REYES
Remote Experience for Young Engineers and Scientists

Symmetries and how to use them in physics

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PhD Physics candidate

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Cosmovitral, Photo: Jesús Cabrera

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How can we explain/understand all of this?
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Are there any constraints about what can happen?
Tara Lipinski - Nagano 1998

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\[ \frac{d\vec{L}}{dt} = 0. \]

Angular momentum conservation

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Symmetry breaking!

So, how do we use these symmetries?

Noether’s theorem:
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- Symmetries $\leftrightarrow$ transformations $\leftrightarrow$ conservation laws.
- Describe transformation: $\theta$. 

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$\theta_1$
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$\theta_1$ $\theta_2$
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\[ \theta_1 + \theta_2 = \theta_1 + \theta_2 \]
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- Different stuff transforms differently:
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\[
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\]

- Different stuff transforms differently:

- Classification: particles.
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- Different stuff transforms differently:
  - $L=0$
  - $L=3$

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Classification: particles.
The particles of our universe

- Our universe, at least locally, is Poincaré symmetric.
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The particles of our universe:

Strong force:
Atomic Nuclei
Heavy ice (or water)

Discovered in 1931

H₂O

Water

1.0 g/ml

Heavy water

1.1 g/ml
Heavy ice (or water)
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D\(_2\)O
The neutron and the proton
Discovered in 1932

**Hydrogen**
- proton: $1.673 \times 10^{-27}$ kg, $938$ MeV/$c^2$
- neutron: $1.675 \times 10^{-27}$ kg, $940$ MeV/$c^2$

**Deuterium**
- proton: $1.673 \times 10^{-27}$ kg, $938$ MeV/$c^2$
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What if there is a symmetry relating them?

Werner Heisenberg
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Isospin symmetry

What if there is a symmetry relating them?

Werner Heisenberg
The pion: $\pi$

Discovered in 1947

Isospin triplet

$\pi^+$  $\pi^0$

$140 \text{ MeV}/c^2$  $135 \text{ MeV}/c^2$

Illustration by Sandbox Studio, Chicago with Pedro Rivas
Isospin and the zoo

Related by isospin symmetry
Isospin and the zoo

Related by isospin symmetry

1960’s:
Isospin and the zoo

Related by isospin symmetry

1960's:
The Eightfold way

- $s = 1$: $K^0$, $K^+$
- $s = 0$: $\pi^-$, $\pi^+$, $\pi^0$, $\eta$
- $s = -1$: $K^-$, $\bar{K}^0$
- $s = 0$: $n$, $p$
- $s = -1$: $\Sigma^-$, $\Sigma^0$, $\Lambda$
- $s = -2$: $\Xi^-$, $\Xi^0$

| Mass       | ~1230 MeV/c$^2$ | ~1380 MeV/c$^2$ | ~1530 MeV/c$^2$ |
The Eightfold way

Difference: 150 MeV/c^2

Mass

- $\Delta^-$: $\sim 1230$ MeV/c^2
- $\Delta^0$: $\sim 1380$ MeV/c^2
- $\Delta^+$: $\sim 1530$ MeV/c^2
The Eightfold way

\[ \text{Difference: } 150 \text{ MeV}/c^2 \]

\begin{align*}
\text{Mass} & \\
\text{\(s = 0\)} & \Delta^- \quad \Delta^0 \quad \Delta^+ \quad \Delta^{+\text{I}} \\
\text{\(s = -1\)} & \Sigma^{-} \quad \Sigma^{*0} \quad \Sigma^{*+} \\
\text{\(s = -2\)} & \Xi^{-} \quad \Xi^{*0} \quad \Omega^{-} \\
\end{align*}

\begin{align*}
\text{\(\sim 1230 \text{ MeV}/c^2\)} & \\
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\end{align*}
The Eightfold way

\[ s = 1 \]
\[ s = 0 \]
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\[ s = -1 \]
\[ s = -2 \]

\[ K^0 \quad K^+ \]
\[ \pi^- \quad \eta \quad \pi^+ \]
\[ K^- \quad K^0 \]
\[ n \quad p \]
\[ \Sigma^- \quad \Sigma^0 \quad \Sigma^+ \]
\[ \Xi^- \quad \Xi^0 \]

Difference: 150 MeV/c²

Mass

\[ \sim 1230 \text{ MeV/c}^2 \]
\[ \sim 1380 \text{ MeV/c}^2 \]
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Experimental value: 1672 MeV/c²
The Eightfold way

Difference: 150 MeV/c^2

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- ~1230 MeV/c^2
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- 1680 MeV/c^2

Experimental value: 1672 MeV/c^2
But beware: symmetry is not always good
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The rest is history

- Dropping parity eventually led to the proposal of the other quarks.

- Z, W and Higgs particle are also the result of a broken symmetry.

- Symmetry as a tool is here to stay, when used properly!
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Further reading

**Discoveries**

[Image of the book](https://www.amazon.com/dp/0618711686/ref=cm_sw_em_r_mt_dp_U_mH7IFb173DZFG)

**Physics**

*(non-technical)*

[Image of the book](https://www.amazon.com/dp/0553103741/ref=cm_sw_em_r_mt_dp_U_TJ7IFbDHQK6JG)

**Mathematics**

*(technical)*

[Image of the book](https://www.amazon.com/dp/0738202339/ref=cm_sw_em_r_mt_dp_U_pl7IFbNBK7ET0)
Further reading

**Discoveries**

- [Leon Lederman with Dick Teresi](https://www.amazon.com/dp/0618711686/ref=cm_sw_em_r_mt_dp_U_mH71Fb173DZFG)

**Physics (non-technical)**

- [Stephen Hawking](https://www.amazon.com/dp/0553103741/ref=cm_sw_em_r_mt_dp_U_TJ71FbDHQK6JG)

**Mathematics (technical)**

- [Howard Georgi](https://www.amazon.com/dp/0738202399/ref=cm_sw_em_r_mt_dp_U_plZ1Fb8ZK7ET0)

Questions?