ (1.8) \ \bar{\nu}_\tau(&lt; 0.018) \end{pmatrix} )</td>
</tr>
</tbody>
</table>

All (the \( \nu_\tau \) just last year) have been directly observed and we know, from experiments at CERN in Europe, that there are only three generations.
Fundamental Forces

1. **Strong**: Binds quarks into particles that feel the strong force. The proton is two *up* and one *down*. The neutron is a *dud*. Echo of this force holds nucleus together. Force is carried by the massless gluon.

2. **Electromagnetic**: Acts on charges, carried by the photon, $\gamma(< 2 \times 10^{-16}\text{eV})$.

3. **Weak**: Responsible for radioactive decay of nuclei, carried by the $W^\pm$ (80.41 GeV) and $Z^0$ (91.187 GeV), study of this force led to discovery of the neutrinos and observation of a small asymmetry between matter and anti-matter.

4. **Gravity**: Mass attraction, carried by the massless graviton. Force is very weak. We do not yet have a proper quantum theory of gravity.
Mysteries

Where is all the Antimatter? Universe started in an explosion (Big Bang) and thus should have produced matter and anti-matter equally.

Why Three Generations? Need at least three to generate an asymmetry between matter and anti-matter. Why no more? Is that asymmetry what causes matter to dominate?

Why Four Forces? Electromagnetic and Weak are actually two aspects of one force, Electroweak. Are all the forces really aspects of one fundamental force?

Dark Matter? Galaxies need more matter than what is glowing to hold themselves together. What is it? A new sort of particle or ordinary stuff not in stars?
Dark Energy? Eventually the Universe should have a Big Crunch because gravity will pull it all back together again. Evidence that something is pushing the Universe apart. What is it?

Underlying Structure? Are quarks and leptons fundamental? Is there something smaller that builds them?

Gravity? Why is it so weak compared to the others? Why can’t we write a quantum theory for gravity?