Physics 102 - December 2, 2009

- Exams
- Projects

[Graph: Physics 102 - Fall 2009 - Exam 2 grade distribution]
The Dark Matter pseudomultiverse ...
String Theory

Before quarks established Before QCD

Spin 0 mesons

Spin 1 mesons

Baryons
### Table

<table>
<thead>
<tr>
<th>Particle</th>
<th>Rest mass : MeV</th>
<th>Average lifetime : s</th>
<th>Most frequent type of decay : %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>γ</td>
<td>0 (&lt; 2 \times 10^{-22})</td>
<td>stable</td>
<td>stable</td>
</tr>
</tbody>
</table>

| Leptons  |                  |                      |                                 |
| μ        | 0 (< 3 \times 10^{-13}) | stable              | stable                          |
| νe       | 0 (< 0.16)       | stable              | stable                          |
| νμ       | 0 (< 18.2)       | stable              | stable                          |
| e        | 0.0105659650     | stable (> 4.2 \times 10^{24} s) | stable                          |

| Mesons   |                  |                      |                                 |
| a        | 134.9766         | 8.4 \times 10^{-17}  | γ γ, γ π 0, 0.01 π π 0            |
| s        | 139.57018        | 2.6033 \times 10^{-6} | γ γ, γ s s, 5.99 π π 0           |
| η        | 547.305          | 312.2                | γ γ, γ π π, 23.0 π π π            |

| K⁺       | 403.677          | 1.2366 \times 10^{-8} | (for K⁺) π⁺, π⁺ π⁺, 63.51 π⁺ π⁺ π⁺ |
| K⁻       | 497.672          | K_{s} 6.935 \times 10^{-11} | K_{L} 6.17 \times 10^{-8} |

| D⁺       | 1864.6           | 0.4126 \times 10^{-12} | π⁺ π⁺ π⁺ 21.16 π⁺ π⁺ π⁺ |
| D⁻       | 1965.6           | 0.496 \times 10^{-13}  | π⁺ π⁺ π⁺ 21.16 π⁺ π⁺ π⁺ |
| Λ⁺       | 1880.3           | 1.051 \times 10^{-12}  | π⁺ π⁺ π⁺ 21.16 π⁺ π⁺ π⁺ |
| Σ⁺       | 1527.0           | 1.653 \times 10^{-12}  | π⁺ π⁺ π⁺ 21.16 π⁺ π⁺ π⁺ |
| Λ⁻       | 1493.9           | 1.930 \times 10^{-12}  | π⁺ π⁺ π⁺ 21.16 π⁺ π⁺ π⁺ |

| Baryons  |                  |                      |                                 |
| p        | 938.27200        | stable (> 1.6 \times 10^{23} s) | p π⁺ π⁺ 100                     |
| n        | 938.27200        | 886.7                | p π⁺ π⁺ 100                     |
| Λ⁺       | 1115.683         | 2.632 \times 10^{-10} | p π⁺ π⁺ 100                     |
| Σ⁺       | 1188.37          | 8.018 \times 10^{-11} | p π⁺ π⁺ 100                     |
| Ω⁺       | 1192.642         | 7.4 \times 10^{-9}   | p π⁺ π⁺ 100                     |
| Σ⁻       | 1197.449         | 1.479 \times 10^{-9} | n π⁺ π⁺ 100                     |
| Λ⁻       | 1314.83          | 2.90 \times 10^{-10} | n π⁺ π⁺ 100                     |
| Ω⁻       | 1321.31          | 1.639 \times 10^{-10} | n π⁺ π⁺ 100                     |
| Ω⁺       | 1672.45          | 8.21 \times 10^{-11} | Λ⁺ π⁺ 100 Λ⁺ K⁺ 99.98 π⁺ π⁺        |

---

**Why Strings?**

Try to understand what is structure of Meons + barons

**Hadrons**

Point particles give troubles

\[ F \sim \frac{1}{r^2} \rightarrow \infty \quad as \quad r \rightarrow 0 \]
Leonard Susskind
Stanford Univ.

Discovered that excitations of relativistic strings have a correspondence to particle states

Also publ. recently cont'd work about future affecting LHC

Holger Bech Nielsen
Niels Bohr Inst.

Yoichiro Nambu
Univ. of Chicago

2008 Nobel Prize in Physics
Travelling wave on string

\[ y = A \sin(kx - \omega t) \]

Standing waves: non-relativistic string with fixed ends

Length \( L \)

\[ \text{0 nodes} \quad V = 2V \]

\[ L = \frac{1}{2} \lambda \quad T = \frac{1}{2} T \]

\[ L = \frac{1}{2} \frac{V}{T} \quad \Rightarrow \quad V = \frac{1}{2} \frac{V}{2L} \]

\[ \text{1 node} \quad V = \frac{2}{2L} \frac{V}{2L} \]

Illustration of how quantized states can come from strings (not for your test yet)

Music
For a string of length \( L = \frac{3\lambda}{2} \), the velocity \( V = \frac{3V}{2L} \) of the wave is given by:

\[
\nu = \frac{nV}{2L} \text{ for frequencies that will resonate on string of length } L
\]

where \( n = 1, 2, 3, \ldots \)

\( V \) is the velocity of wave propagation and depends on string tension and mass/length.
60's, early 70's
Susskind, Nielsen, Nambu independently discovered that the mathematical description of relativistic string vibrations/rotations is similar to that for particles with different masses/spins in quantum field theory

Birth of String theory
Quantum Mechanics + Gravitation $\rightarrow$ Quantum Gravity

Add "graviton" to quantum field theory

two interacting particles (Feynman diagrams)

must sum over all possibilities at all momenta

quantum loops of virtual particles

graviton at 0 momentum
by zero distance

Causes calculation to misbehave badly
Quantum Gravity + String Theory

massless Spin 2 graviton state
unavoidable + Natural in String theory

Short distance behavior problem goes away

Quantum Gravity is natural in String theory
String theory
Bosons only
misbehaves (ghost particles)
unless done in 26 dimensions mathematically

Not like the real world

String theory
Bosons + Fermions
misbehaves (ghost particles)
unless done in 10 dimensions mathematically
plus
Supersymmetry
like real world?
Maybe

Supersymmetry

ψ(x₁, x₂) → ± 1/2 ψ(x₂, x₁)

normal matter
Spin ½ electron
Spin 1 photon

→ Selectrons spin 0
→ Photons spin ½
Super symmetry predicts doubling of particle spectrum

→ Not observed

→ Supersymmetry broken (Nobody knows how/why yet)

\[ \text{Mass} \]

\[ \text{Supersymmetric matter} \]

\[ \text{Mass to big to be seen (yet)} \]

\[ \text{Normal Matter} \]
Extra Dimensions

General Relativity

Einstein 1915

Geometrical Theory
4 dimensions

Theodor Kaluza
(German 1885 - 1954)

1919 - 1921

Showed that if you solve
Einstein's GR equations in 5-d
get Electromagnetism +
Gravitation!
Where is this extra dimension?

1926 → Compactification

Oskar Klein (1894–1977)

Let R → small
Superstring Theory in mid-80's

5 consistent theories known
hoped one might prove to be the

Theory of Everything

I
II A
II B
Heterotic $E_8 \times E_8$
Heterotic $SO(32)$
Duality discovered - deep relationships among the 5 theories

\[ \text{Strong} \quad \rightarrow \quad \text{S-duality} \]

\[ \text{Weak} \quad \rightarrow \quad \text{T-duality} \]

- \( I \)
- \( II A \)
- \( II B \) (Small)
- Heterotic \( E_8 \times E_8 \)
- Heterotic \( SO(32) \)

1995 - All 5 superstring theories in 10-d come from single 11-d theory
M-Theory

Inst. for Advance Study (Princeton)

Edward Witten (1951 - )

Is this the TOE?
Other structures in String Theory

P-Branes

0-Branе  0-Brane  Point
1-Branе  1-Brane  String
2-Branе  2-Brane  Membrane
3-Branе  3-Brane
...
9-Branе  9-Brane

D-Branе  (Dai, Leigh, Polchinski; + indep by Horava)  1989

P-Branе where one end of an open string is attached.
Extra dimensional pseudomultiverse

Image from [http://abyss.uoregon.edu/~js/qc/qc.html](http://abyss.uoregon.edu/~js/qc/qc.html)
Ekpyrotic multiverse (cyclic Brane collisions)