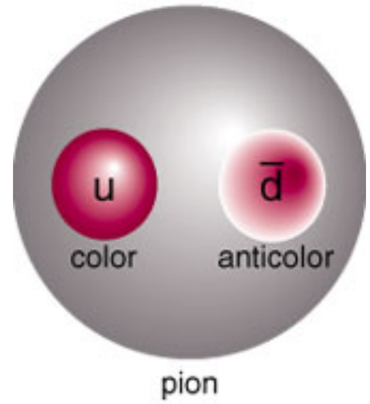
Mesons



quark wave function of the pion

Consider π^- (t=1 and t_0=1). The only possible combination is

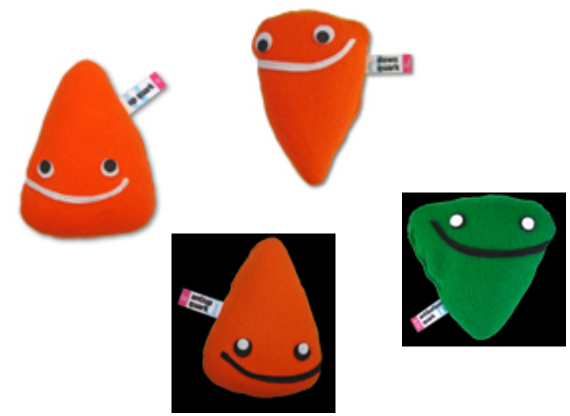
$$|\pi^-\rangle = |\bar{u}d\rangle$$

In general, it is possible to find several linearly independent components corresponding to the same t and t_0. The appropriate combination is given by isospin coupling rules. Furthermore, the wave function must be antisymmetric among the quarks. This problem is similar to that of a two-nucleon wave function!

T=1 triplet:

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\tau_-|\pi^-\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\pi^+\rangle = -|u\bar{d}\rangle$$



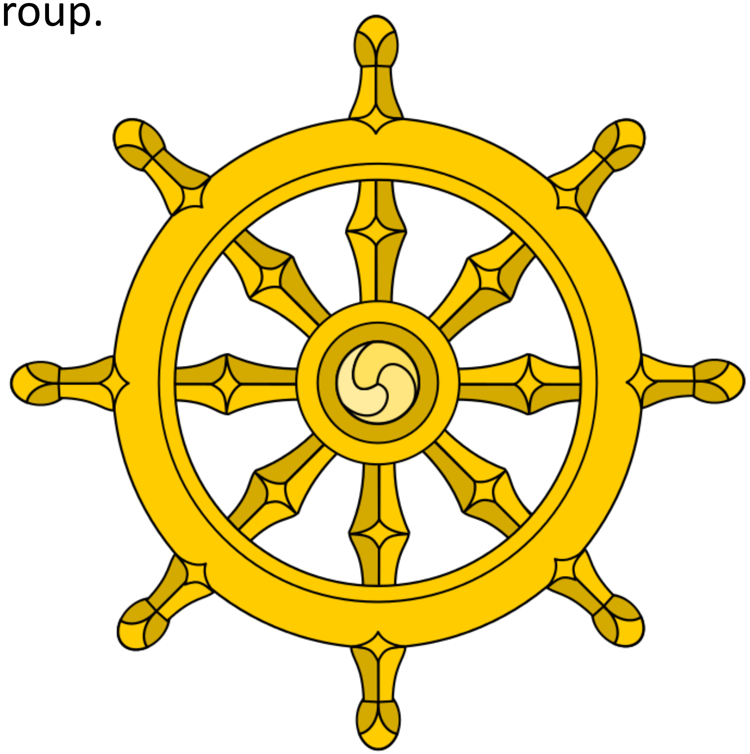
What about the symmetric combination?

T=0 singlet:

$$|\eta_0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$$

To produce heavier mesons we have to introduce excitations in the quark-antiquark system or invoke *s*- and other more massive quarks

The Eightfold Way is a term coined by Murray Gell-Mann for a theory organizing baryons and mesons into octets (alluding to the *Noble Eightfold Path* of Buddhism). The Eightfold Way is a consequence of flavor symmetry. Since the strong nuclear force affects quarks the same way regardless of their flavor, replacing one flavor of quark with another in a hadron should not alter its mass very much. Mathematically, this replacement may be described by elements of the SU(3) group. The octets and other arrangements are representations of this group.



The Dharma wheel
(represents the Noble Eightfold Path)

The lightest strange mesons are kaons or K-mesons. Since s-quark has zero isospin, kaons come in two doublets with t=1/2:



$$\left\{K^+(u\bar{s}), K^0(d\bar{s})\right\}, \quad \left\{K^-(\bar{u}s), \bar{K}^0(\bar{d}s)\right\}$$



$$Y = \mathcal{A} + \mathcal{S} + \mathcal{C} + \mathcal{B} + \mathcal{T}$$ hypercharge

$$Q = -t_0 + \frac{1}{2}Y$$

the SU(3) symmetry limit is met for massless u,d,s quarks

$$\pi^-(\bar{u}d) + p(uud) \rightarrow K^0(d\bar{s}) + \Lambda(uds)$$ strangeness is conserved!

Pseudoscalar mesons

$$\vec{J} = \vec{\ell} + \vec{S}, \quad \vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$$

$\vec{J}$ total angular momentum

$\vec{\ell}$ orbital angular momentum

$\vec{S}$ total spin

S can be either 0 or 1. The mesons with the relative zero orbital angular momentum are lower in energy. For the pion, S=0, hence J=0. Consequently, pions are "scalar" particles. But what about their parity? The parity of the pion is a product of intrinsic parities of the quark (+1), antiquark (-1) and the parity of the spatial wave function is +1. Hence, the pion has negative parity: it is a pseudoscalar meson.

With (u,d,s) quarks, one can construct 9 pseudoscalar mesons (recall our earlier discussion about the number of gluons!):

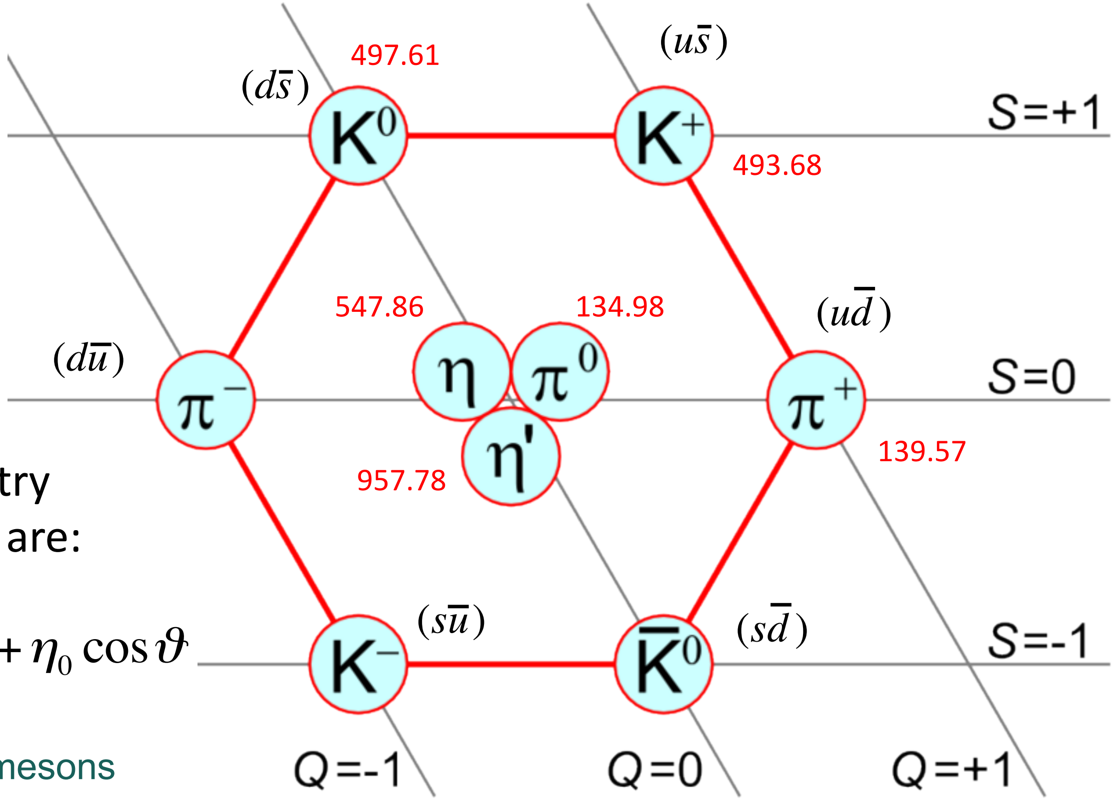
9 (nonet)=8 (octet)+1 (singlet)

Members of the octet transform into each other under rotations in flavor space (SU(3) group!). The remaining meson, η_0, forms a 1-dim irrep.

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\eta_8\rangle = \frac{1}{\sqrt{6}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle\right)$$

$$|\eta_0\rangle = \frac{1}{\sqrt{3}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle\right)$$



In reality, since the SU_3 (flavor) symmetry is not exact one, the observed mesons are:

$$\eta = \eta_8 \cos\vartheta + \eta_0 \sin\vartheta \qquad \eta' = -\eta_8 \sin\vartheta + \eta_0 \cos\vartheta$$

ϑ – Cabibbo angle, ~11° for pseudoscalar mesons

masses are in MeV/c^2

The eta was discovered in pion-nucleon collisions at the Bevatron (LBNL) in 1961 at a time when the proposal of the Eightfold Way was leading to predictions and discoveries of new particles.

CP violation in Kaon decays

$$|K^0\rangle = |d\bar{s}\rangle \qquad |\overline{K^0}\rangle = |s\bar{d}\rangle$$ (Q=0)

$$\mathcal{C}|K^0\rangle = |\overline{K^0}\rangle \qquad \mathcal{P}|K^0\rangle = -|K^0\rangle$$

$$\mathcal{C}|\overline{K^0}\rangle = |K^0\rangle \qquad \mathcal{P}|\overline{K^0}\rangle = -|\overline{K^0}\rangle$$

$$\mathcal{CP}|K^0\rangle = -|\overline{K^0}\rangle$$

$$\mathcal{CP}|\overline{K^0}\rangle = -|K^0\rangle$$

Hmmm… Those are not CP eigenstates

$$|K_L^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right) \qquad |K_S^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right)$$

Long | Short

$$\mathcal{CP}|K_L^0\rangle = -|K_L^0\rangle$$

$$\mathcal{CP}|K_S^0\rangle = +|K_S^0\rangle$$

The main decay modes of K_S are: $K_S \to \pi^+ + \pi^-$ (69%) or $\pi^0 + \pi^0$ (31%)

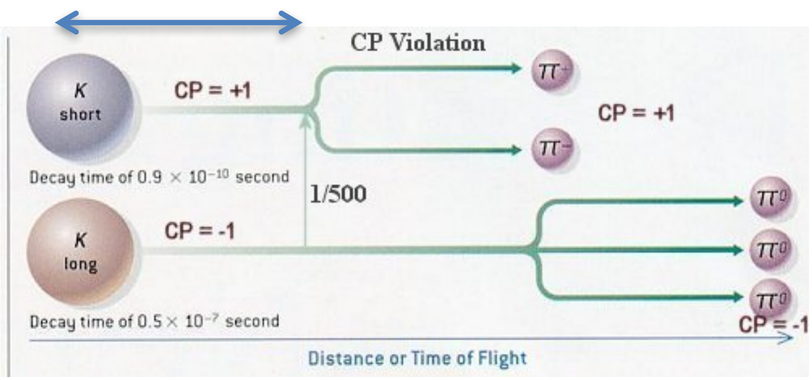
… and both decays conserve CP. What about K_L ?

$$K_L \rightarrow \pi^+ + \pi^- + \pi^0$$
$$\pi^0 + \pi^0 + \pi^0$$
$$\pi^{\pm} + e^{\mp} + \nu_e$$
$$\pi^{\pm} + \mu^{\mp} + \nu_\mu$$

Three-body decay, very slow!

These decays are called semileptonic decays, producing one meson and two leptons. They account for about 67% of K_L decays compared to 33% for the 3π mode.

1m



$T(K_S)=(8.954\pm0.004)\times10^{-11}$ s

$T(K_L)=(5.116\pm0.021)\times10^{-8}$ s

Cronin & Fitch experiment, 1964

17 m beamline; K_S should not be observable more than ~1m down the beam line

Given the disparity of the lifetimes of the two kaon species, you expect to see only the long-lived version at the end of the beam tube, but they found about 1 in 500 decays to be 2-pion decays, characteristic of the short-lived species.

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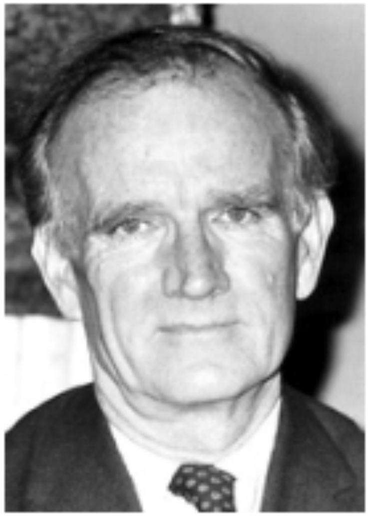
The Nobel Prize in Physics 1980

James Watson Cronin
Prize share: 1/2



Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"*

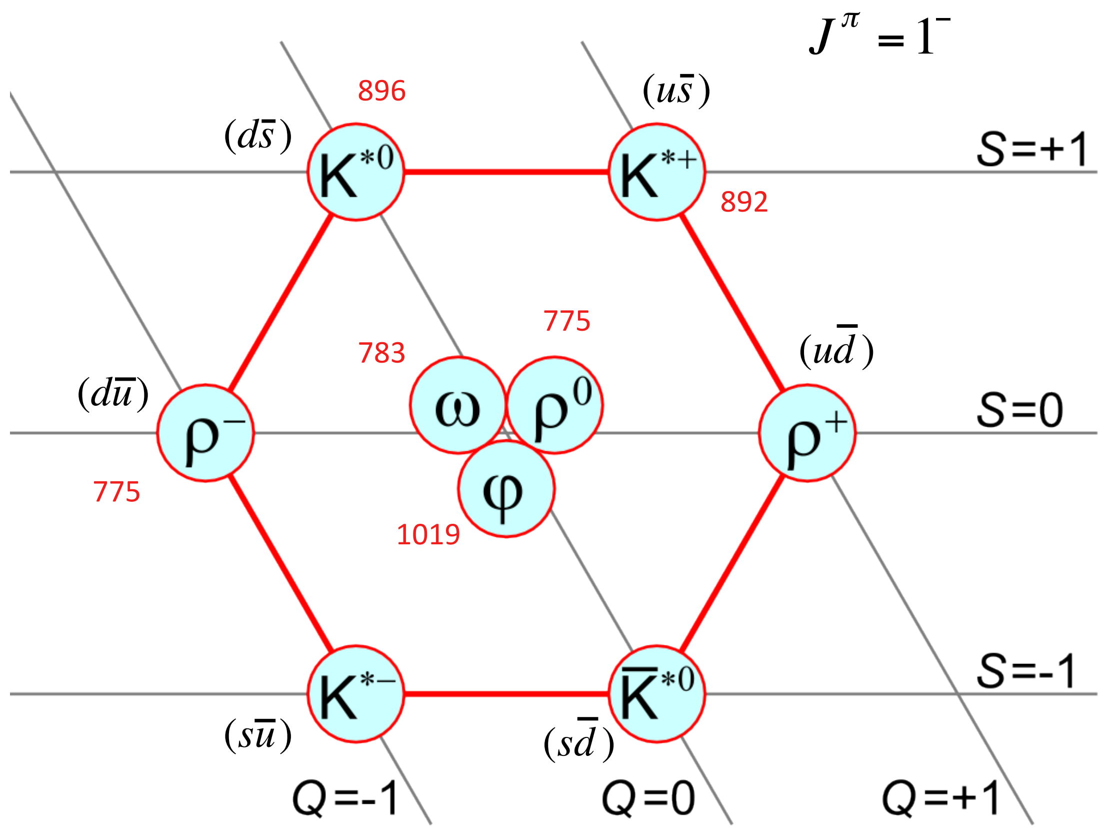
Vector mesons

Here *S*=1, hence *J*=1. They have negative parity. The vector mesons are more massive than their pseudoscalar counterparts, reflecting the differences in the interaction between a quark and an antiquark in the *S*=0 and *S*=1 states.

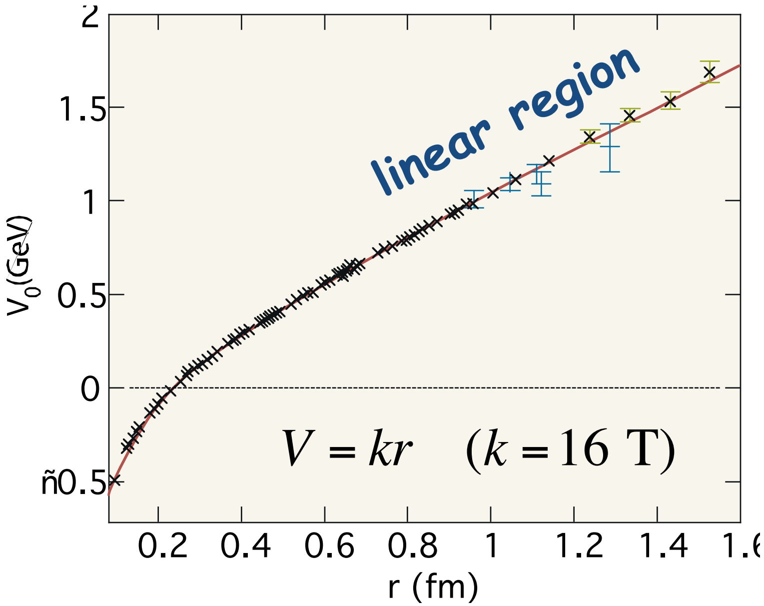
$$|\rho^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\omega\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$$

$$|\varphi\rangle = |s\bar{s}\rangle$$

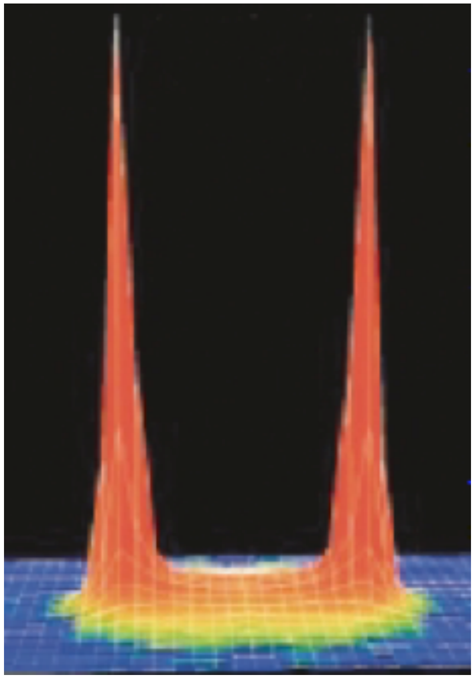


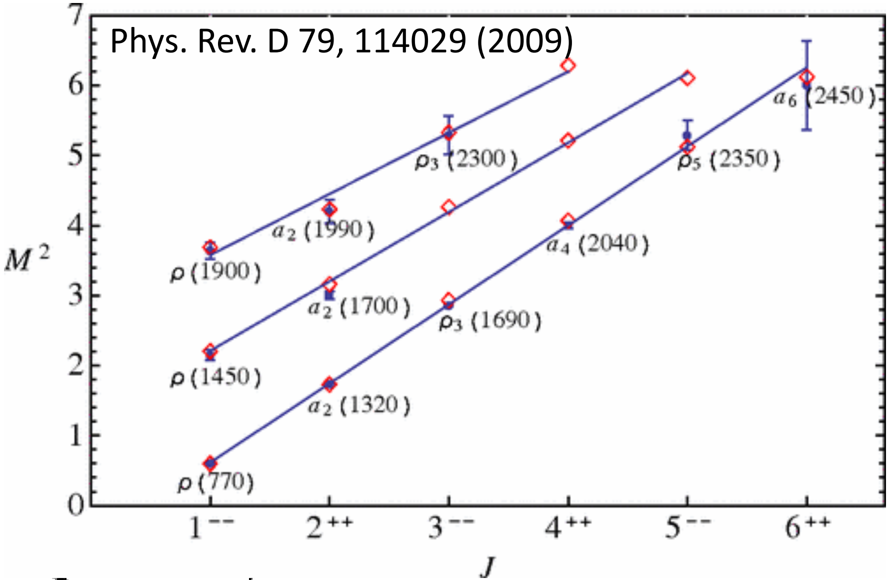
Flux tubes and confinement



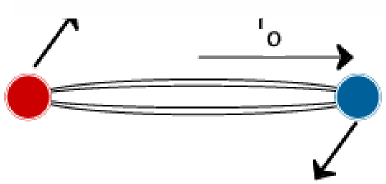
Lattice "measurement" of the quenched static potential

Phys. Rev. D 51, 5165 (1995)



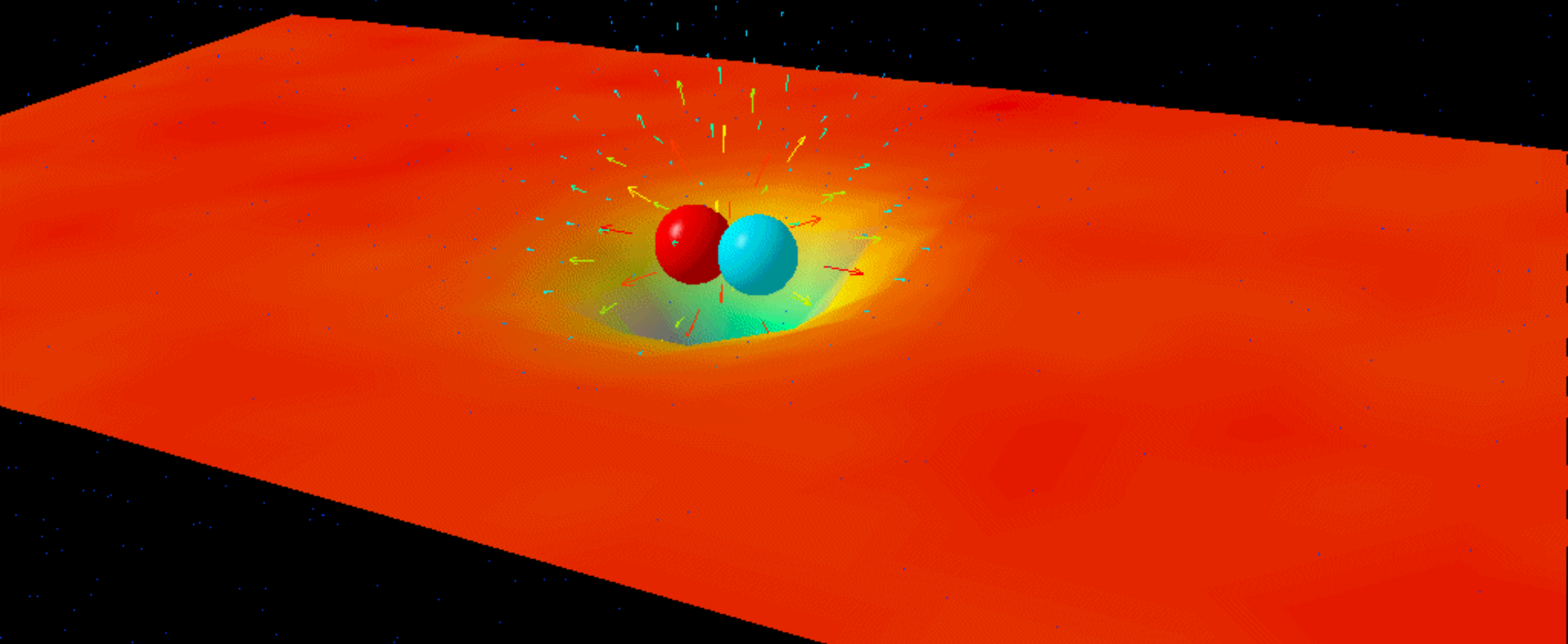


Phys. Rev. D 79, 114029 (2009)



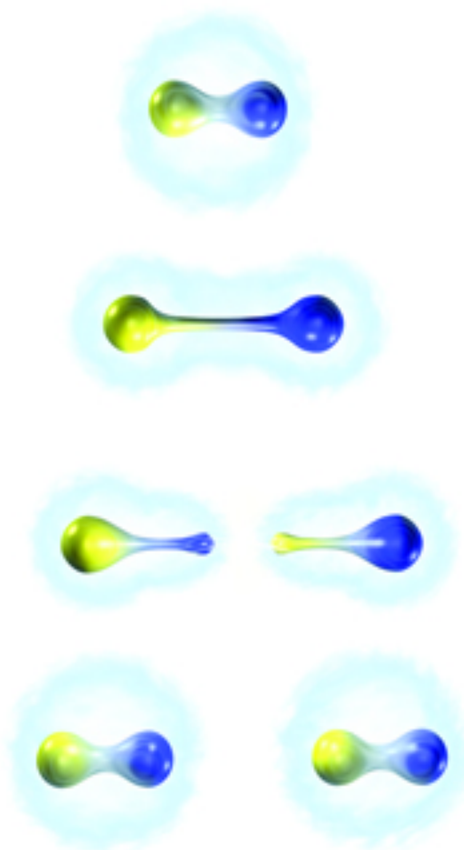
Regge trajectories (Nambu 1970)

The origin of the linear potential between quarks may be traced to the flux tube: a string of gluon energy density between the quark pair. The QCD vacuum acts like a *dual superconductor*, which squeezes the color electric field to a minimal geometrical configuration, a narrow tube. It costs energy for the flux to spread out in space. The tube roughly has a constant cross section and with constant energy density. Because of this, the energy stored in the flux increases linearly with the length of the flux.



This animation shows the suppression of the QCD vacuum from the region between a quark-antiquark pair illustrated by the coloured spheres. The separation of the quarks varies from 0.125 fm to 2.25 fm, the latter being about 1.3 times the diameter of a proton. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quark-antiquark pair. The vector field illustrates the gradient of this reduction. The tube joining the two quarks reveals the positions in space where the vacuum action is maximally expelled and corresponds to the famous "flux tube" of QCD. As the separation between the quarks changes the tube gets longer but the diameter remains approximately constant. As it costs energy to expel the vacuum field fluctuations, a linear confinement potential is felt between quarks.

http://www.fair-center.eu



Quarks do not exist in isolation. Attempts to separate quarks from one another require huge amounts of energy and results in the production of new quark-antiquark pairs.

The theory of the strong interaction predicts the existence of glueballs-particles that consist only of gluons (above), and so-called hybrids composed of two quarks and a gluon (below).