Searches for new physics in precision atomic experiments

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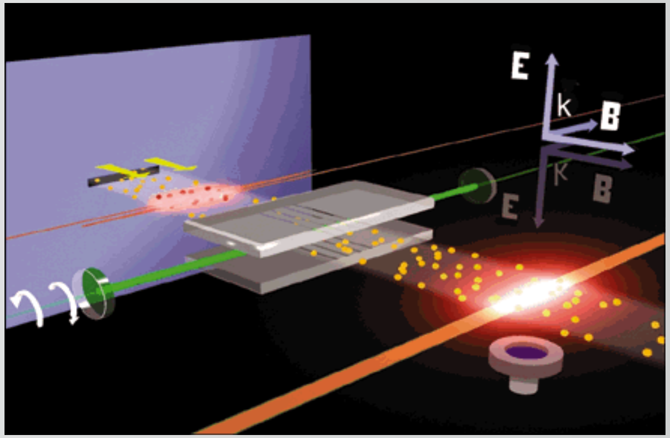
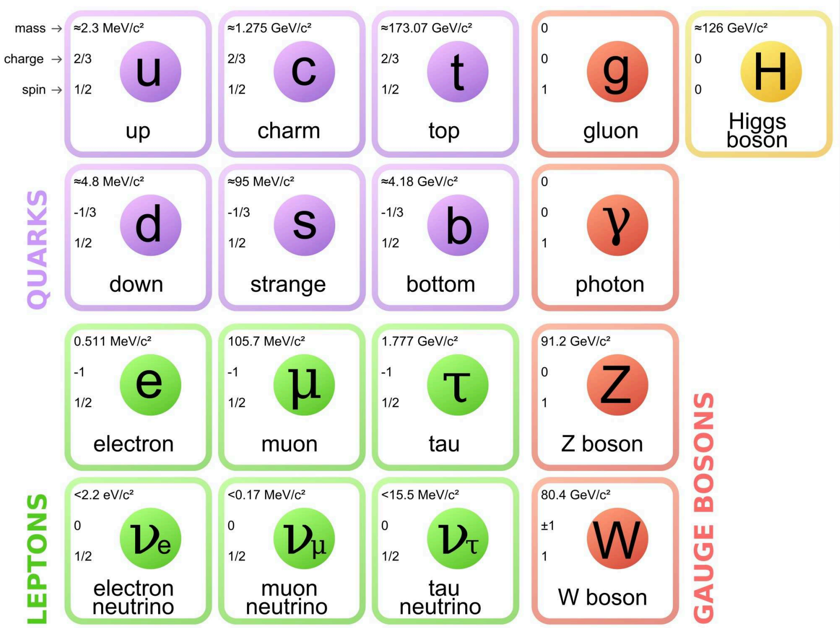


Canberra International Physics Summer School 2023 “Fields and Particles”

Standard Model particle content



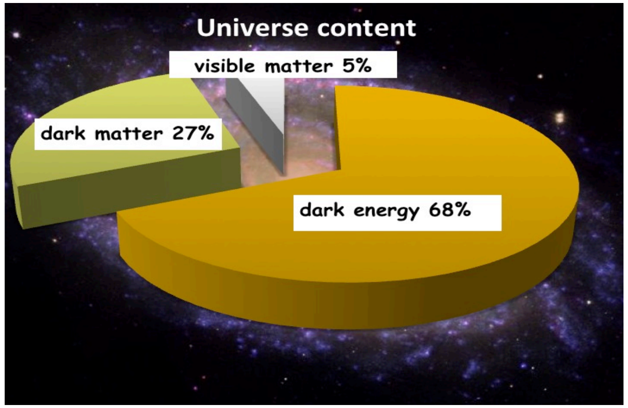
mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

- All SM particles have been discovered!

Searching for new physics

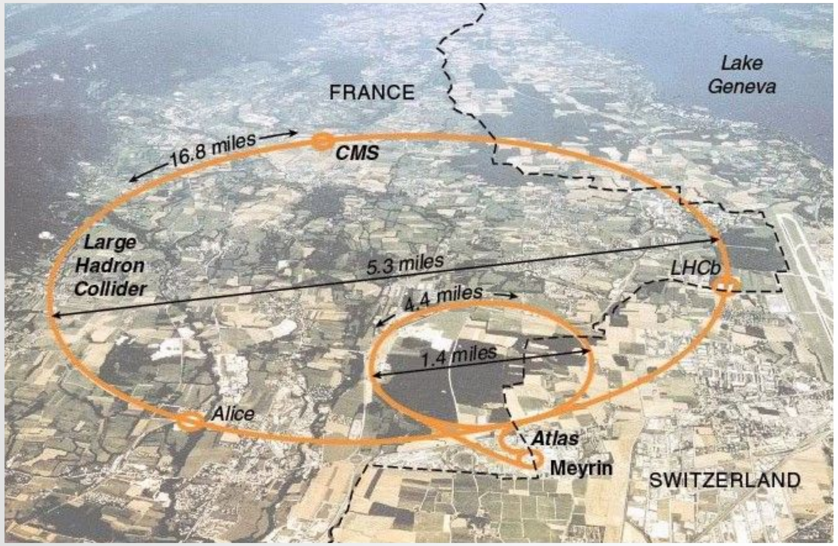
SM cannot explain

- Matter-antimatter asymmetry of universe



- Dark matter
- Dark energy

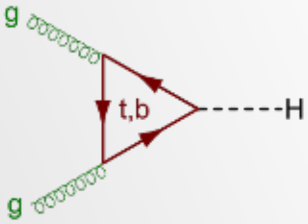
High energy



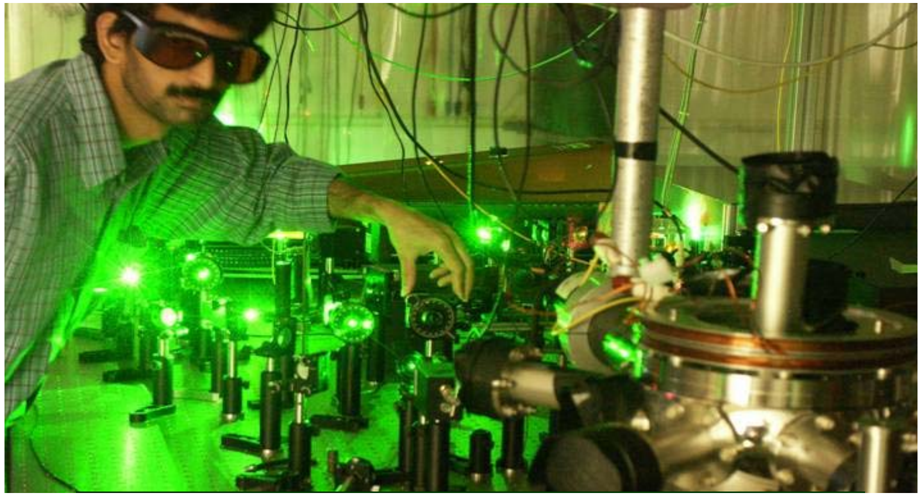
Large Hadron Collider, energies to 13 TeV

Produce particles *directly*

$$E = mc^2$$

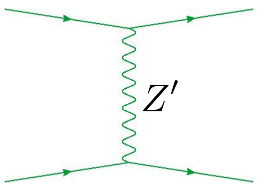


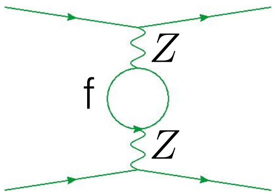
Low energy, high precision



Probe *virtual* processes, may reach >> TeV

$$\Delta E \, \Delta t \sim \hbar$$





Plan

Lecture 1. How can atoms be used to test the SM and search for new physics?

- Atomic parity violation

Lecture 2. Time-reversal-violating electric dipole moments

- Atomic EDMs, enhancement mechanisms

Lecture 3. Precision atomic theory

- Many-body methods, relativistic Hartree-Fock, QED in many-electron atoms

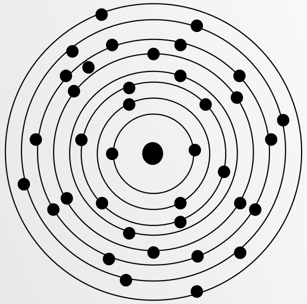
Lecture 4. Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

Lecture 1.

How can atoms be used to test the SM and search for new physics?

The atom as a laboratory for new physics searches

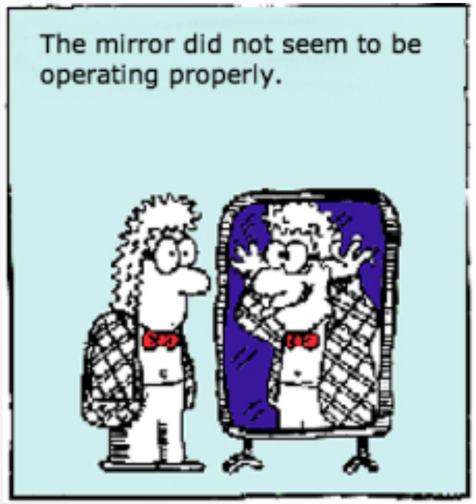


- Electromagnetic interaction
- Weak interaction
- Strong interaction

are present in atoms and may be probed and tested

The weak interaction does not conserve parity, $\boldsymbol{r} \rightarrow -\boldsymbol{r}$

The weak interaction may be *isolated* by studying parity-violating effects



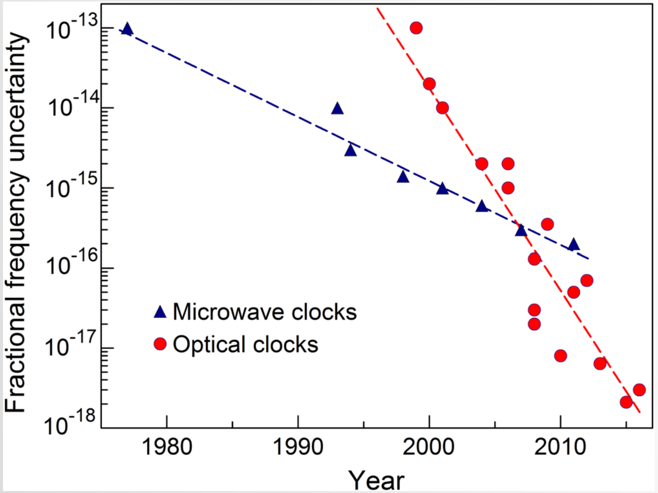
The complexity/simplicity of the system may be varied by changing nuclear charge (Z), isotope, ionisation degree, state

- Possibilities for enhancement
- May choose more theoretically tractable system

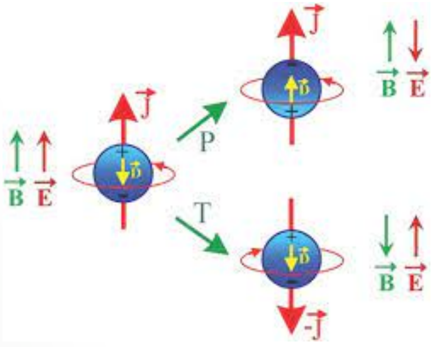
Searches for new physics in atomic experiments

Variation of fundamental constants

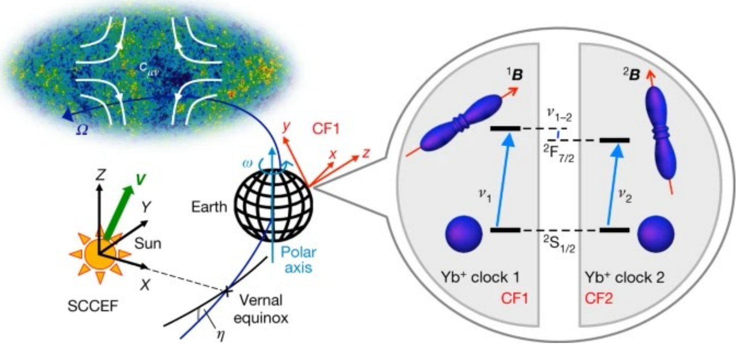
E.g., fine structure constant, proton-to-electron mass ratio, nuclear g-factors in clock experiments



Violation of fundamental symmetries P, CP, CPT



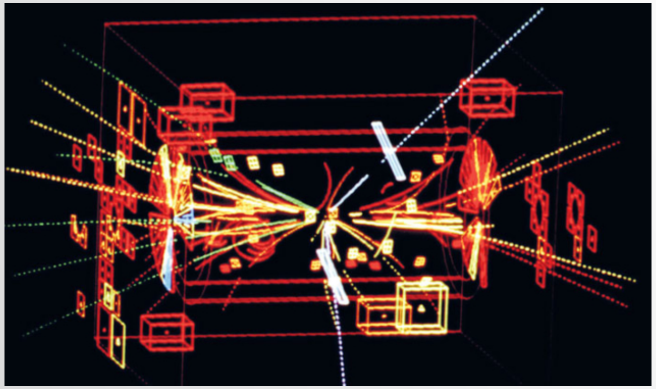
Tests of Lorentz symmetry, general relativity, gravitation,…



For a review, see Safronova et al., Rev. Mod. Phys. (2018)

Neutral weak currents

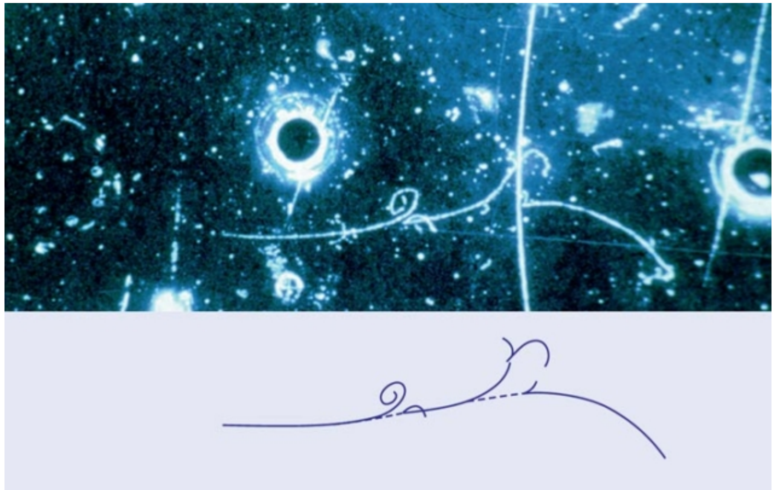
- Neutral weak currents were discovered at CERN (1973) in neutrino-nucleon and antineutrino-electron scattering experiments
- First observation of neutral weak *electron-nucleon interactions* seen in atomic parity violation experiment with bismuth at Novosibirsk, Russia (1978)
- Neutral weak e-N interactions seen shortly after in scattering experiments of electrons off deuterons and protons at the Stanford linear collider (1978)



- In 1983, weak bosons Z, W^+, W^- produced directly at CERN

https://cerncourier.com/a/finding-the-w-and-z/

Hadronic neutral current event: neutrino-nucleon scattering

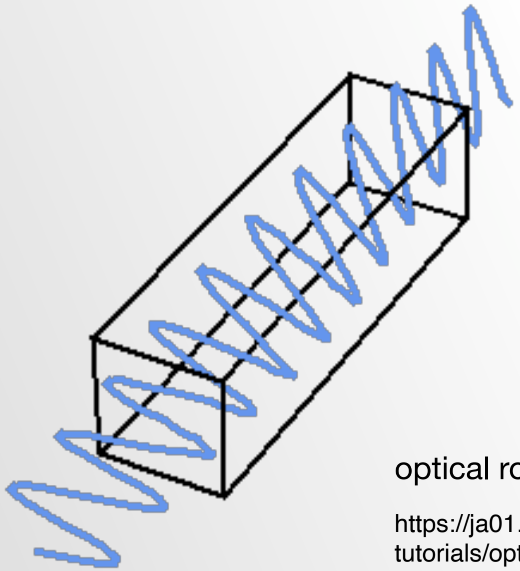


Leptonic neutral current event: antineutrino-electron scattering

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

Bismuth experiment

- e-N weak interaction produces optical activity
- Plane of polarisation of light is *rotated* on passing through bismuth vapour
- *Coherent, macroscopic parity-violating effect*

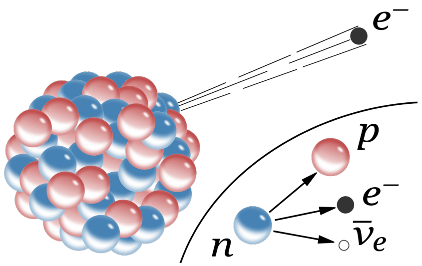


optical rotation animation

https://ja01.chem.buffalo.edu/
tutorials/opticalactivity.html

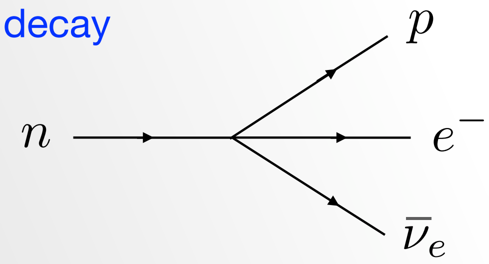
> *The discovery of a new kind of a parity nonconserving weak interaction of electrons with nucleons is an example of a situation when a branch of physics (in this case, atomic spectroscopy) long since believed to be classical, again proves to be at the forefront of our understanding of nature… Table-top apparatus has proved to be an important addition to the experimental methods traditional for elementary particle physics. I am convinced that this case is not the last and that the time of table-top experiments in studying fundamental properties of matter is far from over.*
>
> — *I. B. Khriplovich*

Fermi’s four-fermion interaction



- Fermi (1934) constructed the first theory of the weak interaction
- Considered interaction to happen at a single point

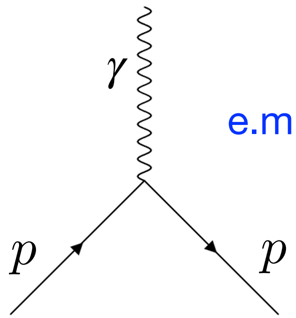
beta decay



$$\bar{p}\gamma_\mu n \, \bar{e}\gamma^\mu \nu_e$$

product of charged nucleon and lepton currents

c.f.



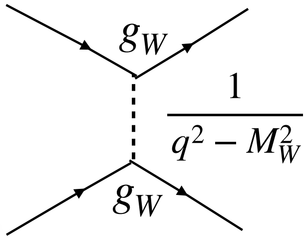
e.m. interaction with proton

$$j_\mu A^\mu = \bar{p}\gamma_\mu p \, A^\mu$$

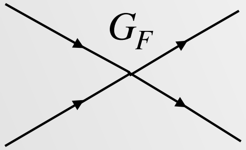
- In the general case, can also construct (scalar) interaction from products of scalar (e.g., $\bar{p}n$), pseudoscalar ($\bar{p}\gamma_5 n$), axial-vector ($\bar{p}\gamma_\mu\gamma_5 n$), and antisymmetric tensor ($\bar{p}\sigma_{\mu\nu}n$) currents

Consider exchange of W boson:

Amplitude $\propto \dfrac{g_W^2}{q^2 - M_W^2}$



- At low energies, $q^2 \ll M_W^2$, propagator $\dfrac{1}{q^2 - M_W^2} \rightarrow -\dfrac{1}{M_W^2}$
  $\rightarrow$ appears as a point-like interaction



Fermi weak interaction constant G_F:

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$

- Weak bosons are very heavy, $W^{\pm}, Z^0 \approx 80 - 90\,\mathrm{GeV}/c^2$, so interaction range is very short, $\hbar/Mc \sim 10^{-3}\,\mathrm{fm}$
- Corresponds to an *effective theory* of the weak interaction

We can now write down all possible contributions to a neutral-weak electron-nucleon interaction. Write explicitly for e-p:

$$\mathrm{G_S}\bar{\mathrm{p}}\mathrm{p}\,\bar{\mathrm{e}}\mathrm{e} + \mathrm{G_P}\bar{\mathrm{p}}\gamma_5\mathrm{p}\,\bar{\mathrm{e}}\gamma_5\mathrm{e} + \mathrm{G_V}\bar{\mathrm{p}}\gamma_\mu\mathrm{p}\,\bar{\mathrm{e}}\gamma^\mu\mathrm{e}$$

$$+\mathrm{G_A}\bar{\mathrm{p}}\gamma_\mu\gamma_5\mathrm{p}\,\bar{\mathrm{e}}\gamma^\mu\gamma_5\mathrm{e} + \mathrm{G_T}\bar{\mathrm{p}}\sigma_{\mu\nu}\mathrm{p}\,\bar{\mathrm{e}}\sigma^{\mu\nu}\mathrm{e} + \mathrm{G'_V}\bar{\mathrm{p}}\gamma_\mu\mathrm{p}\,\bar{\mathrm{e}}\gamma^\mu\gamma_5\mathrm{e}$$

$$+\mathrm{G'_A}\bar{\mathrm{p}}\gamma_\mu\gamma_5\mathrm{p}\,\bar{\mathrm{e}}\gamma^\mu\mathrm{e} + \mathrm{iG'_S}\bar{\mathrm{p}}\mathrm{p}\,\bar{\mathrm{e}}\gamma_5\mathrm{e} + \mathrm{iG'_S}\bar{\mathrm{p}}\mathrm{p}\bar{\mathrm{e}}\gamma_5\mathrm{e}$$

$$+\mathrm{G'_T}\epsilon_{\mu\nu\rho\tau}\bar{\mathrm{p}}\sigma^{\mu\nu}\mathrm{p}\,\bar{\mathrm{e}}\sigma^{\rho\tau}\mathrm{e}$$

S - scalar; P - pseudo scalar; V - vector

A - axial vector; T - tensor

Parity-violating (“P-odd”) terms are primed

P-odd, T-even	Atomic parity violation
P-odd, T-odd	Electric dipole moments

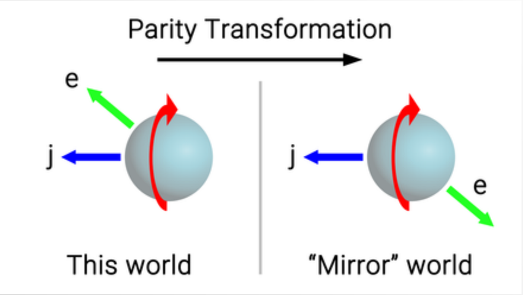
Fundamental symmetries

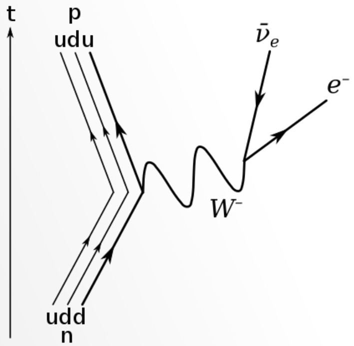
The weak interaction violates fundamental symmetries *parity P* and the combined symmetry *charge conjugation and parity (CP).*

Parity violation

First observed in 1957 in the beta decay of ^{60}Co.

$$^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^- + \bar{\nu}_e + 2\gamma$$



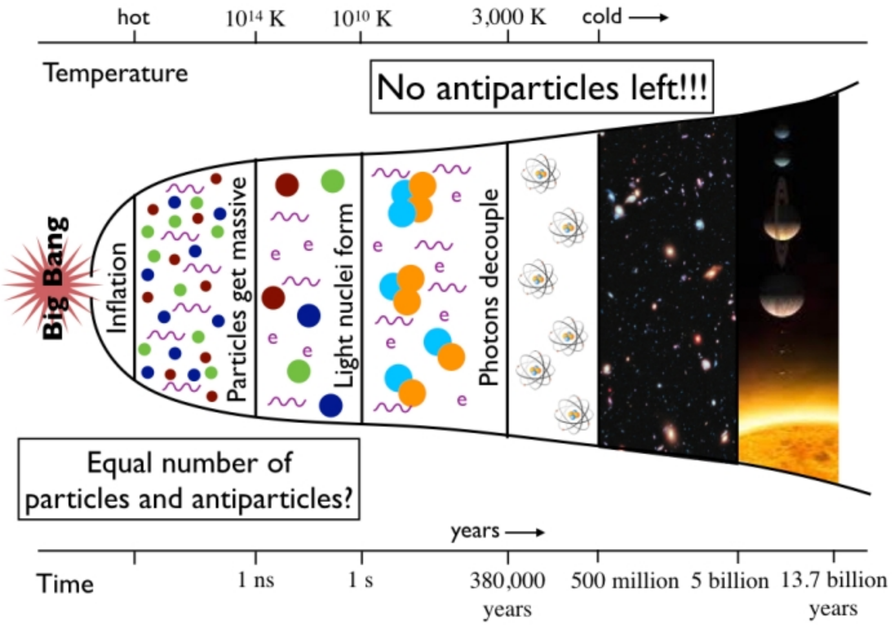


Foundational to SM.

CP violation

First observed in 1964 in decays of neutral K mesons.

CP-violation necessary to produce matter-antimatter asymmetry of the universe! (Sakharov conditions)



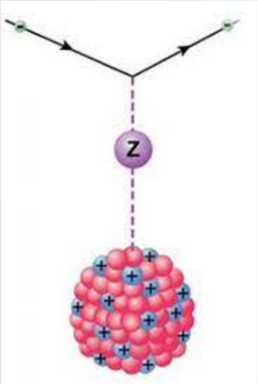
Not enough CP violation in the SM!

CPT symmetry is an exact symmetry in SM.

Violations of fundamental symmetries in atoms

Precision atomic theory *needed* to extract fundamental parameters from atomic experiments for comparison with SM

Atomic parity violation (APV)



APV amplitude:

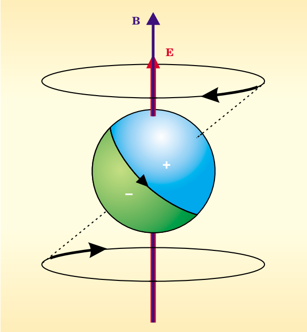
$$E_{PV} = \xi\, Q_W$$

from atomic structure theory

nuclear weak charge

Electric dipole moments (EDMs)

Parity- and time-reversal-violating



Atomic EDM:

$$d_{atom} = \zeta S + K d_e + \ldots$$

from atomic structure theory

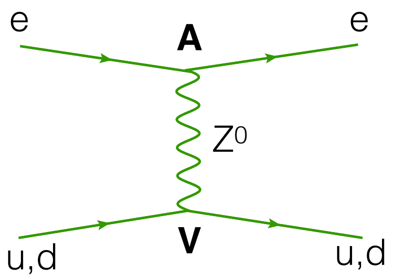
nuclear Schiff moment

electron EDM

Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu \gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Standard model tree-level couplings

$$C_{1n} = C_{1u} + 2C_{1d} = -\frac{1}{2}$$
$$C_{1p} = 2C_{1u} + C_{1d} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

Leads to parity-violating interaction Hamiltonian for electrons

$$h_{\mathrm{PV}} = -\frac{G}{2\sqrt{2}} Q_W \rho(r) \gamma_5$$

where Q_W is *nuclear weak charge.*

SM value known well, $Q_W^{\mathrm{SM}} = -73.23(1)$

Parity-violating nature

Non-relativistic limit:

$$h_{\mathrm{PV}} \propto \boldsymbol{\sigma} \cdot \mathbf{p}$$

Parity operation:

$$\boldsymbol{\sigma} \to \boldsymbol{\sigma}$$
$$\mathbf{p} \to -\mathbf{p}$$

Enhancement with Z

Parity-violating amplitude:

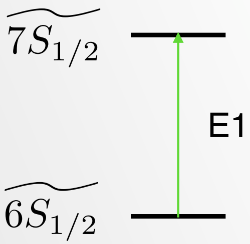
$$E_{\mathrm{PV}} \propto R(Z) Z^3$$

relativistic
enhancement
factor

nuclear charge

Bouchiat, Bouchiat (1974)

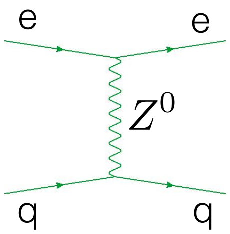
Atomic parity violation in cesium



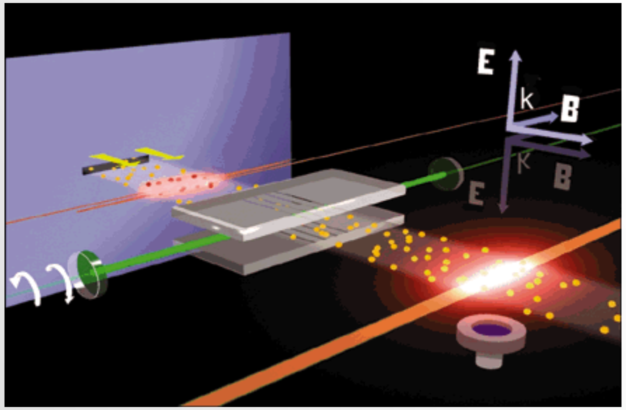
Weak interaction mixes opposite-parity states,

$$|\widetilde{S_{1/2}}\rangle = |S_{1/2}\rangle + \sum_n \frac{\langle nP_{1/2}|H_{\rm PV}|S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}}|nP_{1/2}\rangle$$

6S - 7S electric dipole (E1) transition amplitude $E_{\rm PV}$



Experiment, 0.35% uncertainty



$$-{\rm Im}(E_{\rm PV})/\beta = 1.5935(1 \pm 0.35\%)\,{\rm mV/cm}$$

β — transition polarisability

Carl Wieman group, Wood et al., Science (1997)

Atomic theory, 0.5% uncertainty

$$E_{\rm PV} = \langle\widetilde{7S_{1/2}}|D_z|\widetilde{6S_{1/2}}\rangle$$

$$= \sum_n \frac{\langle 7S_{1/2}|D_z|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}}$$

$$= \xi\, Q_W$$

Dipole operator $\mathbf{D} = \sum_i e\mathbf{r}_i$,

Weak operator $H_{\rm PV} = \sum_i (h_{\rm PV})_i$,

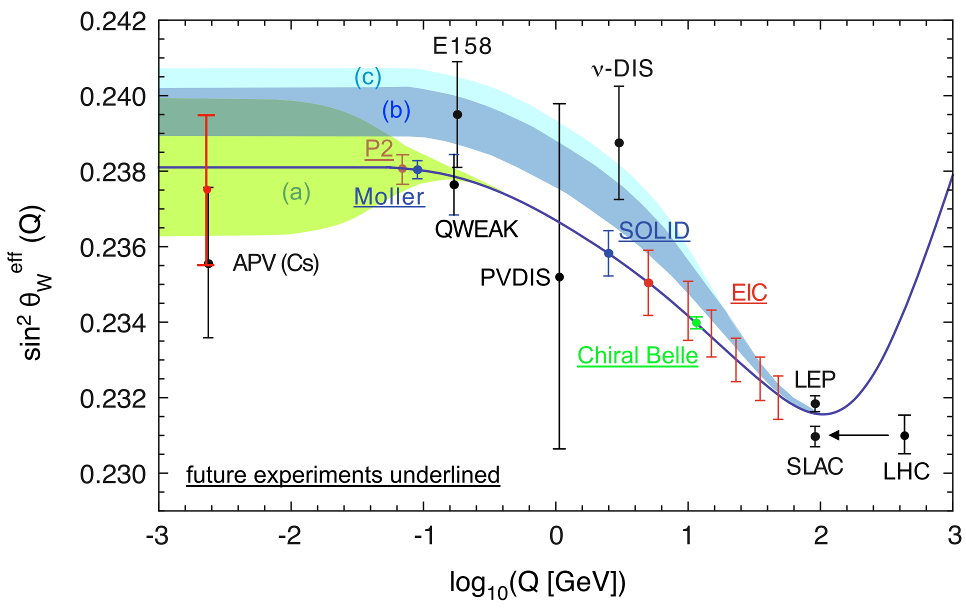
Energies E

Dzuba, Flambaum, Ginges, PRD (2002); Flambaum, Ginges, PRA (2005)
Porsev, Beloy, Derevianko, PRL (2009); Dzuba, Berengut, Flambaum, Roberts, PRL (2012)

Tests of the standard model

- Experiment and theory: nuclear weak charge: $Q_W = -73.07(28)(33) \quad \Rightarrow \quad Q_W - Q_W^{\mathrm{SM}} = 0.16(43)$

Running of the Weinberg angle



Weinberg angle — aka "weak mixing angle"

- fundamental parameter of SM
- Mixes W and B fields to produce the massive Z^0 and massless photon
- At tree level:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Figure from: Gwinner and Orozco, Quantum Sci. Technol (2022)

New result for vector polarizability shifts APV result (red): G. Toh et al., PRL (2019)

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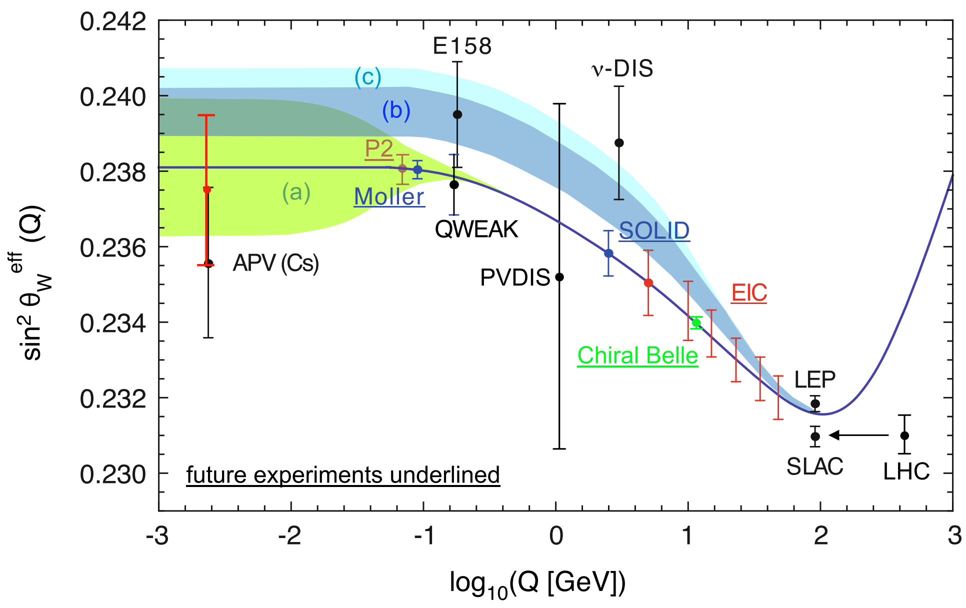


QWEAK - electron-proton scattering **Ross Young**
E158 - electron-electron scattering @ SLAC
PVDIS - parity-violation in deep inelastic scattering
ν-DIS - neutrino deep inelastic scattering
Tevatron - proton-antiproton collider
LEP - Large Electron Positron collider
SLAC - Stanford Linear Collider, electron-positron collider
LHC - Large Hadron Collider, proton-proton collider

Dark Z boson:
(a) 50 MeV; (b) 15 MeV; (c) 15 MeV, in tension with expt.

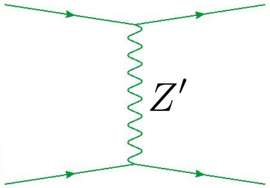
Figure from: Gwinner and Orozco, Quantum Sci. Technol (2022)
New result for vector polarizability shifts APV result (red): G. Toh et al., PRL (2019)

Searches for new physics

New tree-level physics

$$Q_W = Q_W^{\mathrm{SM}} + \Delta Q_W$$

e.g.



$$\mathcal{L}_{\mathrm{PV}} = \mathcal{L}_{\mathrm{PV}}^{\mathrm{SM}} + \mathcal{L}_{\mathrm{PV}}^{\mathrm{new}}$$

$$\mathcal{L}_{\mathrm{PV}}^{\mathrm{SM}} = \frac{G_F}{2\sqrt{2}} g_A^e \bar{e}\gamma_\mu\gamma_5 e \sum_q g_V^q \bar{q}\gamma^\mu q$$

$$\mathcal{L}_{\mathrm{PV}}^{\mathrm{new}} = \frac{4\pi\kappa^2}{\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Probing mass scale:

$$\Lambda \geq \left(\frac{8\sqrt{2}\pi\kappa^2}{(\Delta Q_W / Q_W^{\mathrm{SM}})\, G_F} \right)^{1/2} \approx 30\kappa\,\mathrm{TeV}$$

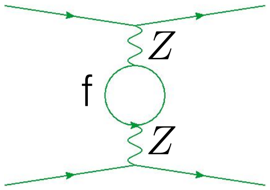
for 0.5%

strongly interacting $\kappa^2 \sim 1$, weakly interacting $\kappa^2 \sim \alpha$

Z' boson: $m_{Z'} \gtrsim 1\,\mathrm{TeV}$

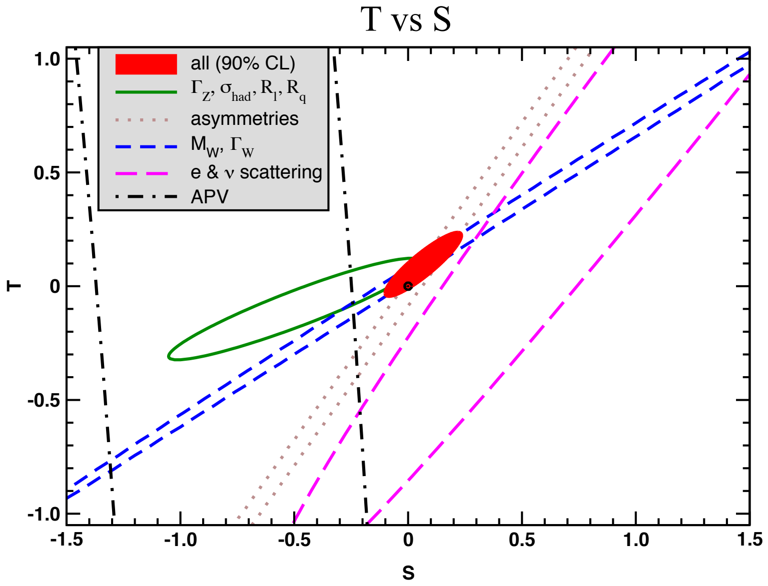
Ramsey-Musolf, PRC (1999)

New radiative corrections



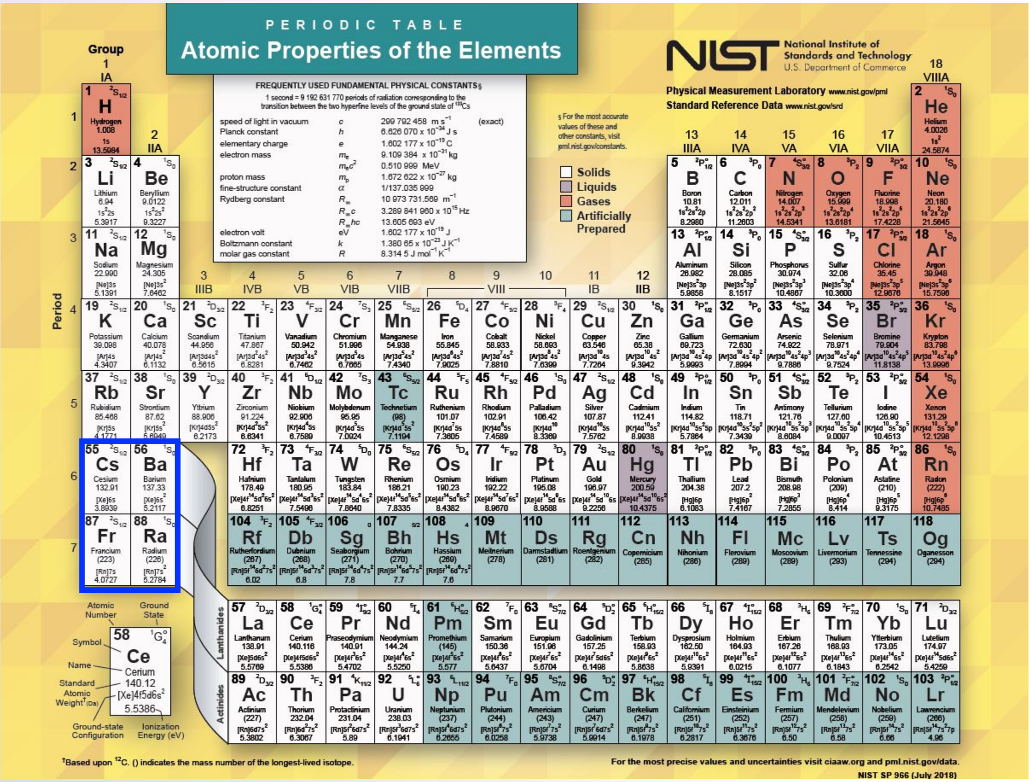
Defined in terms of Peskin-Takeuchi parameters S, T

$$Q_W - Q_W^{\mathrm{SM}} = -0.800\, S - 0.007\, T$$



Erler and Freitas, Particle Data Group review (2016)
(new APV results now centred around SM value)

Experiments in preparation/progress



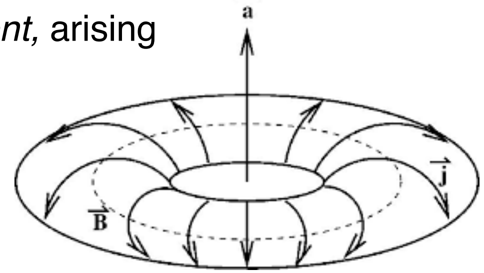
Neutral atoms: Cs (Purdue) ; Fr (TRIUMF; Tokyo)

Singly-ionized atoms: Ba+ (Seattle) ; Ra+ (Groningen)

- Our *precision atomic theory* group at UQ is aiming towards 0.1% uncertainty in APV calculations

Related studies:

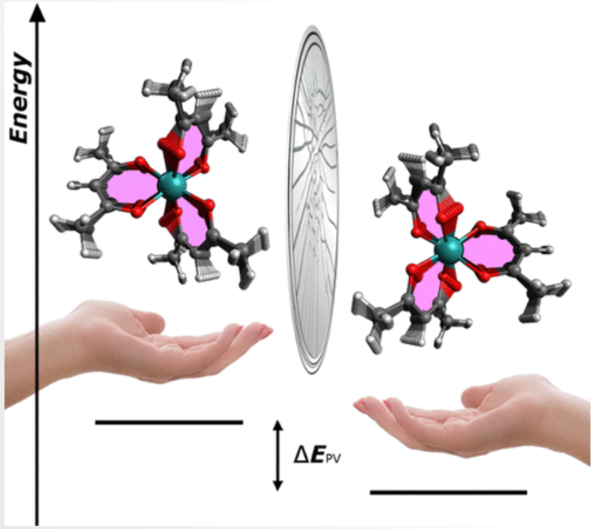
- Atomic parity violation along an isotope chain
- What about couplings arising from C_{2q}, Z-boson exchange with axial vector coupling to quarks and vector coupling to electrons?
    - Leads to *nuclear-spin-dependent* effects in atoms
    - Another effect from a different mechanism dominates — the *nuclear anapole moment,* arising from parity violation within the nucleus



To consider:

Homochirality of biological molecules:
DNA is right-handed;
Amino acids are left-handed;
Sugars are right-handed.

Could the weak interaction play a role in the preferred production of molecules of one handedness over another?



Resources:

Ginges and Flambaum, *Violations of fundamental symmetries and tests of unification theories of elementary particles*, Phys. Rep. 397, 63 (2004)

Safronova *et al*., *Search for new physics with atoms and molecules*, Rev. Mod. Phys. **90**, 025008 (2018)

Ramsey-Musolf, *Low-energy parity violation and new physics*, Phys. Rev. C. **60,** 015501 (1999)

Khriplovich, Parity nonconservation in atomic phenomena, Phys. Rev. C. **60,** 015501 (Gordon and Breach, Philadelphia, 1991)

Summary

Lecture 1. How can atoms be used to test the SM and search for new physics?

- Atomic parity violation

Next lecture. Time-reversal-violating electric dipole moments

- Atomic EDMs, enhancement mechanisms