PHYSICS:

A STORY OF SYMMETRY

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Introduction

Today's considerations:

- Symmetries in Classical Physics
- Symmetries in Modern Particle Theory
- Symmetries of the future

Noether's Theorem

The central connection between symmetries and Physics is known as Noether's theorem:

Continuous Symmetries $\Rightarrow$ Conservation Laws

When formulated mathematically, this theorem produces 'charges' which satisfy:

$$\frac{d}{dt}Q_N = 0$$

Classical Symmetries

There are a number of symmetries we assume in Physics, such as:

- Invariance on location
- Invariance on time
- Invariance on angle

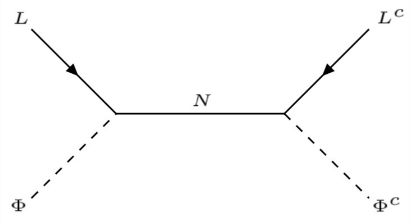
These symmetries generate the conservation laws:

- Conservation of Momentum
- Conservation of Energy
- Conservation of Angular Momentum

Modern Particle Theory

In modern particle theory, we represent each particle by a ‘field’, then build a model from these fields, including interactions between particles.

This model may be then represented through Feynman diagrams:



Modern Particle Theory

However we know there exist forces, so where do they come in?

The particles we introduced can often exhibit symmetries, known as 'gauge symmetries'.

The inclusion of these gauge symmetries requires us to also include gauge fields, which mediate forces.

$$SU(3)_c \Rrightarrow \text{Gluons} \Rrightarrow \text{Strong Force}$$

$$SU(2)_L \times U(1)_Y \Rrightarrow \text{Vector bosons} \Rrightarrow \text{Electro-weak Force}$$

Breaking Symmetries

Sometimes, the symmetries we find may be 'broken', meaning they are not in the theory as we expect.

The most famous example of this is the 'Higgs Mechanism.' Mathematically this is represented by the change in symmetry:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

and neatly relates the electro-weak charges to the electric charge:

$$Q_e = T_3 + \frac{1}{2}Y$$

Breaking Symmetries

The existence of this symmetry breaking approach to particle physics was verified by:

- the discovery of the $W^{\pm}$ bosons in January 1983,
- the discovery of the Z boson in June 1983,
- the discovery of the Higgs boson in 2012.

The Future of Symmetry?

There are a number of problems we have in physics at the moment:

- Dark Matter
- Neutrino Masses
- $g - 2$ muon magnetic moment

It is assumed that by extending out our symmetries, we can resolve some of these problems.

Extending Symmetries

There are two major approaches being taken:

1. Refining the internal symmetries of the Standard Model.
    - Collect all our current symmetries into a single symmetry, known as a '*Grand Unified Theory*' (GUT);
    - Include additional symmetries.
2. Extending symmetries of Space-time
    - SUperSYmmetry (SUSY)

SUSY

The most famous approach is likely Supersymmetry, which is a theory which extends space-time to a 'super-space', and in the process generates a symmetry between bosons (integer spin) and fermions (half-integer spin).

The existence of this super-space would present many answers to current problems, including a viable dark matter candidate, the neutralino.

The neutralino we know must be stable, due to a symmetry of the system known as R-parity.

Concluding Remarks

- We began with simple symmetries which are manifest throughout physics;
- This was then developed to find that the fundamental forces are themselves manifestations of symmetry;
- Finally, we rely upon the effectiveness of symmetries to try and develop our understanding.