Fundamental Interactions

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Elementary fermions

- Neutrino oscillations and mixing matrix
- Neutrino masses
- Quark mixing
- Baryon- and lepton number violation
- New forms of weak interaction

Discrete symmetries

- Parity
- Time reversal and CP violation
- CPT and Lorentz invariance

Properties of known basic interactions

- QED
- QCD
- Gravitation

Neutrino oscillations

Neutrino oscillation $\rightarrow$ different neutrino masses (Δm_{ij}^2)

(Super-Kamiokande, 1998)

Mixing matrix (Maki-Nakagawa-Sakata-Pontecorvo, MNSP):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unknown parameters:

- θ_{13} mixing angle
- sign of Δm_{23}^2
- the phase δ

$\delta \neq 0 \rightarrow$ CP violation $\rightarrow$ high intensity neutrino beams are needed

- super-beams (pion and muon decay)
- β beams (β decay of boosted radioactive ions – pure flavour)
  CERN $\rightarrow$ Frejus Underground Laboratory
- neutrino factories (decay of stored, accelerated muons)

Neutrino masses

Why so small?
- Majorana mass term (ν and anti-ν are identical)
- seesaw mechanism (beyond SM physics)

ν oscillation: only Δm_{ij}^2 is measurable
- sign of Δm ?
- absolute magnitude of m ?
  fluctuations of microwave backgroung radiation → $\Sigma m_i < 0.61$ eV/c^2

Direct mass measurement:
- kinematics of β decay, electron spectrum close to the end point
  KATRIN (Karlsruhe, 2012-): triton β decay
  MARE (Milano, Genova, planned): ^{187}Re

Neutrino masses 2.

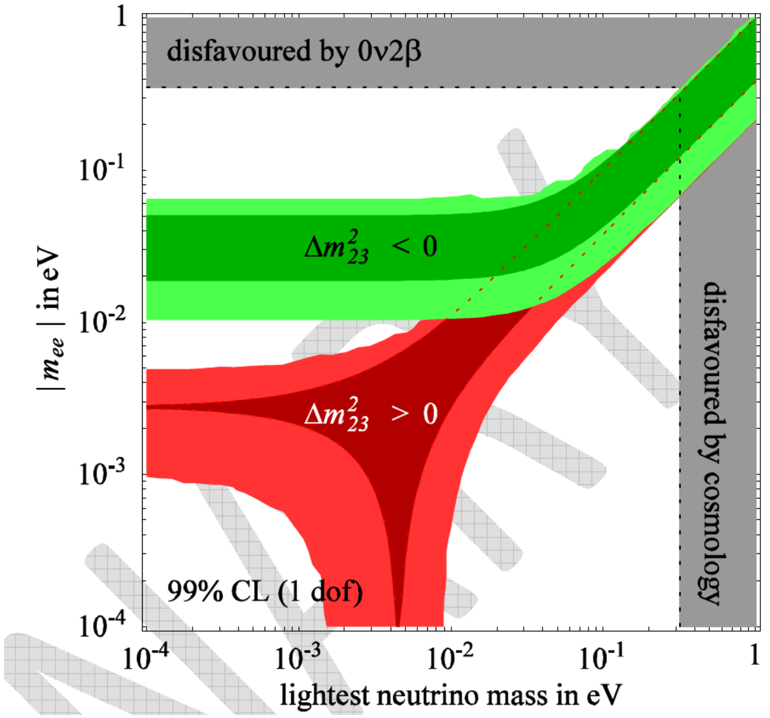
Neutrinoless double β decay – allowed if neutrinos are Majorana particles

Future experiments:

Name	Nucleus	Mass*	Method	Location		Expected start date	Expected final sensitivity (eV)
CUORE	^{130}Te	200 kg	Bolometric	LNGS	EU	2012	0.05–0.10
EXO-200	^{136}Xe	160 kg	Liquid TPC	WIPP	USA	2010	0.13–0.19
GERDA	^{76}Ge	35 kg	Ionization	LNGS	EU	2010	0.08–0.13
LUCIFER	^{82}Se	18 kg	Bolometric	LNGS	EU	2014	0.05-0.07
MAJORANA	^{76}Ge	30 kg	Ionization	DUSL	USA	2013	0.08–0.13
NEXT	^{136}Xe	100 kg	Gas TPC	LSC	EU	2013	u.e.
SNO+	^{150}Nd	40 kg	Scintillation	SNOlab	CAN	2011	0.1
SuperNEMO	^{82}Se or ^{150}Nd	100 kg	Tracking, calorimetry	LSM	EU	2013	0.04–0.15

Experimental constraints on neutrino masses:
(from neutrino oscillations)

$$\langle m_{ee} \rangle = \left| \left|U_{e1}^2\right| m_1 + \left|U_{e2}^2\right| m_2 \; e^{i\phi_1} + \left|U_{e3}^2\right| m_3 \; e^{i\phi 2} \right|$$



Quark mixing

Unitarity of CKM matrix earlies questioned, but recently confirmed at the $6 \cdot 10^{-4}$ level (value of V_{us} shifted by 2.5 σ)

Measurement of CKM matrix elements:

- V_{us} – precise measurement of K-decay branching ratios
- V_{ud} – nuclear decays, free neutron decay, pion decay

Baryon and lepton number violation

Grand Unified Theories: baryon – lepton transitions are allowed,
but B - L conserved
$\rightarrow$ proton decay, $p \rightarrow \pi^0 e^+$ allowed

if in addition neutrinos are Majorana fermions:
B – L is also violated $\rightarrow$ baryon-antibaryon oscillations allowed

Family number violation

Family number is not conserved in SM due to mixing matrices

- neutrino oscillations are allowed
- Decays like $b \rightarrow s\gamma$ and $\mu \rightarrow e\gamma$ are allowed,
  but are suppressed by a factor $(\Delta m_\nu/m_W)^4$ – not yet observed

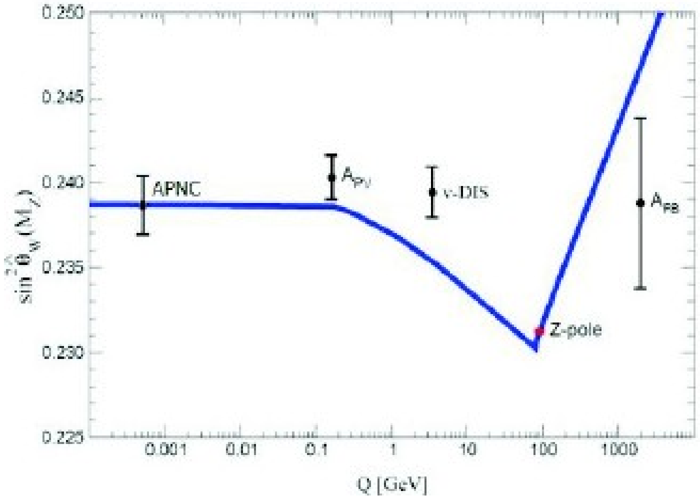
BR of $\mu^+ \rightarrow e^+\gamma < 1.2 \cdot 10^{-11}$ (MEGA at LAMPF, Los Alamos)
MEG at PSI: 10^{-13} sensitivity is aimed

$\tau \rightarrow 3\mu$ – upper limit for BR at LHC

Discrete Symmetries – Parity

Atomic parity violation

- correction to EM interaction due to the Z^0 boson
  → atomic transitions otherwise forbidden
- strength is measured by the *weak charge,* Q_W $[Q_W(e) = -(1-4\sin^2\theta_w)]$
  e.g. ^{133}Cs: $Q_w^{exp} = 73.16 \pm 0.0049$, $Q_w^{theor} = 73.16 \pm 0.03$
  → determination of θ_w at low energy
- effect increases with Z faster than Z^3
  → high Z atoms
  ^{87}Fr trapping (LNL, TRIUMF, RCNP/CYRIC)



- single ions in radiofrequency traps
  KVI, Groningen: future Ra$^+$ experiment

Discrete Symmetries – CP violation, Time reversal violation

CP and T violation are equivalent if CPT is conserved
source: complex phase in CKM matrix
QCD θ term
– explain CP violation in K^0 and B^0, but not baryon asymmetry

Permanent electric dipole moment of a fundamental quantum system

- electron: enhanced in heavy paramagnetic atoms
  - present limit: $d_e < 2 \cdot 10^{-27} e$ cm – using ^{205}Tl, enhancement: $d_{Tl} = -585\, d_e$
  - larger enhancement is expected in polar molecules (e.g. YbF, Imperial College, London)
- neutron:
  - present limit: $d_n < 3 \cdot 10^{-26} e$ cm
  - future: ~ 10^2 factor improvement using ultracold neutrons (ILL Grenoble, PSI Villigen)
- nuclei: diamagnetic atoms
  - limit for Hg: $d_{Hg} < 3 \cdot 10^{-29} e$ cm
  - new experiments: ^{129}Xe (Princeton, TU Munchen),
    ^{225}Ra (Argonne NL, KVI Groningen) etc.

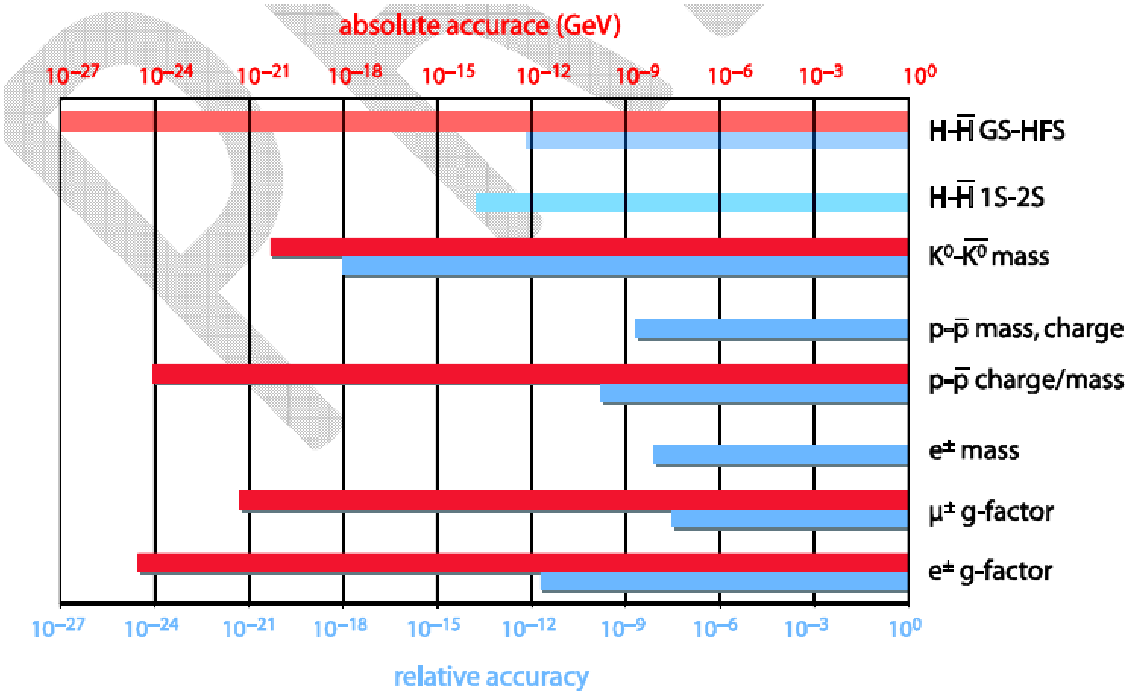
Discrete Symmetries – CPT and Lorentz invariance

CPT theorem: CPT is conserved in local, causal, Lorentz invariant theories

Violation of CPT/Lorentz invariance occurs in theories unifying SM and gravity
e.g. string theory: spontaneous breaking of Lorentz symmetry
→ nonzero VEV of Lorentz tensors
→ signals in high precision measurements at low energy

Alternative explanation of baryogenesis

Tests of CPT: comparison of mass and charges of particles and antiparticles



Known basic interactions – QED and fundamental constants

- Lamb shift
- magnetic moment anomaly, a = (g-2)/2 for electron and muon
- light hydrogen-like ions
- light few body atoms
- highly charged heavy ions
  - test QED in strong electric fields

    Lamb shift of U^{92+} has been measured in GSI

    magnetic moment of a heavy ion (HITRAP in GSI)
  - nonexponential orbital electron capture decay of ^{140}Pr and ^{142}Pm
- many electron atoms – theoretical work needed
- variation of fundamental constants with time

  e.g. optical clock measurement → $1/\alpha \cdot d\alpha/dt < 10^{-17}$/ year

Known basic interactions – QCD and hadronic atoms

- pion-pion and pion-Kaon system (DIRAC at CERN)

- pionic hydrogen, deuterium, ^3He, ^4He (PSI)

- Kaonic atoms, K^-p, K^-d, $K^-\,^3He$, $K^-\,^4He$ (SIDDHARTA at LN Frascati)
  → nuclear bound states of K^- with few nucleons predicted
  planned experiments: AMADEUS at LNF, E15 at J-PARC

- antiprotonic atoms (planned experimets FLAIR at GSI)

Known basic interactions – Gravity

Test the equivalence principle for antimatter → free fall of antimatter

- antineutron? - no way to slow down
- antihydrogen: planned AEGIS experiment at CERN Antiproton Decelerator → measure the gravitational mass of anti-hydrogen with 1% precision

Non-Newtonian gravity – additional Yukawa term in Newton's law:

$$V(r) = -G\frac{mM}{r}\left(1 - \alpha e^{-r/\lambda}\right)$$

motivation:

- theories containing large extra dimensions with bulk gauge field
- modification of gravity at small distances to explain the smallness of the cosmological constant

possible measurements:

- $\lambda < 10$ nm: neutron scattering
- larger λ: mechanical experiments (torsion pendulums)