Chiral symmetry

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Outline

Handedness

Chiral symmetries

Chiral symmetry breaking

Heating matter

Handedness

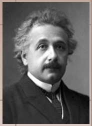
Chiral symmetries

Chiral symmetry breaking

Heating matter

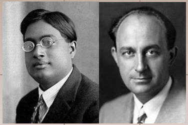
One fact about relativity

Nothing moves faster than light



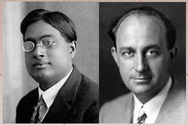
One fact about quantum mechanics

Point-like particles have angular momentum



One fact about quantum mechanics

Point-like particles have angular momentum integer or half-integer multiples of $\hbar$



Put them together

Chirality!

Handedness of matter

Neutrinos travel as fast as light

Handedness of matter

Neutrinos travel as fast as light
Just one chirality of neutrino
interacts with matter

Chirality of the universe

The universe is left-handed!

What about quarks?

Protons and neutrons are made of quarks

very light particles

Chiral symmetry is pretty good

but both chiralities found in nature

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Another fact about quantum mechanics

The state of a quantum system specified by probability amplitude $\psi(x)$ where

$$\int |\psi(x)|^2 = 1$$

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Another fact about quantum mechanics

The state of a quantum system specified by probability amplitude $\psi(x)$ where

$$\int |\psi(x)|^2 = 1$$

Overall phase of ψ has no physical meaning so ψ and $\mathrm{e}^{i\alpha}\psi$ describe same system

Flavours of particles

If distinct particles

1. feel exactly the same kinds of forces

Flavours of particles

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Flavours of particles

If distinct particles

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then they are called

different flavours of the same particle

Wavefunctions of flavours

A wavefunction of two flavours of particles is the collection of two wavefunctions:

$$\Psi = \begin{pmatrix} \psi \\ \phi \end{pmatrix}$$

with normalization

$$\int (|\psi|^2 + |\phi|^2) = \int \Psi^\dagger \Psi = 1$$

Phases of flavours

The phase of such a wavefunction is a matrix

$$U = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \qquad \text{and} \qquad \Psi \to U \begin{pmatrix} \psi \\ \phi \end{pmatrix} = U\Psi.$$

Phases of flavours

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$$U = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \qquad \text{and} \qquad \Psi \to U \begin{pmatrix} \psi \\ \phi \end{pmatrix} = U\Psi.$$

Normalization is ensured if $(U\Psi)^\dagger(U\Psi) = \Psi^\dagger\Psi$. This means $U^\dagger U = 1$.

Unitary (flavour) symmetries

Since Ψ and $U\Psi$ are the same physics is independent of U

Unitary (flavour) symmetries

Since Ψ and $U\Psi$ are the same physics is independent of U

Symmetry under multiplication by U!

Chiral symmetries

If the particles are massless then
there is a flavour symmetry for each chirality

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Spontaneous symmetry breaking

If Hamiltonian has a symmetry
but ground states do not
then we have spontaneous symmetry
breaking

Nambu-Goldstone Modes

Spontaneous breaking of unitary symmetry implies low energy excitation about equilibrium;
called Nambu-Goldstone mode

A simple example

Crystals break translational symmetry

A simple example

Crystals break translational symmetry
Phonons are Nambu-Goldstone bosons

Hadrons show broken chiral symmetry

mass(proton) $\simeq$ mass(neutron) $\simeq$ 938 MeV

mass(rho) $\simeq$ 770 MeV

mass(pi) $\simeq$ 140 MeV

The pion is a Nambu-Goldstone boson

A fact about quarks

Chiral symmetry is broken spontaneously

Handedness

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Broken symmetries can be mended

Crystals break translational symmetry

Broken symmetries can be mended

Crystals break translational symmetry

Mended by vaporising them

Mending chiral symmetry

Broken chiral symmetry can be mended

Mending chiral symmetry

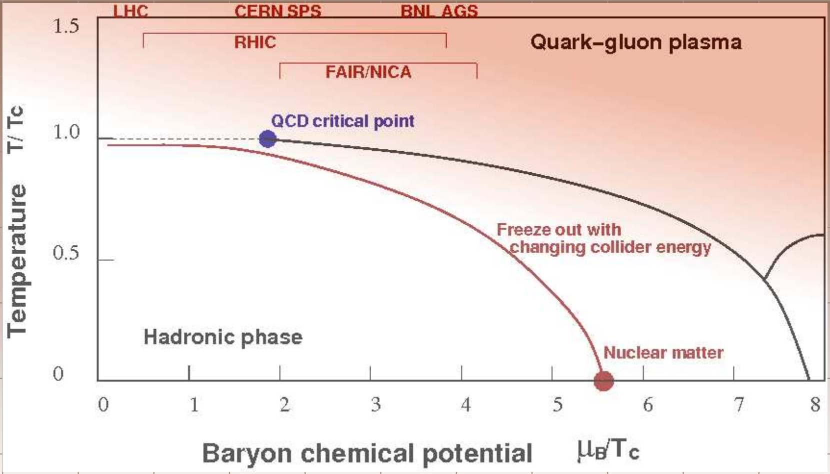
Broken chiral symmetry can be mended by heating to 2,000,000,000 Kelvin

Mending chiral symmetry

Broken chiral symmetry can be mended by heating to 2,000,000,000 Kelvin

New fact about nature established in 2011

Phase diagram of matter



Methods

Theory: lattice gauge theory, supercomputers

Experiments: relativistic heavy-ion colliders

Astrophysics: neutron stars, early universe

Methods

Theory: lattice gauge theory, supercomputers
Experiments: relativistic heavy-ion colliders
Astrophysics: neutron stars, early universe
Wikipedia: quark matter, lattice theory