Flavour Physics

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Moscow International School of Physics 2022

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Lecture 2

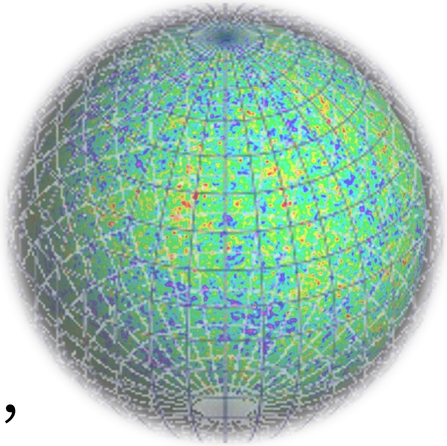
Symmetries

Where we discuss why not only symmetries but their breaking
is good for our Universe

Symmetries

A thing is symmetrical if there is something we can do to it so that after we have done it, it looks the same as it did before.

R. Weyl



i.e. if you work without visible results, it's not because you're a loser or a loafer, it's just a symmetry!

Example: pavements in Moscow are being repaired regularly, while their quality unchanged: this is not a corruption, this is symmetry.

“There are two troubles in Russia: fools and roads” – this is a result of imposed symmetries under roadworks and education.

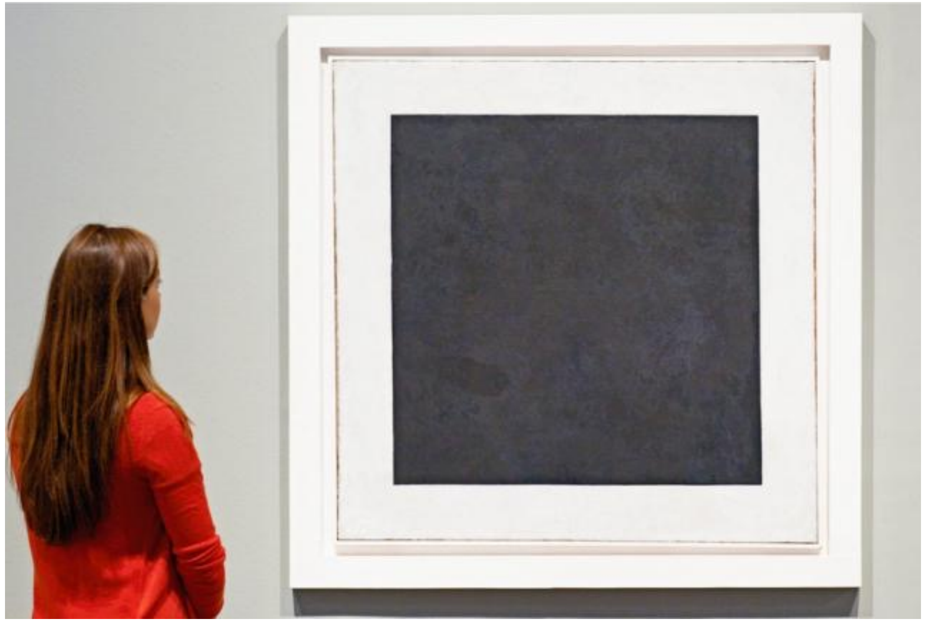
Symmetry seems to be a basic concept not only in physics!

Symmetries in Nature

Nature often exhibits certain kinds of symmetry in the objects that we find in the world around us. Symmetry is fascinating to the human mind, and everyone likes objects or patterns that are in some way symmetrical.

It is interesting which of this is primarily: does Nature try to please us or we try to reverently treat Nature…

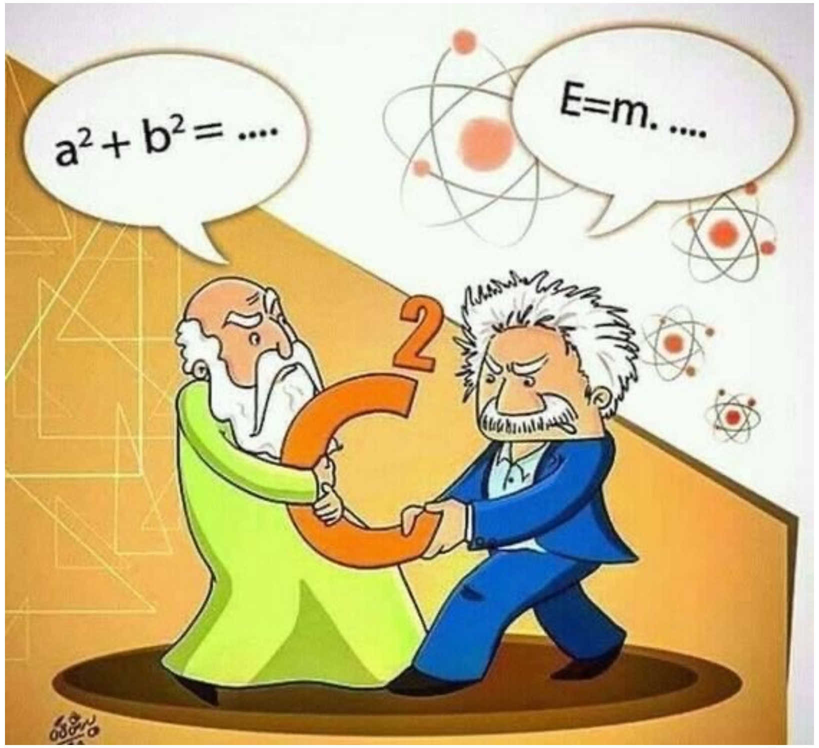
Interesting fact: Malevich's "Black Square" hung upside down in the Tretyakov Gallery for many years.



In science, we have to pretend that we are materialists and thus admit to being just observers who have to figure out the rules of "The Game". With our perception and logical observation, we guess that it is Nature loves symmetries, and we only echo this love.

Symmetries in Nature

Until the 20th century principles of symmetry played a little role in physics. From ancient Greeks the observed symmetries were considered as an intrinsic harmony of the laws of Nature (e.g. Pythagoras explained patterns in Nature like the harmonies of music as arising from number – the basic constituent of existence.) But nobody tried to deduce a law from the symmetry principle.



A great advance made by Einstein in 1905 was to put symmetry first, to regard the symmetry principle as the primary feature of Nature that constrains the allowable dynamical laws. E.g. the transformation properties of the electromagnetic field were not to be derived from Maxwell’s equations, but rather were a consequence of relativistic invariance and largely dictated the form of Maxwell's equations.

Symmetries and conservation laws

A more important implication of symmetry in physics is the existence of conservation laws. Every continuous symmetry of a physical system entails a conservation law, i.e. there exists an associated time independent **conserved** quantity. This connection was revealed in 1918 by Emmy Noether through her famous theorem.

For example, the laws of energy and momentum conservation follow from the fact that experiments yield the same results wherever and whenever they are done.

It turns out that symmetries, that we like, are slave chains not allowing too much freedom!

Symmetries are restrictions

On the one hand, these restrictions sometimes are not bad thing – a certain guarantee of stability:
a brick may fall on your head, but it will do so according to the restrictions imposed by conservation laws, and this unpleasant meeting can be mitigated.

On the other hand, imposing of the maximum number of symmetries completely deprives the possibility of any dynamics in the Universe. Life completely dies (all lives, having completed a sad circle, faded away) and there is nobody to admire the perfect symmetry.

Why Nature hasn't killed all live?

Obviously, it's important to Nature to show off in front of someone! Nature seems to need an observer!

A reasonable compromise is required: restrictions are needed to avoid chaos, but some freedom must also be left for dynamics. Nature has obviously found a solution. This lecture (just the fact of it) is a proof of that.

Isn't the solution to break symmetries a little bit? This allows freezing the overall picture while allowing small movements over a static background.

Nature loves not perfect, but slightly broken symmetries?

We'll see that Nature introduces first a conservation law, but then add small violation;

violation $\ll$ *conservation*

Does Nature love not perfect, but slightly broken symmetries?



we do the same: we prefer slightly broken symmetries

Another example is syncopation in music (Lacrimosa), when the symmetry of the rhythm is broken.

Are slightly broken symmetries still symmetries?

The difference between being a circle and being nearly a circle is not a small difference; it is a fundamental change so far as the mind is concerned. There is a sign of perfection and symmetry in a circle that is not there the moment the circle is slightly off that is the end of it is no longer symmetrical.

R. Feynman

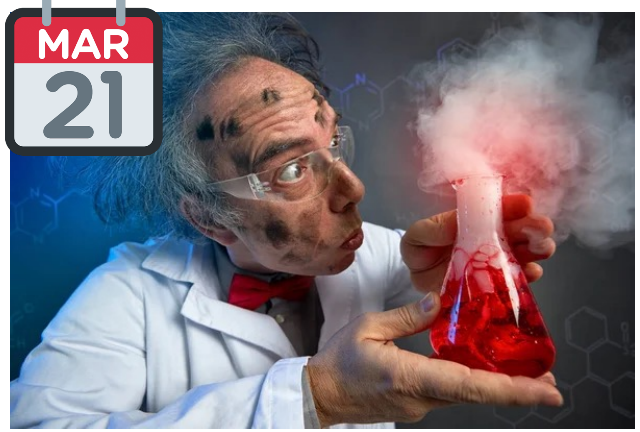
In one of his lectures, Feynman describes a gate in Japan (Nikkō Yomeimon) that at first glance is so perfectly created that it seems flawless. But if you go closer, you'll see that there is one tiny imperfection. It is rumored that the builders of that gate put the imperfection there to make sure the Gods don't get jealous and angry at the perfection of man. So, perhaps Nature is only nearly symmetrical so that we would not get jealous of its perfection!

Continues Symmetries

Those related to space-time geometry and internal.

- Time translational invariance → energy is conserved
- Invariance under a change in phase of the wave functions of charged particles → electric charge is conserved.

Gauge – a number of lead balls in a pound of ammunition. Gauge invariance: This number stays the same if the lead balls are colored differently. We are interested in quantity, not color.

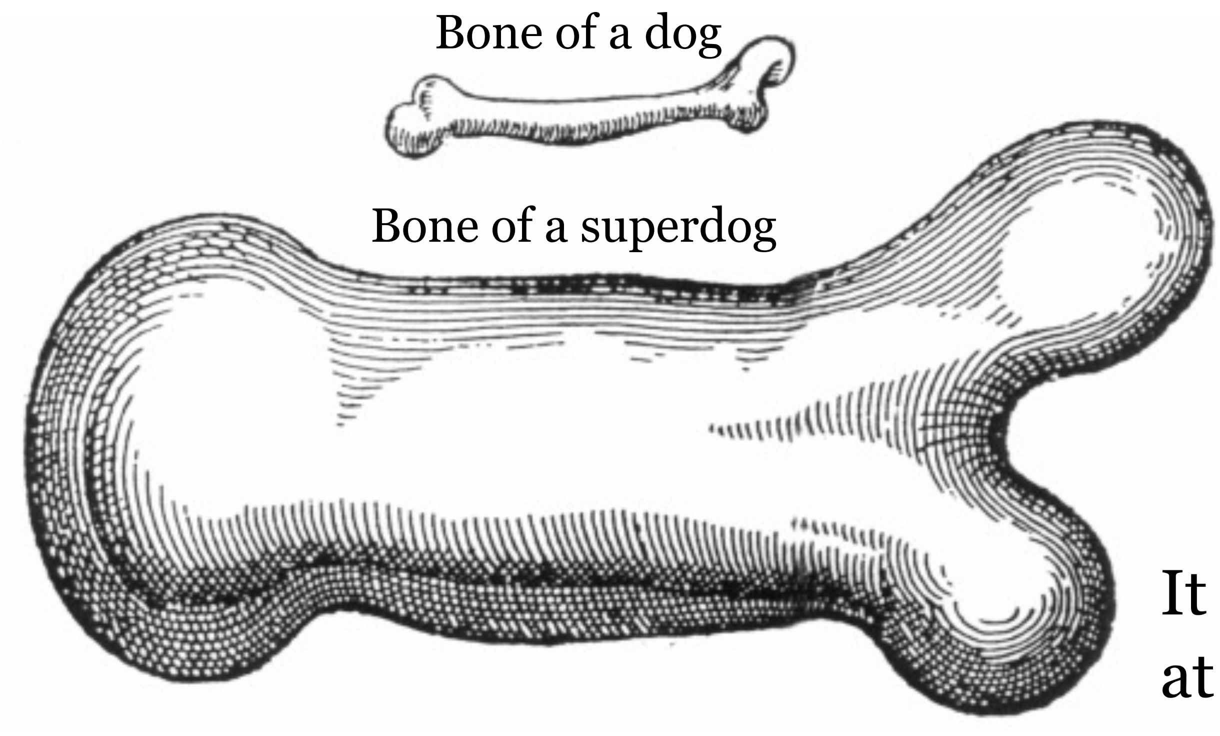


What symmetry does not exist in nature?

Scale symmetry!

The fact that the laws of physics are not unchanged under a change of scale was discovered by Galileo. He realized that the strengths of materials were not in exactly the right proportion to their sizes.


DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue scienze
Attenenti alla
MECANICA & I MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filosofo e Matematico primario del Serenissimo
Grand Duca di Toscana.
Con una Appendice del centro di granità d'alcuni Solidi.
IN LEIDA,
Appresso gli Elsevirii. M. D. C. XXXVIII.



Galileo was so impressed with this discovery that he considered it to be as important as the discovery of the laws of motion…

It is really important: the theory should contain at least one scale parameter. So SM does!

The first hadronic flavour: strange

Physicists guessed correctly with the name of the hadrons that arrived in 1947 from cosmic rays. Strange particles brought the most surprises, related to symmetries.

Isospin

+1/2 $K^+(\bar{s}u)$ $\overline{K^0}(s\bar{d})$

-1/2 $K^0(\bar{s}d)$ $K^-(s\bar{u})$

-1 +1 Strangeness

Why are these particles strange?

– produced (always in pair) as copiously as the π’s;

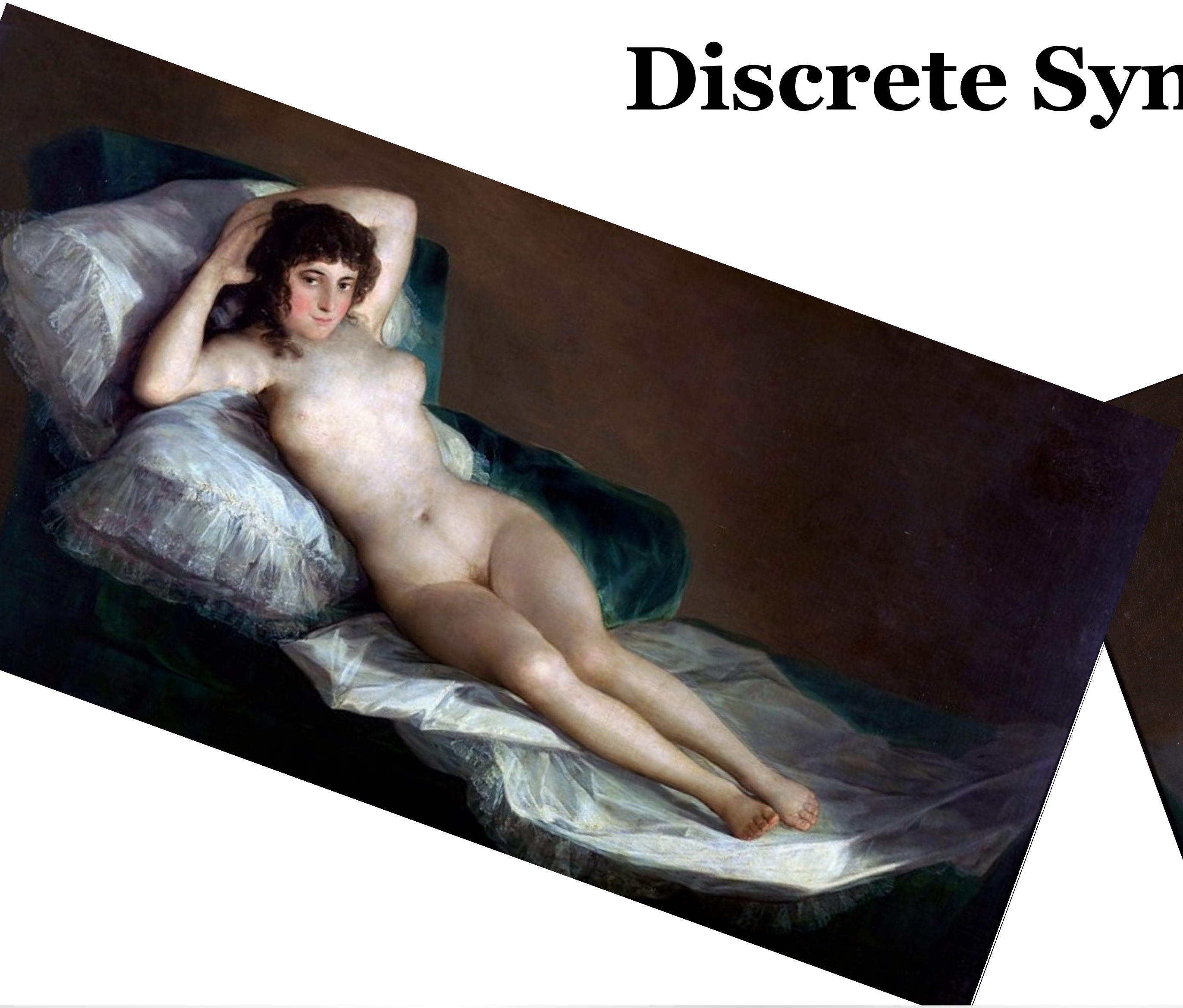
– lifetime is ~10^{-10} s;

Produced through strong interaction, decay through weak interaction

There should be a reason to inhibit the decay through strong interactions.
Introduce a new quantum number, call it "strangeness" and then wait for new strangeness.

C

Discrete Symmetries



Mirror symmetry Mirror symmetry

Space inversion $(x, y, z) \to (-x, -y, -z)$ inverts all space coordinates used in the description of a physical process. Equivalent to mirroring with respect to a plane, (for instance $x \to -x$) followed by a rotation around an axis perpendicular to the plane.

Parity conservation or P-symmetry implies that any physical process will proceed identically when viewed in mirror image.

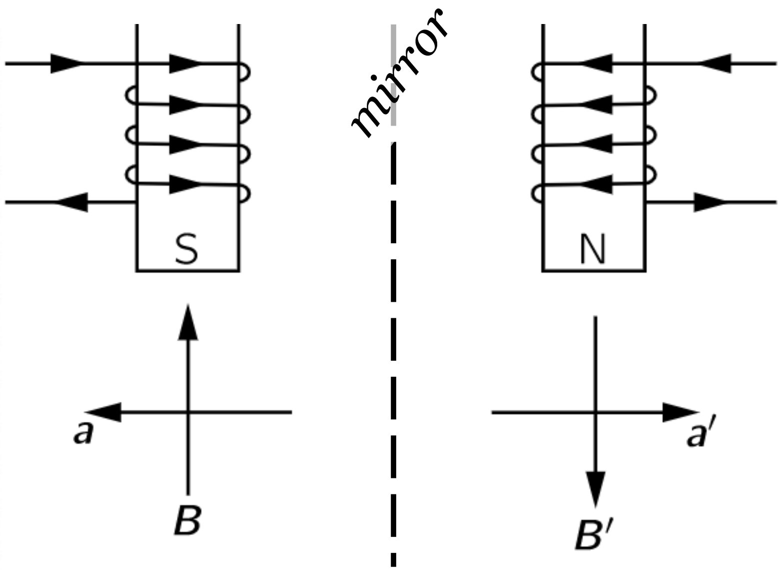
Does this sound too obvious?
E.g. are there any doubts, that these two dices give the same chances to gamblers?

Mirror asymmetry is difficult to assume in pure mechanics, what about electrodynamics, where both real vector and axial vectors field exists?

Mirror symmetry

Consider electromagnet and its mirror reflection

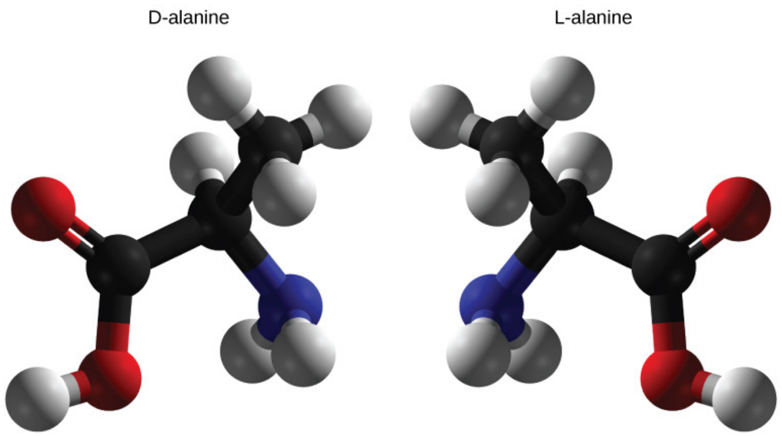
the coil will wind the other way, everything that happens inside the coil is exactly reversed, and the current goes in the opposite direction

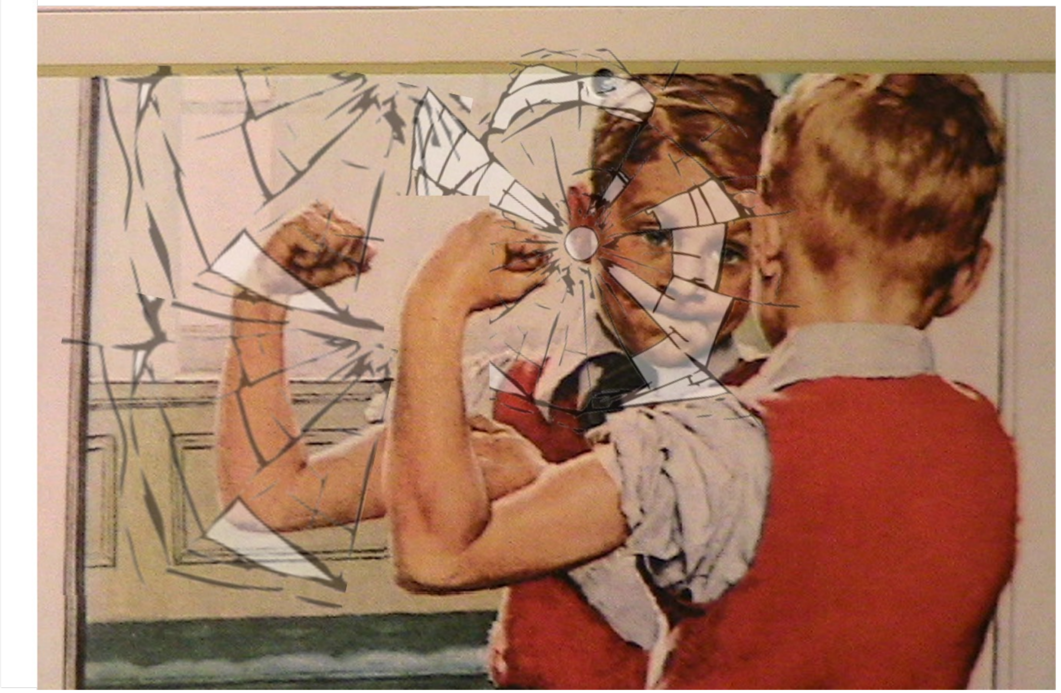


We can see that the poles of magnets changed from north to south. Is it OK, if north in mirror becomes south? Never mind changing north to south; these too are mere conventions. Care only about phenomena. An electron moving through one field, going into the screen will deviate in the indicated direction according to the physical law. The force is reversed, and that is very good because the corresponding motions are then mirror images! *Why everything ended successfully although there seemed to be problems along the way (magnetic field behaves as axial vector, but the magnetic force is still true vector!)?*

If it's too trivial, then would you explain **Why…**

L-alanine is one of the most abundant amino acids in proteins, while D(beta)-alanine is the main component of the bacterial wall;





Is the male potency in mirror is the female beauty? Do not even try to imagine this!

They both are sailed in internet-shops:

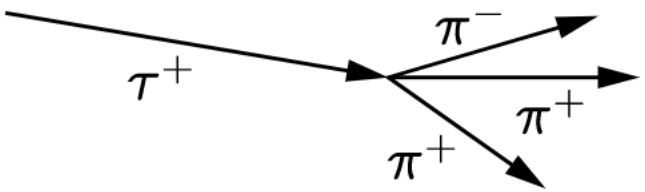
- L-alanine promotes male potency,
- D-alanine is a cosmetic product.

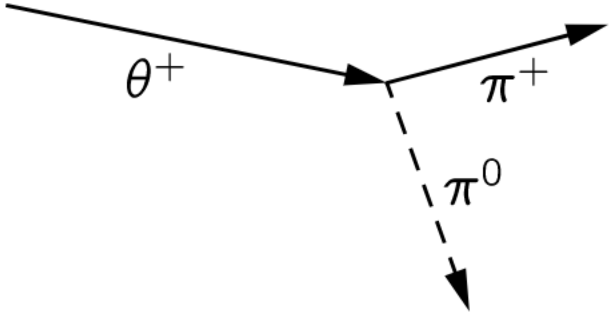
…are their prices different?

Living objects do not respect mirror symmetry

it's a biology problem but physics has nothing to do with it?
Yes! until physics faces the same problem itself!

What about physics objects?





In 1950th we had a particle called a τ^+, decaying into three π's, and a θ^+, which decays into two π's. The τ and the θ are equal in mass within the experimental error; their lifetimes were found to be almost exactly the same; moreover, whenever they were produced, they were made in the same proportions, ~14% τ's & ~86% θ's. Definitely, they are the same particle that have two decay modes. But, parity conservation says, it was *impossible* to have these both modes come from the same particle.

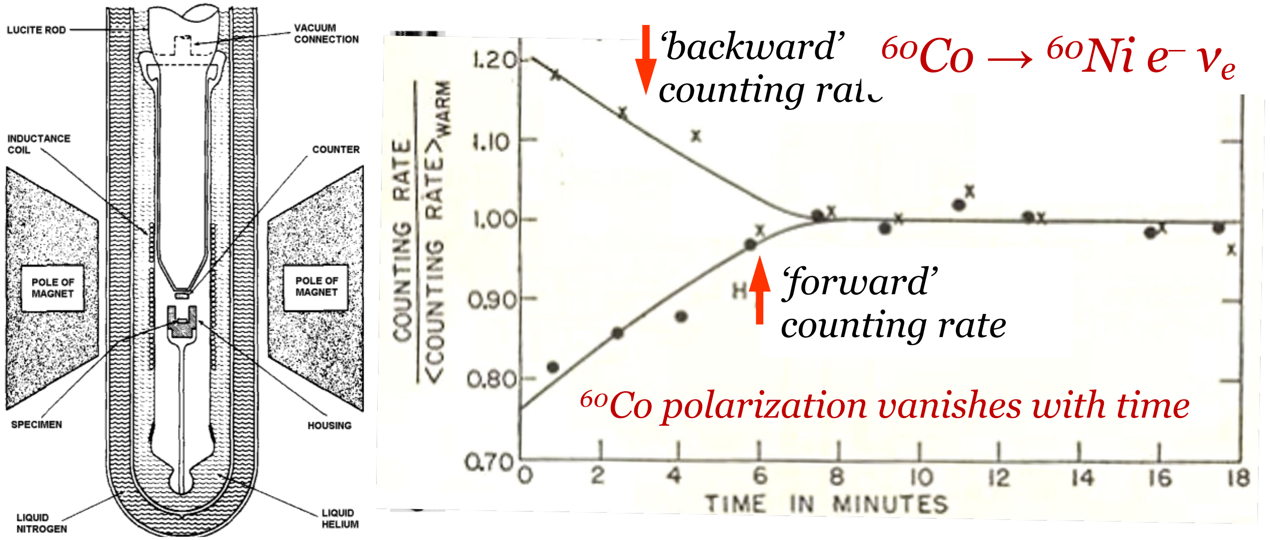
P-violation in weak decays

Miss Wu following the suggestions of Lee and Yang using a *very strong magnet* at a *very low temperature* found that the atoms of cobalt lined up in a field whose B vector points upward, emit electrons in a downward direction.

Doesn't sound very stupendously?

Let's say otherwise: If we were to put it in a corresponding experiment in a “mirror”, in which the cobalt atoms would be lined up in the opposite direction, they would spit their electrons *up*, not *down;* the action is *unsymmetrical*.

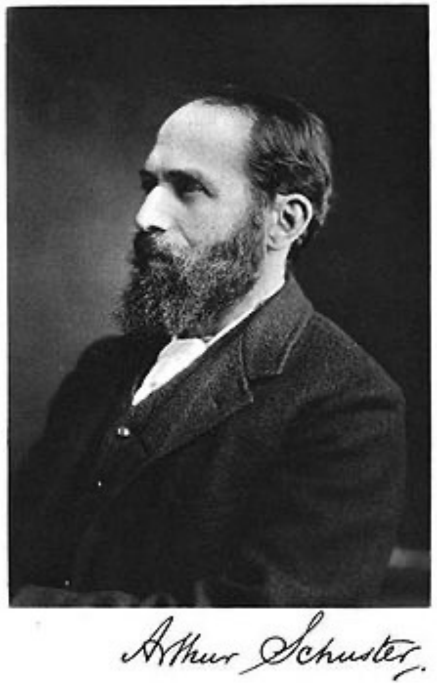
The Wu experiment (1956)



Electrons are preferentially emitted opposite to ^{60}Co spin

north and south are still mere conventions? No, Cobalt distinguishes them..

Antimatter



Was proposed 30 years before Dirac's derivation by A. Schuster (1898, immediately after electron discovery). In letters to "Nature" he conjectured: *"...if there is negative electricity, why not negative gold, as yellow as our own?..."*. He coined the concept of "antimatter", hypothesized antiatoms, and whole antimatter solar systems, which would yield energy if the atoms meet with atoms of normal matter (annihilation).

Although Schuster's conjectures were not taken seriously for 30 years, he made a correct conclusion based on symmetry considerations! He just couldn't find convincing arguments.

Antimatter

Was discovered theoretically by P. Dirac (1928) in merging quantum mechanics to special relativity.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Charge conjugation symmetry

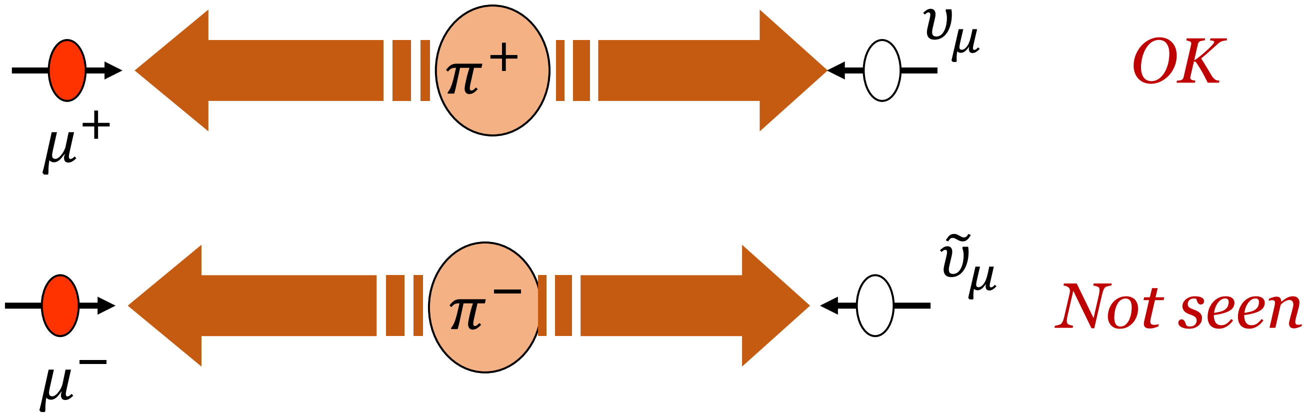
Charge conjugation (C) is the mathematical transformation that turns a particle into its antiparticle: $\psi \xrightarrow{C} i(\bar{\psi}\gamma_0\gamma_2)^T$

Symmetry under charge conjugation (C-symmetry) suggests that experiments made with particles and antiparticles would give the same result. It is true for a wide range of phenomena – nuclear forces, electrical phenomena, and even such weak ones like gravitation – over a tremendous range of physics, all the laws for these seem to be symmetrical.

C symmetry is broken by the weak interactions, just like P

Lederman (1956)

$\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$

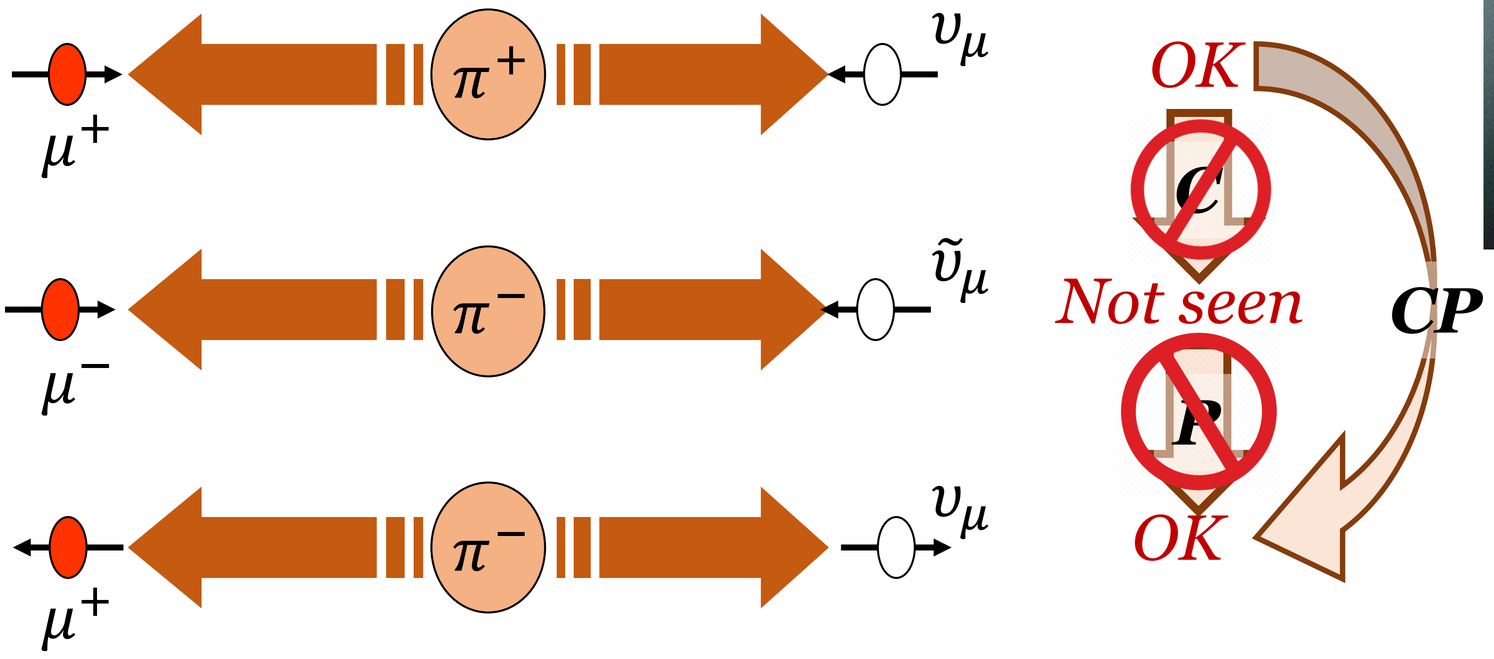


results of experiment and C-flipped experiment are not the same!

But before experimental evidence, C-violation was suggested theoretically: Ioffe-Okun-Rudik & Oehme-Lee-Yang (1956): the way of P-violation suggested by Lee-Yang leads to C-violation: Pseudoscalar product (L●P) is invariant under T, therefore by CPT-theorem while T is conserved, C-parity have to be violated together with P.

CP is a restored symmetry?

$\pi^{\pm} \to \mu^{\pm} \nu_{\mu}$



L.Landau (1956) introduced CP symmetry as a mean to restore broken C and P symmetries.

Landau insisted on strict CP conservation to have beautiful world with no matter-antimatter difference.

The idea of exact CP-symmetry supports the idea of two-component massless neutrinos.

More strangeness from strange

K^0 and $\bar{K}^0$ are not are CP eigenstates, but their mixture $K_S = {}^1/_{\sqrt{2}}(K^0 + \bar{K}^0)$ and $K_L = {}^1/_{\sqrt{2}}(K^0 - \bar{K}^0)$ are CP eigenstates with CP$= +1$ and -1, correspondingly.

θ_0 $S=+1$

$\bar{\theta}_0$ $S=-1$

$\theta_1 = \frac{1}{\sqrt{2}}(\theta_0 + \bar{\theta}_0)$

$\theta_2 = \frac{1}{\sqrt{2}}(\theta_0 - \bar{\theta}_0)$

States of definite lifetime

If $\theta_1 \to \pi^+\pi^-$

$\theta_2 \not\to \pi^+\pi^-$ only 3 body

Gell-Mann & Pais (1952) (but relying on C-symmetry) concluded that K_S and K_L are physical particles that have their own (different) masses and lifetimes. CP-odd state could decay 3-body only and, thus, has much greater lifetime than CP-even one.

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

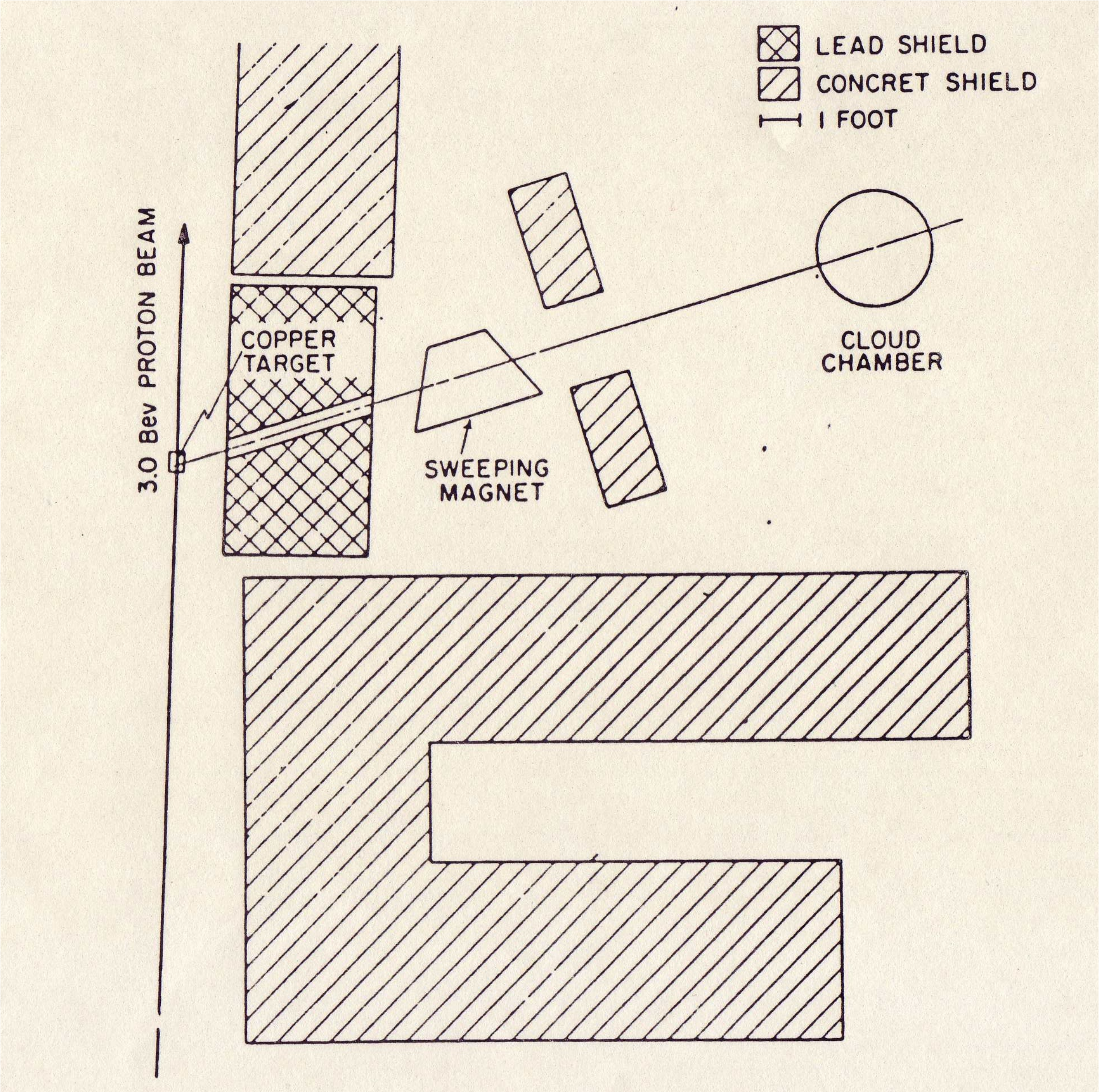
A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

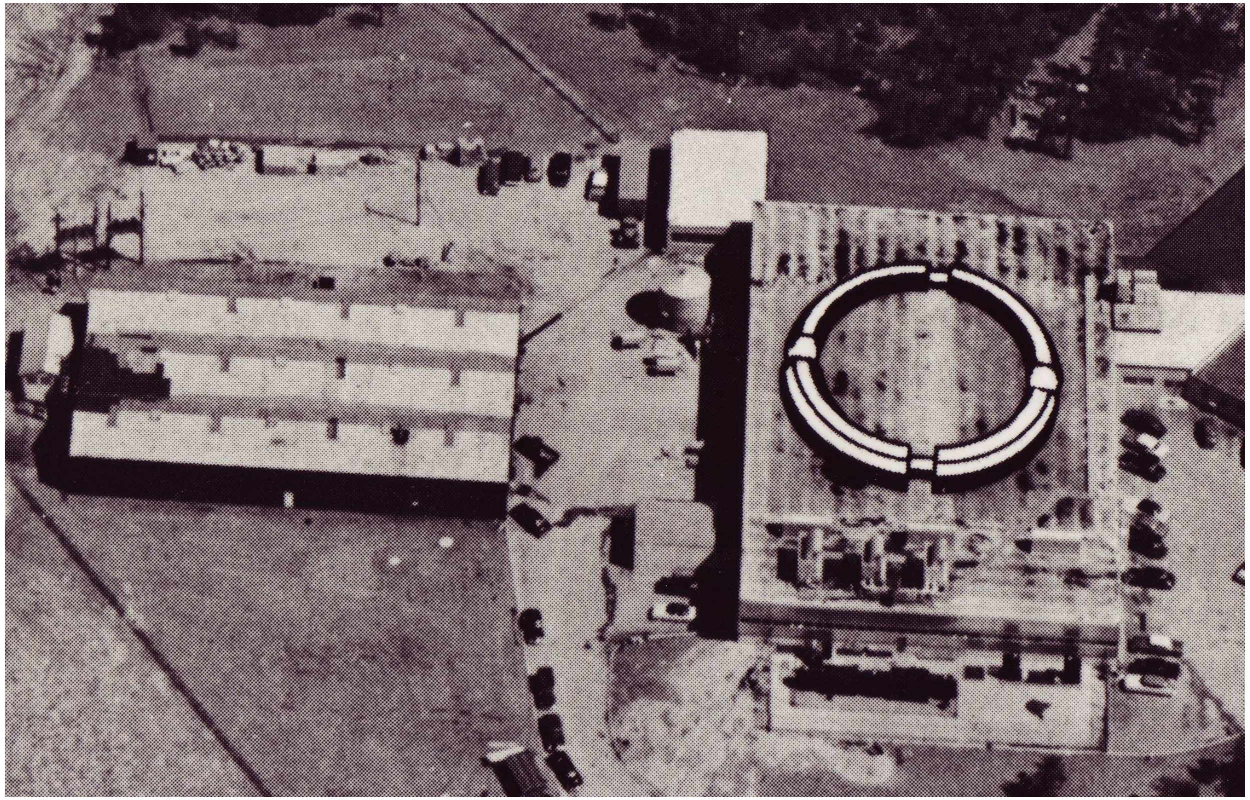
(Received November 1, 1954)

At any rate, the point to be emphasized is this: a neutral boson may exist which has the characteristic θ^0 mass but a lifetime $\neq \tau$ and which may find its natural place in the present picture as the second component of the θ^0 mixture.

One of us, (M. G.-M.), wishes to thank Professor E. Fermi for a stimulating discussion.

Observation of K_L





Observation of Long-Lived Neutral *V* Particles*

K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
Columbia University, New York, New York
AND
W. Chinowsky, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

CP violation

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

Perhaps, the saddest story in JINR history

One more looser…

PHYSICAL REVIEW VOLUME 132, NUMBER 5 1 DECEMBER 1963

Anomalous Regeneration of $K_1{}^0$ Mesons from $K_2{}^0$ Mesons*

L. B. Leipuner, W. Chinowsky,† and R. Crittenden
Brookhaven National Laboratory, Upton, New York

and

R. Adair,‡ B. Musgrave,§ and F. T. Shively†
Yale University, New Haven, Connecticut

(Received 13 March 1963; revised manuscript received 27 August 1963)

A beam of 1.0-BeV/c $K_2{}^0$ mesons passing through liquid hydrogen in a bubble chamber was seen to generate $K_1{}^0$ mesons with the momentum and direction of the original beam. The intensity of $K_1{}^0$ production was far greater than that anticipated from conventional mechanisms, and the suggestion is made that the $K_1{}^0$ mesons are produced by coherent regeneration resulting from a new weak long-range interaction between

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits,

… found too large (few %) CP-violation. But this was a big motivation for the final success.

Happy end

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

$$\frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} \approx \frac{1}{500}$$

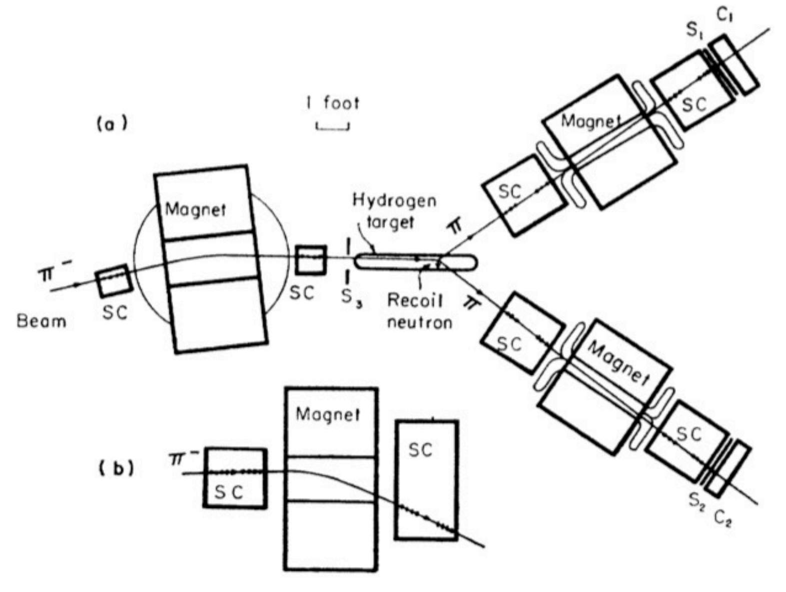
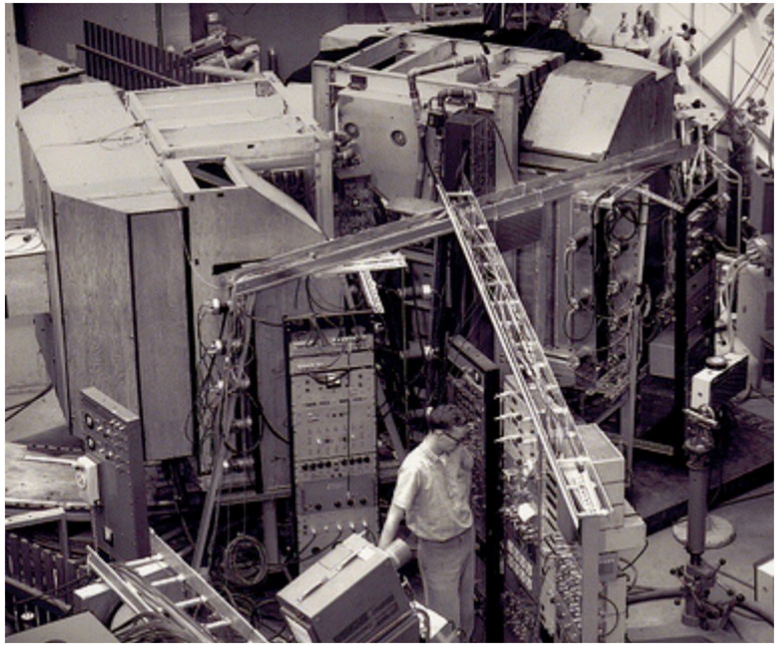
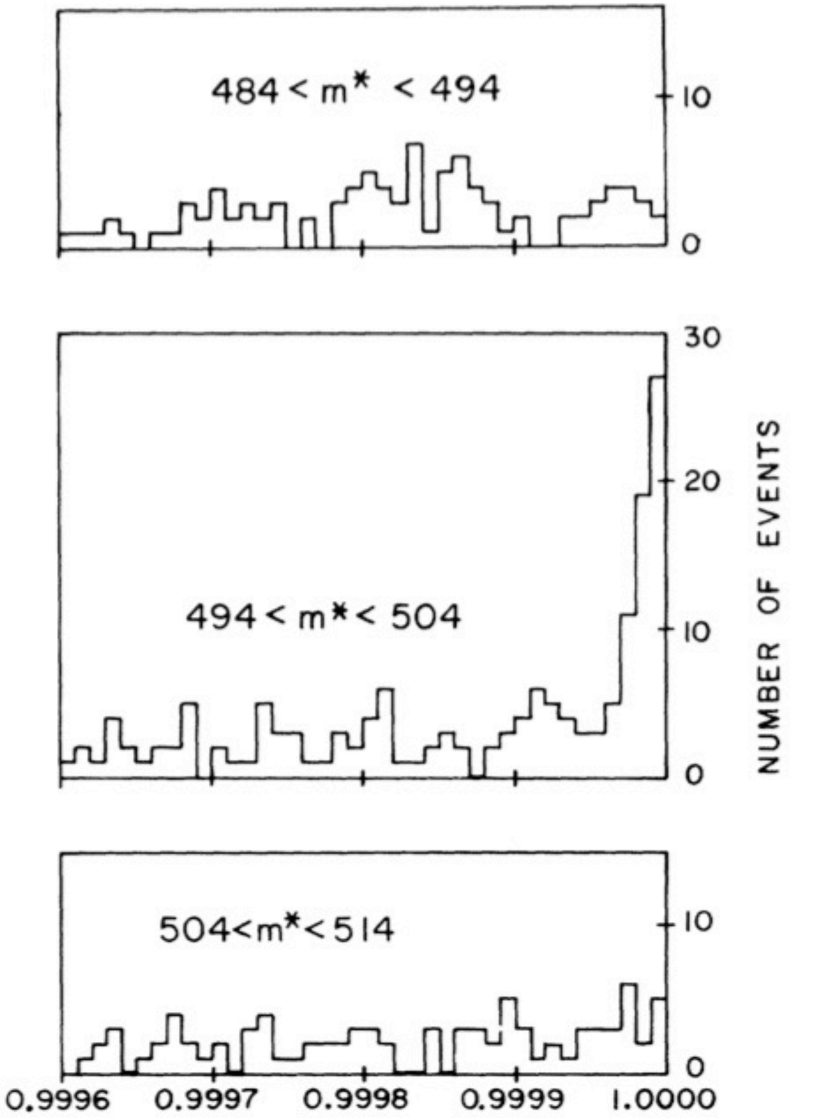


FIG. 1. Schematic views of the experimental apparatus.





CP violation and Universe evolution

Big Band seemingly started from matter-antimatter symmetric initial state. Why didn't matter and antimatter annihilate all at the beginning? If they avoided annihilation, where the rest of antimatter lurks now?

Are there antimatter dominated regions of the Universe? Possible signals:

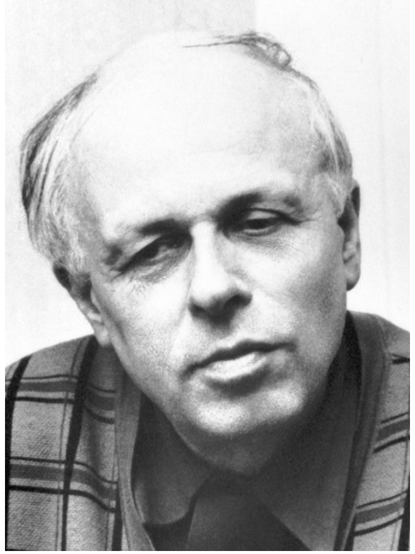
- Photons produced by matter-antimatter annihilation at domain boundaries

  not seen nearby anti-galaxies ruled out

- Cosmic rays from anti-stars

  best prospect: Anti-^{4}He nuclei (searches ongoing…)

Sakharov conditions…



Necessary for evolution of matter dominated universe, from symmetric initial state (1967):

I. baryon number violation
II. C & CP violation
III. thermal inequilibrium

Sakharov's ideas changed attitudes toward CP violation. Before 1967, the violation of symmetry between matter and antimatter seemed to spoil the beautiful picture of the world. After Sakharov's paper it became clear that the world exists thanks to this violation.

Suppose equal amount of matter (X) and antimatter ($\bar{X}$)

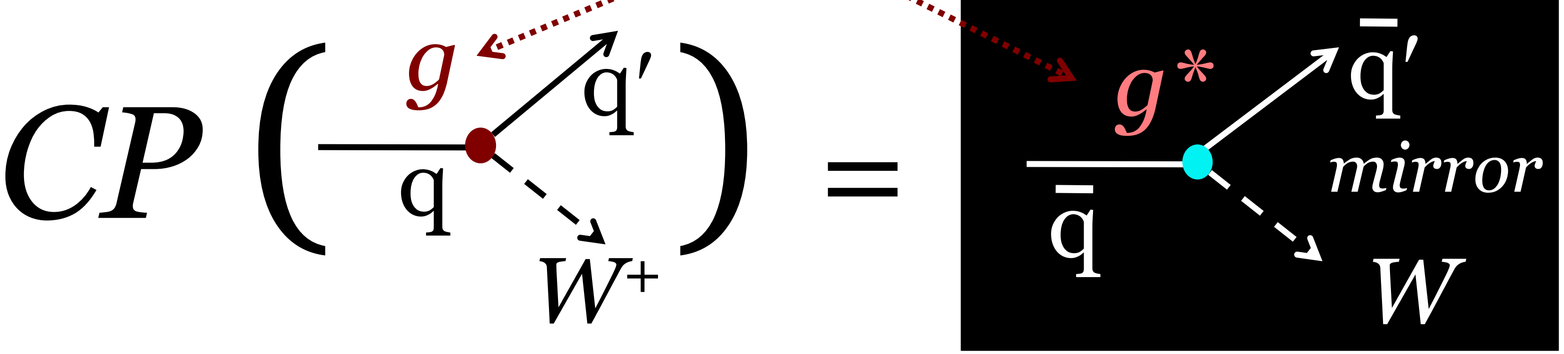
X decays to A(baryon number N_A) and B(baryon number N_B) with probabilities p and $(1-p)$

$\bar{X}$ decays to $\bar{A}$(baryon number $-N_A$) and $\bar{B}$(baryon number $-N_B$) with probabilities $\bar{p}$ and $(1-\bar{p})$

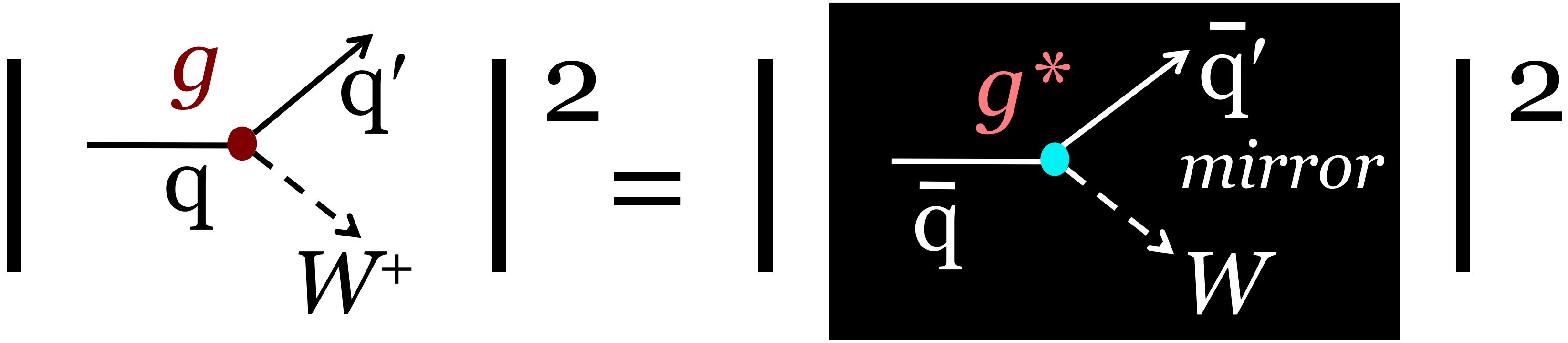
Generated BAU: $\Delta N = pN_A + (1-p)N_B - \bar{p}N_A - (1-\bar{p})N_B = (p-\bar{p})(N_A - N_B) \neq 0$

How to enable CP Violation in QFT?

what about different "charges" g ⍰ g^*?



However, even if g complex, in the rate calculations its phase is not seen:



Oh, it's hard work

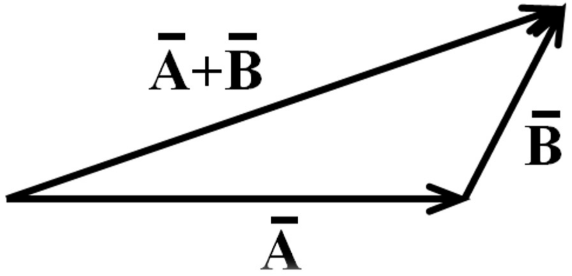
as $|g|^2 = |g^*|^2$

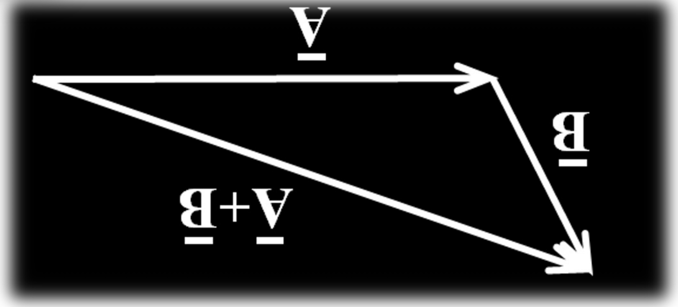
What about two competing amplitudes?

A-real; $B=|B|\,e^{i\varphi}$
$\bar{A}=A$; $\bar{B}=|B|\,e^{-i\varphi}$

still not working

$|A+B| = |\bar{A}+\bar{B}|$



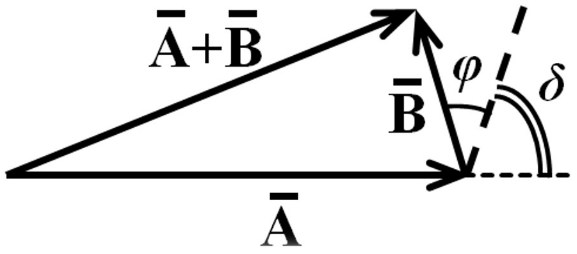


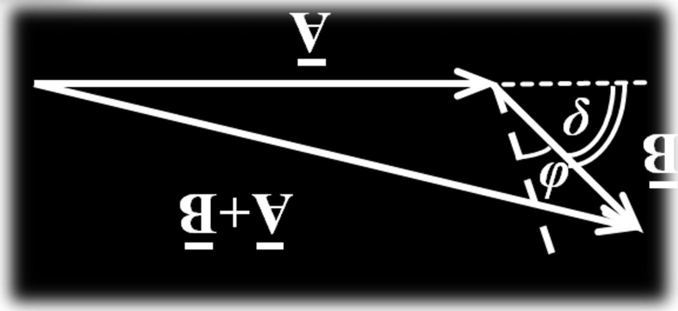
need a reference phase difference that is not changed under CP

$|A+B| \neq |\bar{A}+\bar{B}|$

A-real; $B=|B|\,e^{i(\delta+\varphi)}$
$\bar{A}=A$; $\bar{B}=|B|\,e^{i(\delta-\varphi)}$
e.g. strong interaction can provide this phase δ

successful



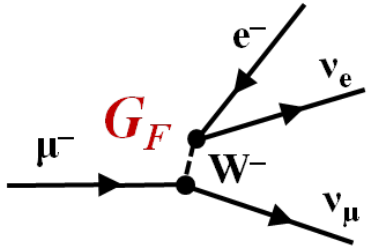


We have done half of the job, but we still do not know how to introduce weak phase

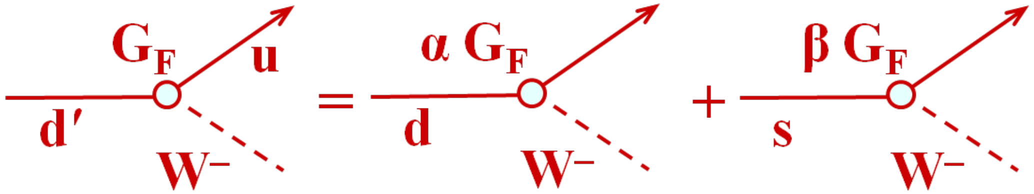
Flavour hints

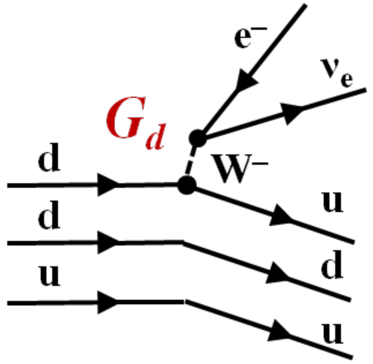
Problem: different weak charges for leptons and quarks:

d→u	s→u
$G_d \approx G_F$	$G_s \approx 0.05\ G_F$



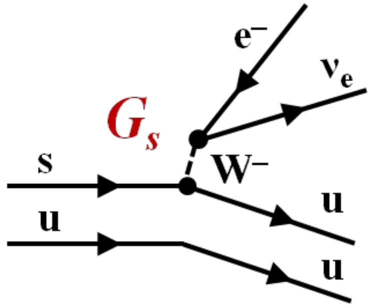
Cabibbo solution: $d' \ = \ \alpha\, d \ + \ \beta\, s$



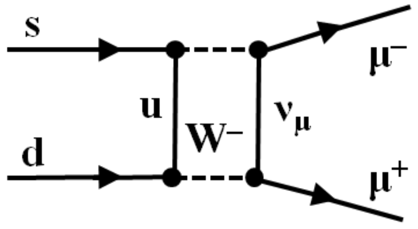


Unitarity: probabilities add up to 1 with $\alpha^2 + \beta^2 = 1\ (\alpha = \cos\theta_C, \beta = \sin\theta_C)$

successfully explains many decays, but there is one important exception which Cabibbo could not describe: $K^0 \to \mu^+\mu^-$ observed rate was MUCH lower than expected ~ $g^8(\cos^2\theta_C \sin^2\theta_C)$



Solution to K⁰ decay problem in 1970 by Glashow, Iliopoulos and Maiani: postulate existence of 4th quark.
Two 'up-type' quarks decay into rotated 'down-type' states: restore symmetry between up and down; and between leptons and quarks generations!



CP violation from quark mixing?

$$L_{W^\pm} = -\frac{g}{\sqrt{2}}(\bar{u}, \bar{c})_L \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_L \gamma^\mu W_\mu^- + h.c.$$

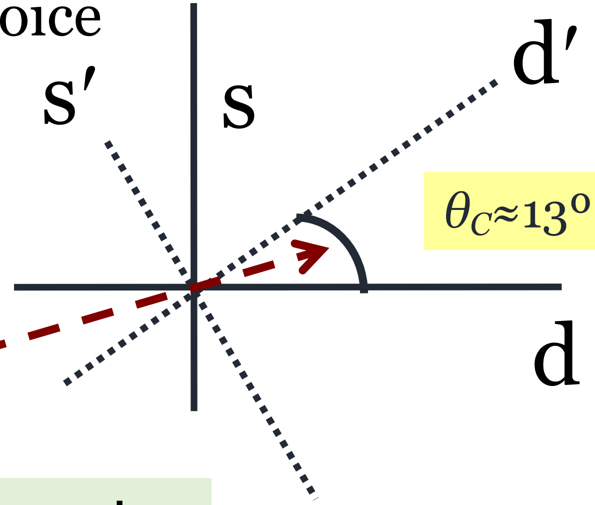
$$\begin{bmatrix} \alpha & \beta \\ -\beta^* & \alpha^* \end{bmatrix}$$

Quark mixing is done by a mixing matrix. Nothing (and nobody) prevents this matrix from being complex! Why not take the complex phase from this matrix as an effective complex weak charge for CP violation?

Alas! Nothing (and nobody) prevents to multiply all u-quarks in the Universe by $e^{i\alpha}$, then multiply all d- and s-quarks by $e^{i\beta}$ and $e^{i\gamma}$. With a proper choice of α, β, γ, we remove all complex phases from the mixing matrix.

It is easy to check by counting parameters for 2×2 matrix:

8 real parameters – 4 unitarity conditions – 3 free quark phases = 1 (Cabibbo angle)



2×2 matrix is REAL! – not enough freedom to introduce imaginary part

The Kobayashi-Maskawa idea

For 3×3 matrix:

18 real parameters
– 9 unitarity conditions
– 5 free quark phases
= 4 (3 Euler angles
+1 phase)

652

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CP-Violation in the Renormalizable Theory of Weak Interaction

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(Received September 1, 1972)

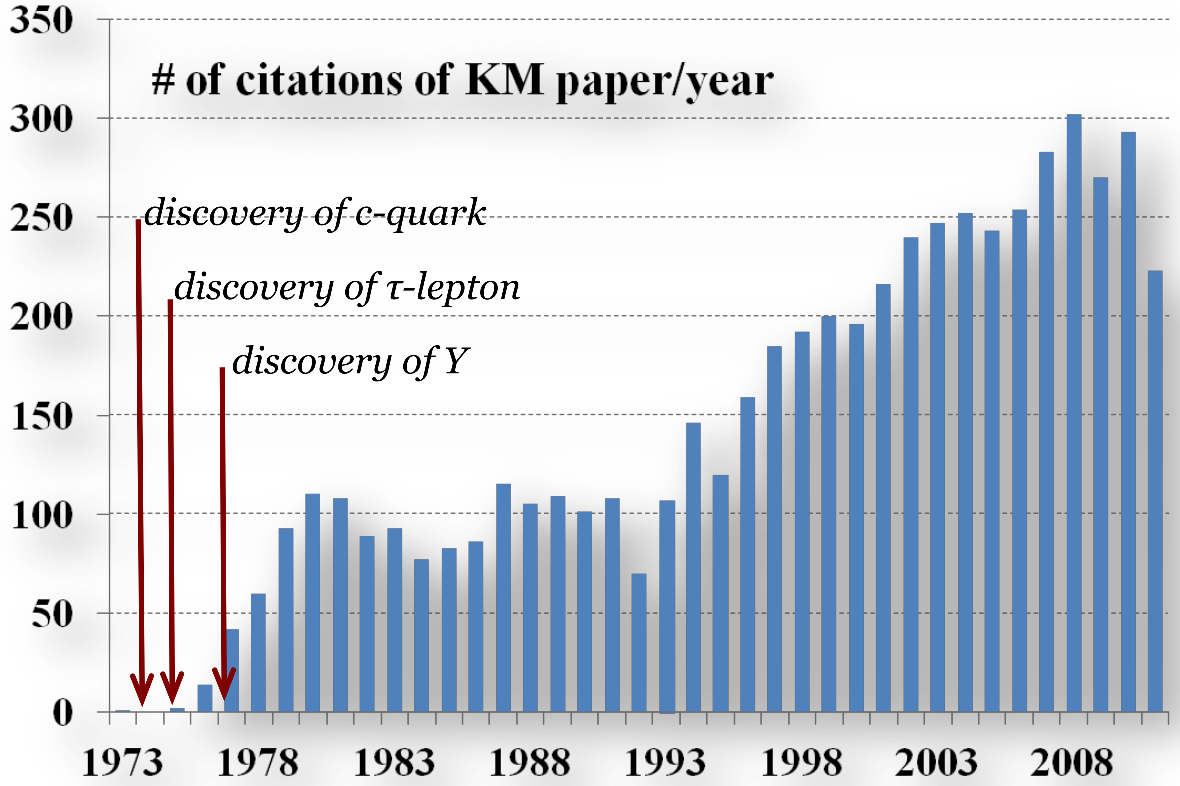
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Wasn't this too trivial idea to try with 3 generations?

Too trivial idea of 3 generations?

It took

- 8 years to come to this “trivial” hypothesis after CP violation observation;
- 2 years after GIM mechanism with full 2-generations proposal…

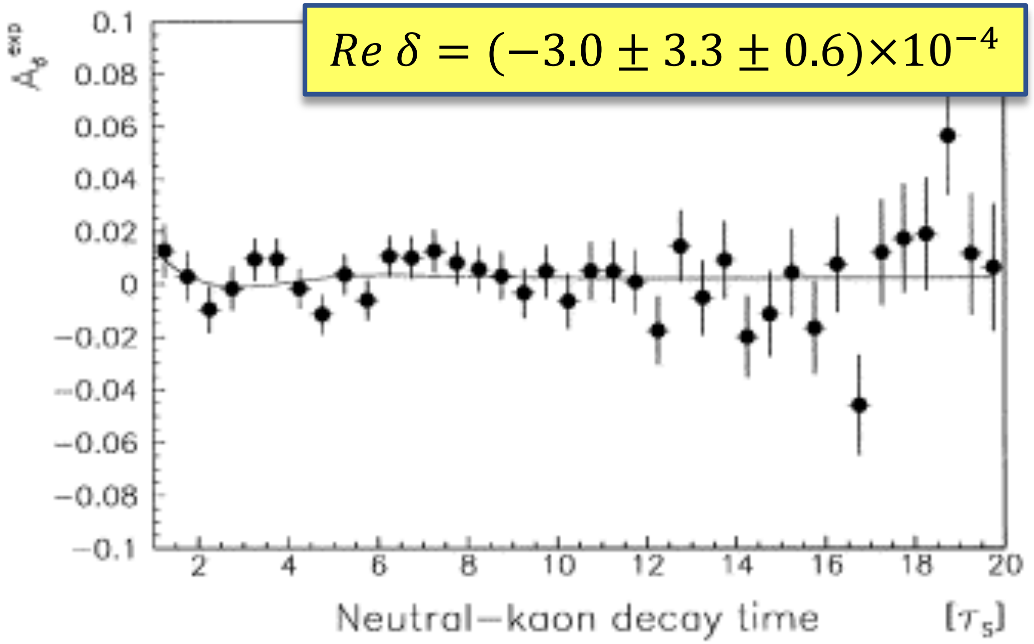


- *0 citations in 2 year after publication*
- *Accepted as reasonable hypothesis only after discovery of the 3-rd generation of leptons*
- *~30 years to be finally accepted as a true theory*
- *more than 7000 citations for 40 years*
- *the 3ᵈ place in topcited articles rank*

CPT symmetry

We know three discrete symmetries: C, P, and T. C and P are maximally violated by weak interaction. CP are better conserved: only small violation has been observed. What about full combination: CPT?

Antimatter was introduced in a way, that any Lorentz invariant local field theory must have the CPT symmetry. But Nature may not care, how we introduced antimatter…



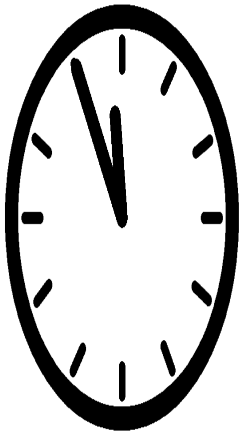
$Re\ \delta = (-3.0 \pm 3.3 \pm 0.6)\times 10^{-4}$

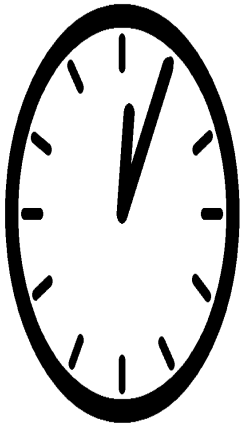
CPT test: check the of mass and lifetimes of particle and antiparticle.

$$\frac{M_{\overline{K}^0} - M_{K^0}}{M_K} < 7.2\times 10^{-19}$$

CPT is the only one of the discrete symmetries that has remained (so far) unbroken.

Time reversal





T symmetry or time-reversal invariance. Suppose you had a movie of some physical process. If the movie were run backwards through the projector, could you tell from the images on the screen that the movie was running backwards?

In everyday life there is an obvious "time arrow" from the past to the future. Irreversibility is due to the very large number of particles involved, while at individual molecules level, we would not be able to discern whether this is working forward or backwards. The everyday ”time arrow" does not seem to have a counterpart in the microscopic world…

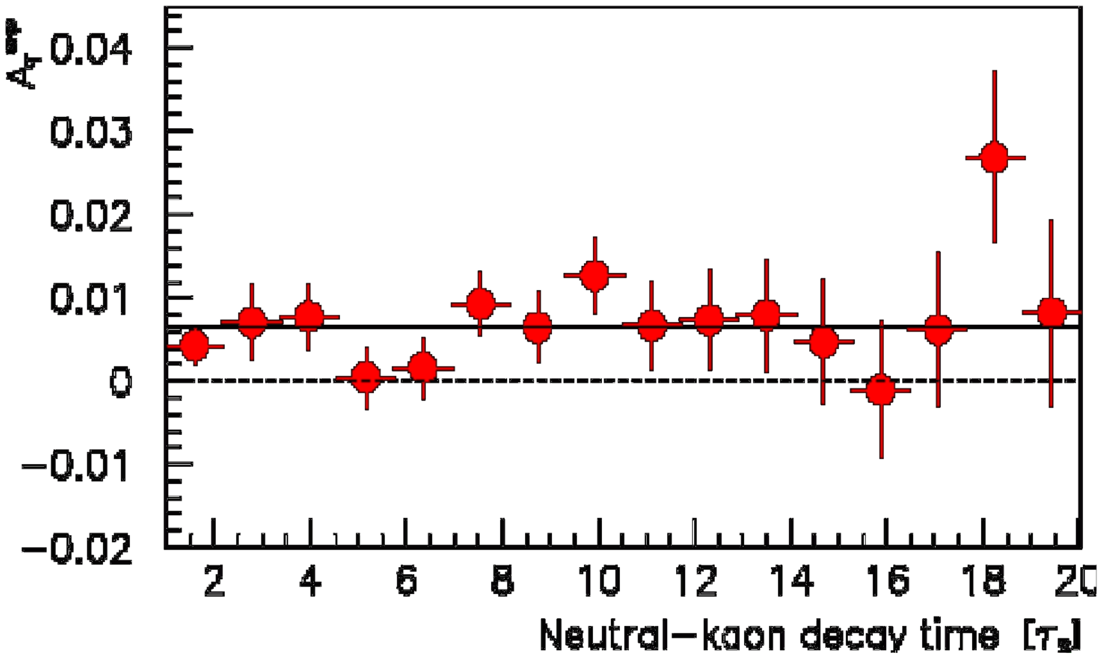
The classical laws are good to describe the interactions of two bodies, but when we talk about 10^{24} bodies, we should use Statistical mechanics… Somewhere in between 1 and 10^{24} particles, time finds arrow?

CPT and Time reversal

CPT symmetry and CP violation give a hint that T symmetry should be violated?

Search for particle and nuclei electric dipole moment. Only upper limits set so far.

Direct search for difference of rates for direct and inversed processes:
CPLEAR search's for a difference in the rates $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$



$$A_T = \frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$

$$\boxed{A_T = (6.6 \pm 1.6) \times 10^{-3}}$$

First direct evidence (~4 sigma) for T-violation