Fundamental Interactions and exotic nuclei

(Part I)

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Introductory remarks

- The study of *Fundamental Interactions*, in the context of nuclear physics, addresses questions in which atomic nuclei serve as a laboratory.

- We do not study the nucleus itself (structure, reactions, etc.) but use many of its rich features to design experiments that are complementary to those using other physical systems (atoms, neutrons, muons, other particles)

- Often considered as a sub-field of particle physics despite the fact that, similar to nuclear physics, much of the activity in particle physics concerns the study of particles themselves (spectroscopy, decay modes, reactions, etc.)

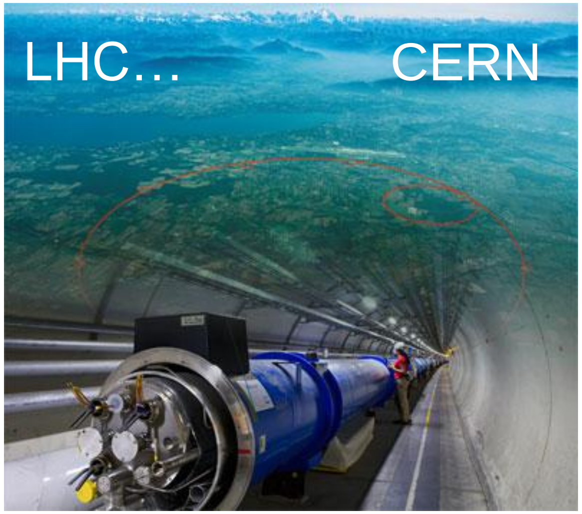
Introductory remarks

- The link with particle physics is made through the reference to the Standard electroweak Model (SM), that describes particles and interactions at the most elementary level.

- Precision experiments with molecules, atoms, nuclei, particles, can test the foundations of the SM (symmetries, assumptions)

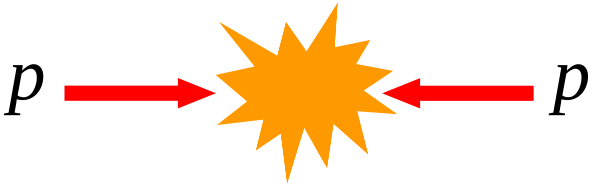
- The goal is to disentangle the rules of the game without paying much attention to the details of the play.

Illustration of two frontiers



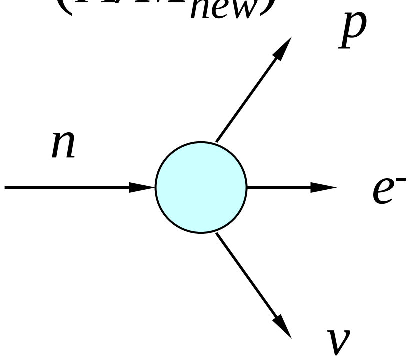
Go for the beast

$$E \sim M_{new}$$



Search for traces

$$E \sim (\Lambda/M_{new})^2$$



Look for interferences

Role of nuclear physics…

…in the foundations of the Standard Model:

- Discovery of a new "force" (β-decay → weak interaction)
- Evidence of the smallness of the neutrino mass (direct measurements of beta decay spectra)
- Determination of the nature (Vector, Axial) of the weak interaction (assumption of *W* vector bosons)
- Discovery of parity violation ("helicity" structure: W_L)
- Test of CVC: exclusion of SCC (first step toward "electro-weak unification")

Scope and Plan

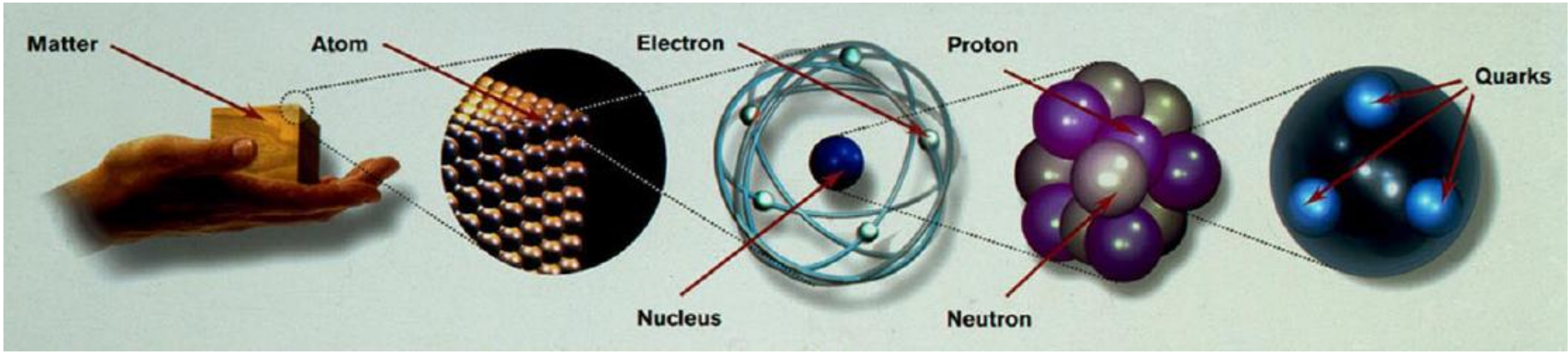
- Overview of selected topics in nuclear beta decay that probe some of the foundations of the Standard Model.
- (not a review).

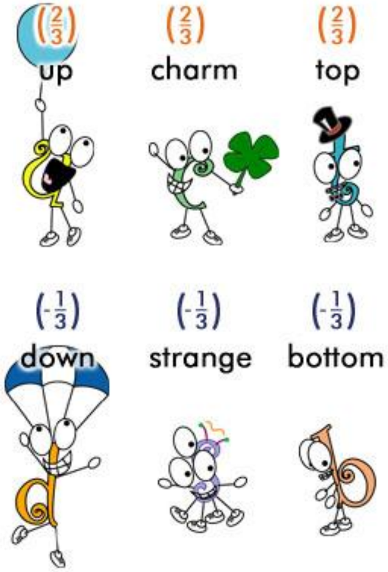
1. Short reminder of the Standard Model building blocks
2. Phenomenology of the Weak Interactions
3. The Universality of the WI; quark mixing and the test of the Unitarity of the CKM matrix
4. Searches for deviations from maximal parity violation
5. Searches for violations of time reversal invariance

A short review of the Standard Model building blocks

Elementary constituents of matter

10^{-1} 10^{-9} 10^{-10} 10^{-14} 10^{-15} m





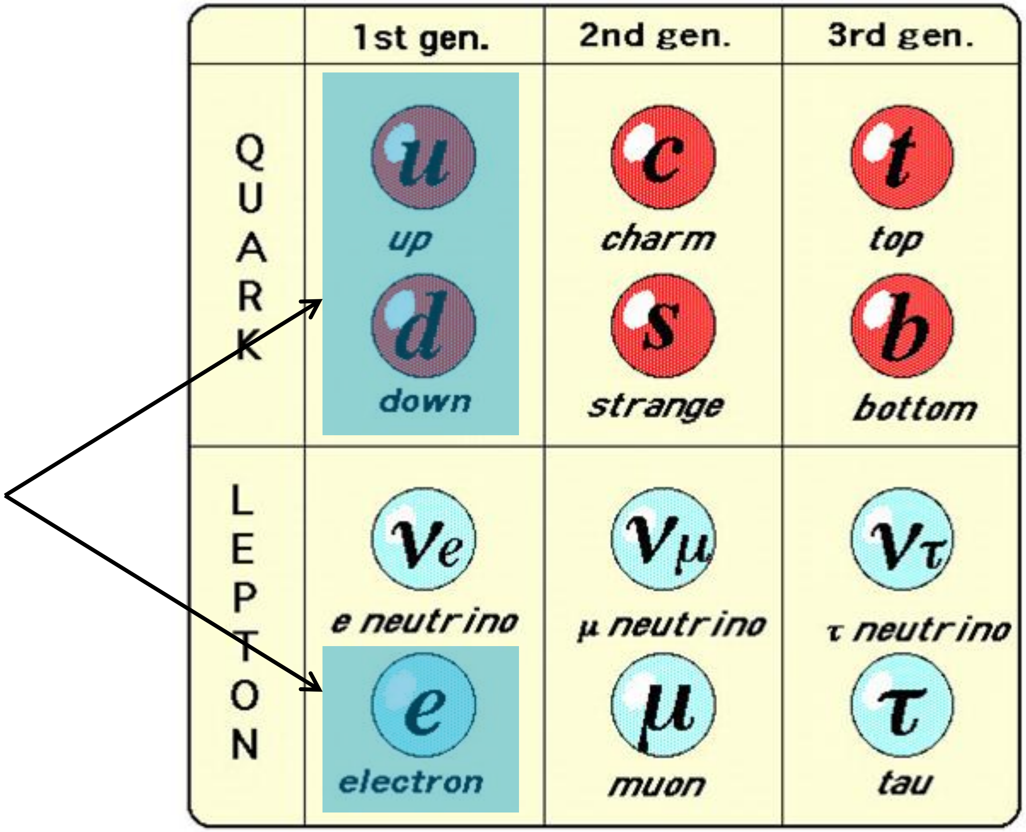
- The 3x2 quark model account for the multitude of hadronic states observed so far.

- Mesons are made out of a quark-anti-quark pair; Baryons are made out of three quarks.

- Isolated quarks are not found in nature.

Quarks and Leptons

The “elements” according to the Standard Model



	1st gen.	2nd gen.	3rd gen.
QUARK	u up d down	c charm s strange	t top b bottom
LEPTON	ν_e e neutrino e electron	ν_μ μ neutrino μ muon	ν_τ τ neutrino τ tau

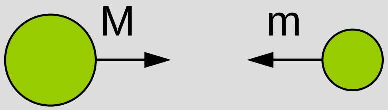
Account for all stable matter around us

→ mass

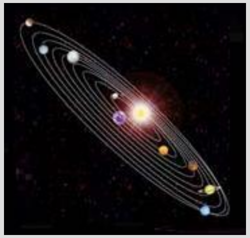
Fundamental Interactions

Infinite range

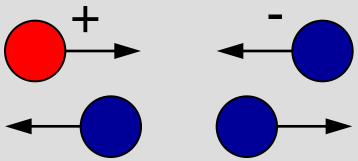
Gravitation



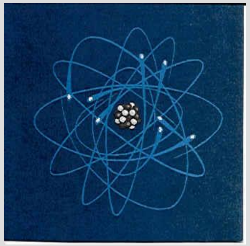
10^{-38}



Electro magnetism



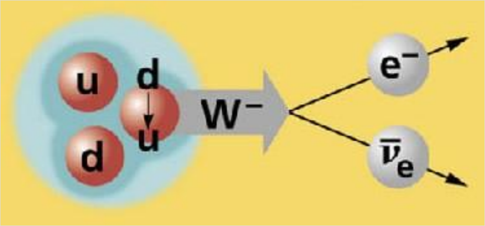
10^{-2}



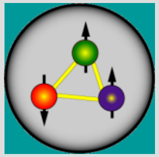
Short range

Weak

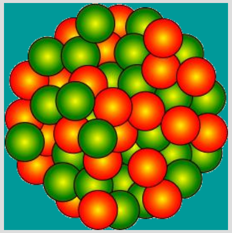
10^{-5}



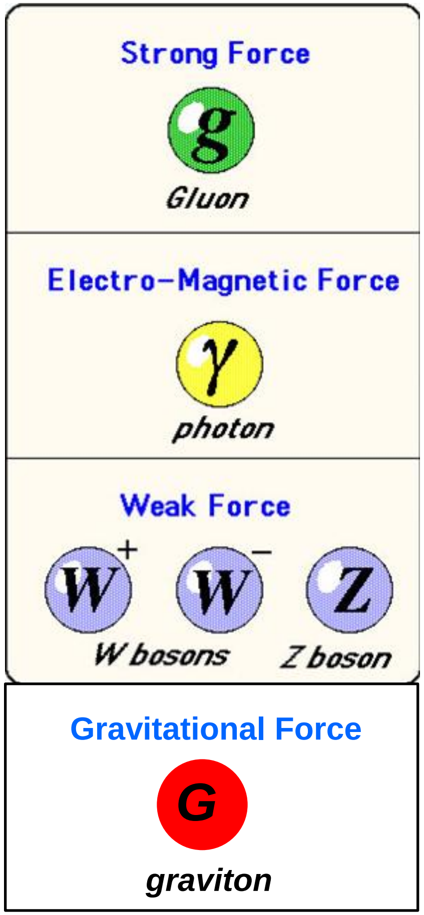
Strong



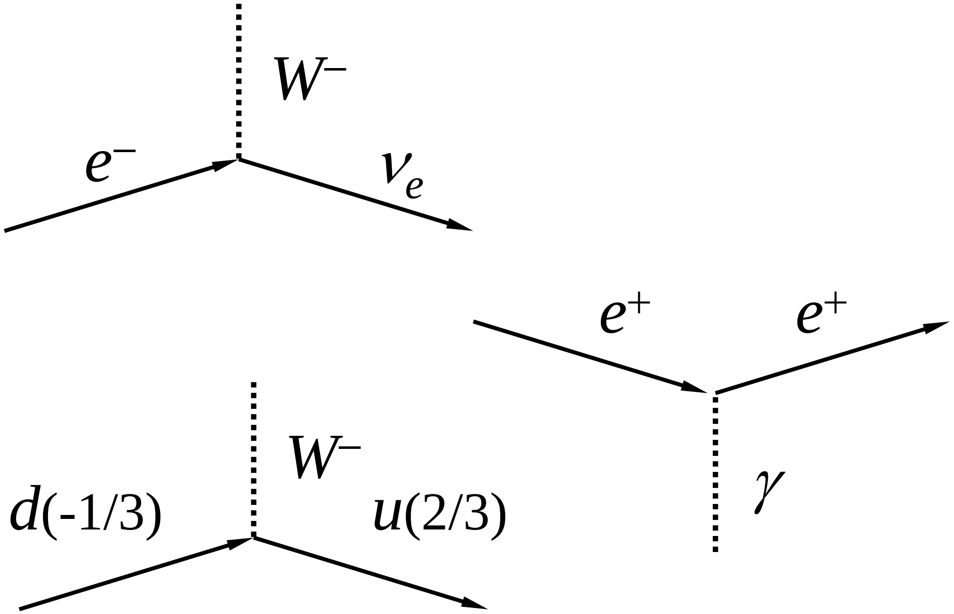
Intensity: 1



Interactions are carried by bosons



Bosons couple to leptons and quarks:

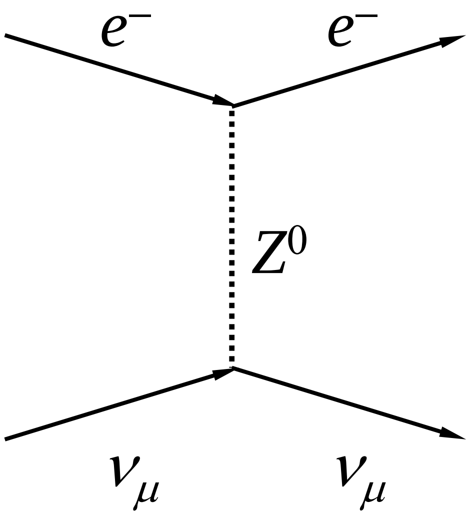


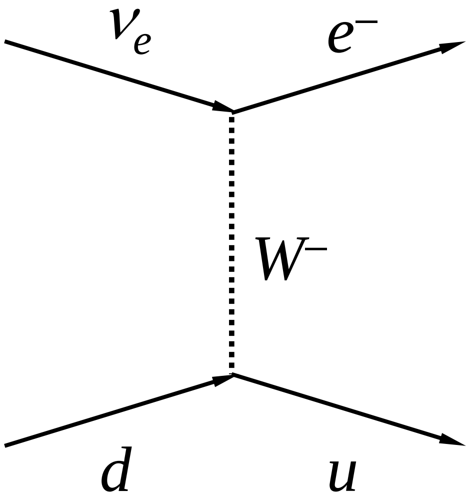
…do not carry lepton and baryon numbers

Phenomenology of Weak Interactions

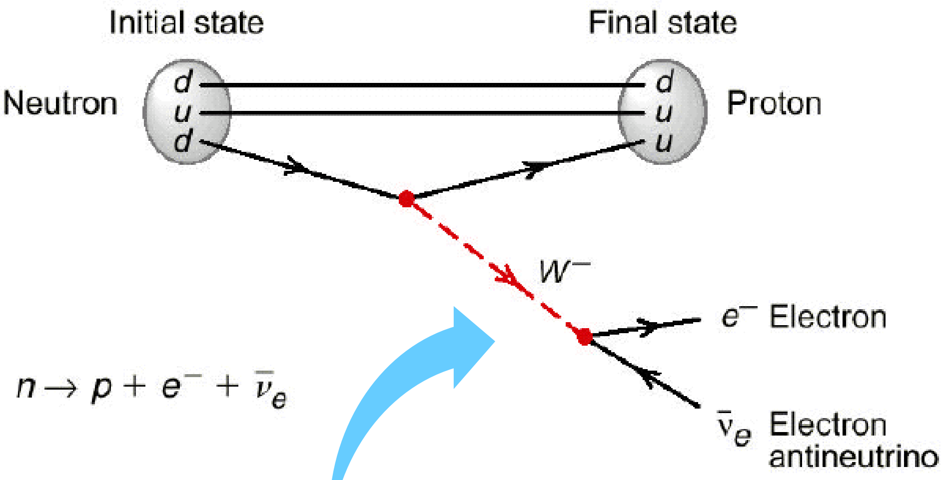
Weak processes

Weak processes are mediated by either Z^0 bosons (“neutral current” processes) or by the W^+ or W^- (“charged current”)

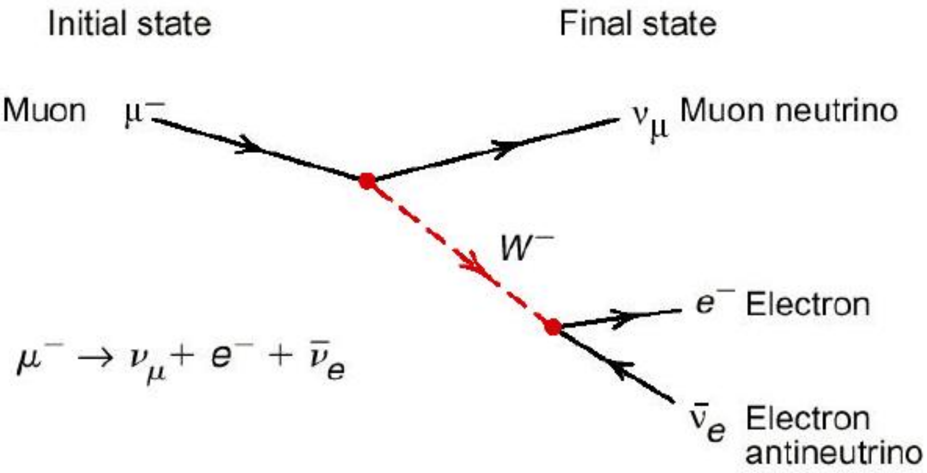




Examples of charged current processes



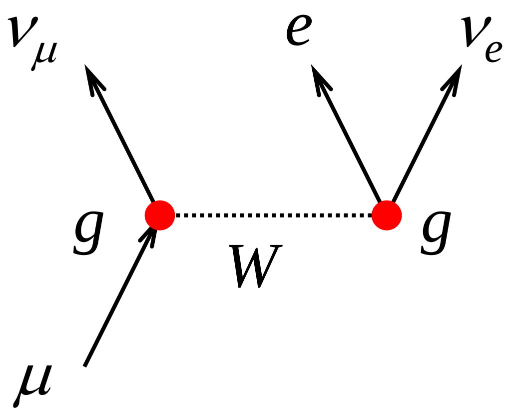
The beta decay of the neutron is reduced (at the elementary level) to the decay of a “down” quark into an “up” quark.



Are there other bosons?
What are their masses, couplings, helicity structure…?

Phenomenology at low energies

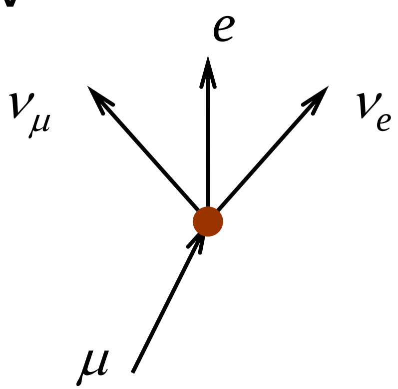
- Example: muon decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



$$M_{if} \propto g\frac{1}{q^2+m_W^2}g \rightarrow \frac{g^2}{m_W^2}$$

$q << m_W$

In muon decay, $q \approx 50$ MeV whereas $m_W \approx 80$ GeV/c^2



The *W* propagation contracts (“contact point interaction”)

Remark

- Assume there is a new interaction, mediated by an unknown boson X, having a similar coupling strength g.

- The amplitude of the process goes like: $\rightarrow \dfrac{g^2}{m_X^2}$

- The experimentally accessible properties ("observables") go like: $\rightarrow \left(\dfrac{g^2}{m_X^2}\right)^2$

- Assume we have obtained a lower limit on m_X from the measurement of some property P.

- To improve the limit on m_X by a factor of say 2, from a new measurement of P requires improving the experimental precision by a factor of 16!

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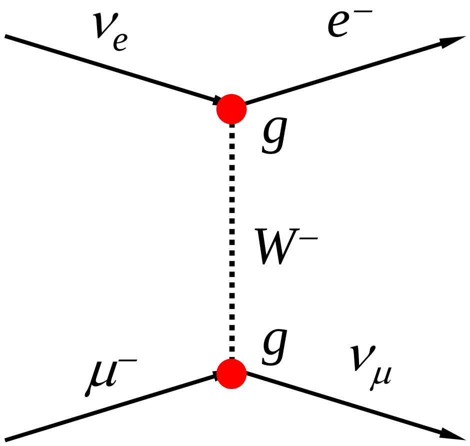
The “strength” of a fundamental interaction

… is a fundamental property of the force.
… tell us how strong bosons couple to particles.

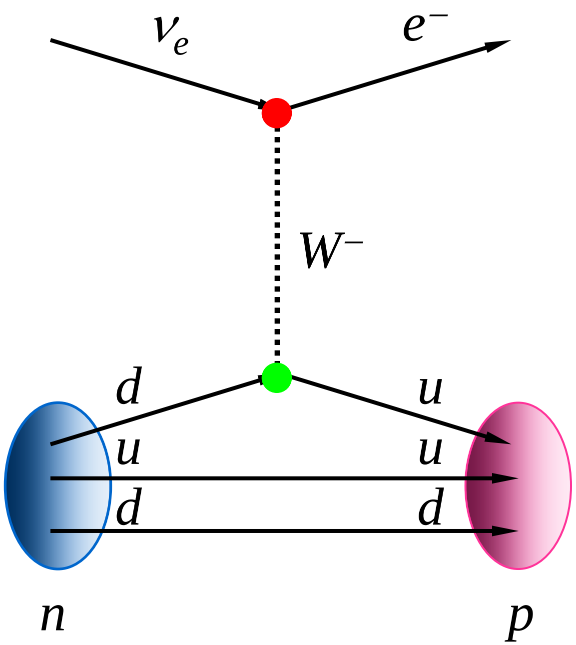
Why is the weak interaction “weak”?
Because…

… it acts at short ranges
… the associated bosons are heavy
… the associated bosons are light
… the intrinsic weak coupling is smaller than the intrinsic em and strong couplings

The strength of the weak interaction

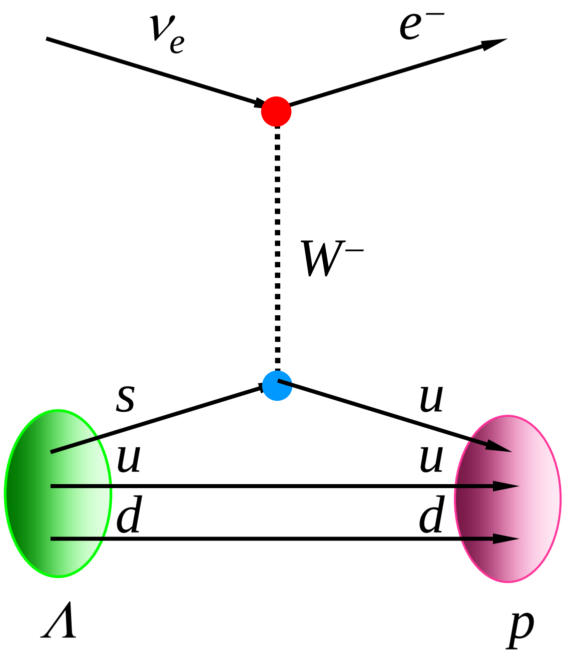


Pure leptonic



Semi-leptonic
(non strange)

Somewhat weaker



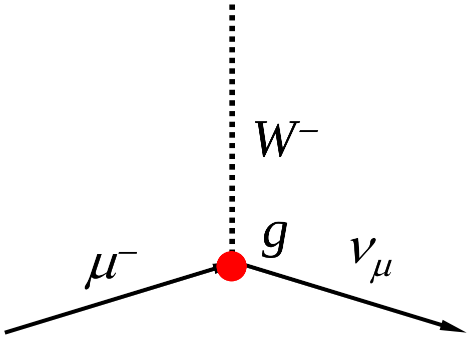
Semi-leptonic
(strange)

Even weaker

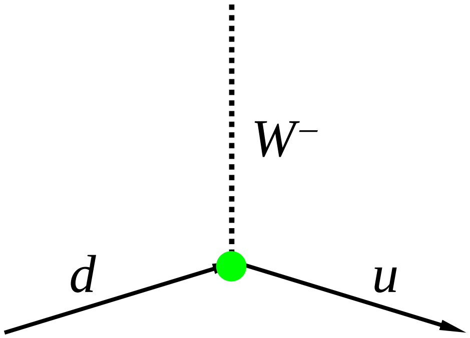
Is the weak interaction “Universal”?

Cabibbo hypothesis

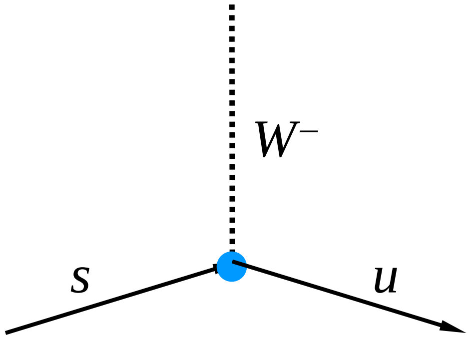
- The interaction is the same (bosons) but the coupling to particles is different for leptons, non-stange hadrons and strange hadrons (like different “charges”)



Pure leptonic



Semi-leptonic
(non strange)



Semi-leptonic
(strange)

θ_C (Cabibbo angle)

$$G_F \propto g^2$$

$$G_V = G_F \cos\theta_C$$

$$G_\Lambda = G_F \sin\theta_C$$

$$(\theta_C \approx 13°)$$

Generalization to three generations

- The Cabibbo scheme was generalized to 3 generations of quarks by Kobayashi and Maskawa (Nobel 2008)

Analogy with ν: the states describing the coupling of particles to weak bosons (“weak eigenstates”) are not the same than the states of the free propagating (*&@%#!?) particles (“mass eigenstates”)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstates

Weak eigenstates

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Mass content of weak states

Remarks

- The values of the CKM matrix elements have to be determined from experiments.

- Some elements have an imaginary part (account for the CP violation observed in *K* and *B* meson decays).

- The CKM matrix has to be unitary (if the model is “complete”)

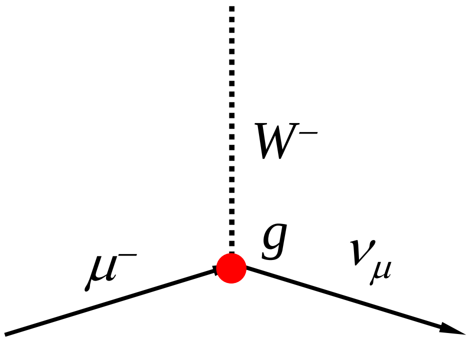
$$\sum_k V_{ki}^{*} V_{kj} = \delta_{ij}$$

- Some unitarity conditions are tested more precisely than others.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

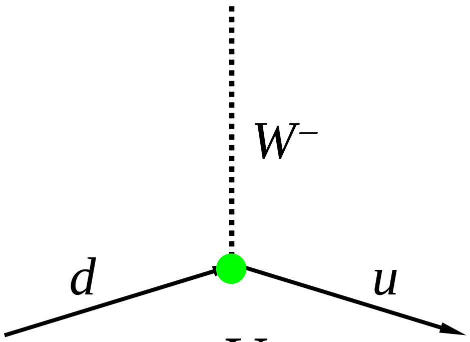
Back to the couplings

Within the quark mixing scheme



g

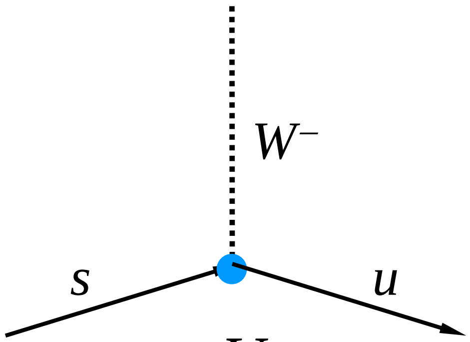
Pure leptonic



gV_{ud}

Semi-leptonic
(non strange)

$$V_{ud} = \cos\theta_C \approx 0.974$$



gV_{us}

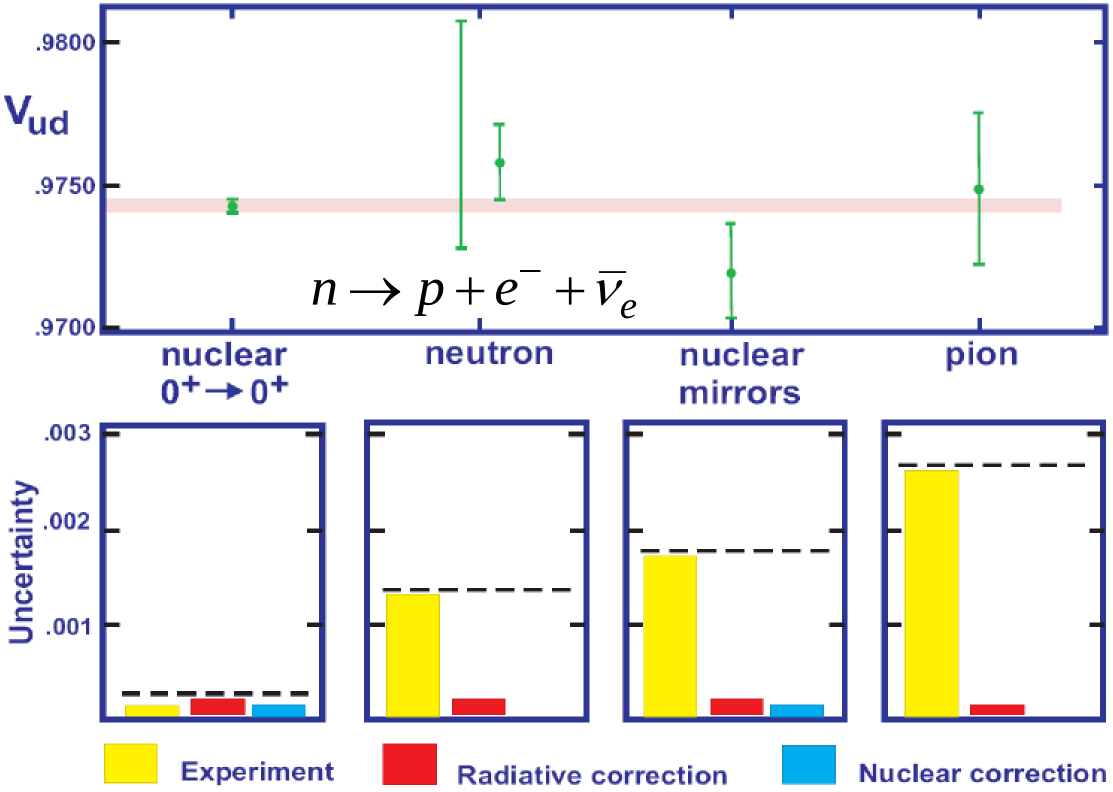
Semi-leptonic
(strange)

$$V_{us} = \sin\theta_C \approx 0.225$$

How can we determine V_{ud}?

Compare the decay rate of a (simple) system made out of u and d quarks with the muon decay rate.

Determinations of V_{ud}



$n \to p + e^- + \bar{\nu}_e$

$\pi^+ \to \pi^0 + e^+ + \nu_e$

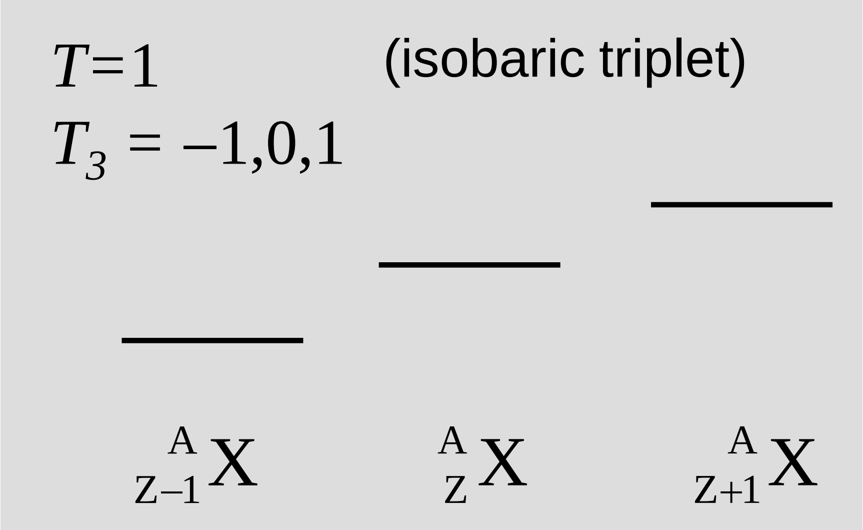
Towner&Hardy@CKM-2010

- $0^+ \to 0^+$: "pure Fermi transitions" (transitions where only the Vector interaction is present.
- "nuclear mirror": transitions $J^\pi \to J^\pi$ between mirror nuclei (Vector and Axial vector interactions).

Allowed and Super-allowed (definitions)

- “Allowed” beta transitions: Leptons (e and ν) do not carry away orbital angular momentum

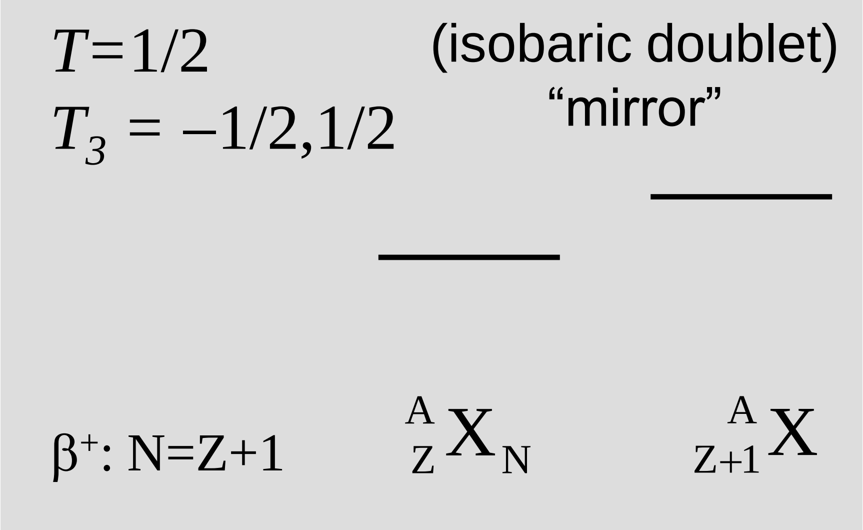
- “Super-allowed” : Transition occurring furthermore within the same isospin multiplet (isobaric analogue states)



$T=1$ (isobaric triplet)

$T_3 = -1,0,1$

${}^{A}_{Z-1}\mathrm{X}$ ${}^{A}_{Z}\mathrm{X}$ ${}^{A}_{Z+1}\mathrm{X}$



$T=1/2$ (isobaric doublet) “mirror”

$T_3 = -1/2,1/2$

β^+: N=Z+1 ${}^{A}_{Z}\mathrm{X}_{N}$ ${}^{A}_{Z+1}\mathrm{X}$

Experiments with nuclei

Decay rate

Fermi’s golden rule (time dependent parturbation theory)

$$\Gamma = \frac{2\pi}{\hbar} \left| \langle \psi_f | H | \psi_i \rangle \right|^2 \rho(E_i)$$

↑ phase space

$$\Gamma \equiv \frac{1}{\tau}$$

$$\rho\tau \propto \frac{1}{\left| \langle \psi_f | H | \psi_i \rangle \right|^2}$$

- $\rho\tau$ (→ *ft*) should then depend only on the interaction
  - f : “statistical rate function” (includes phase space)
  - t : partial half-life (includes branching ratio)

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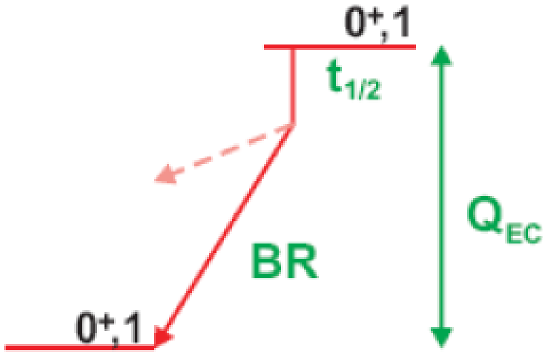
Experimental inputs for pure Fermi transitions



$$ft = \frac{K}{G'^2_V \left|M_V\right|^2}$$

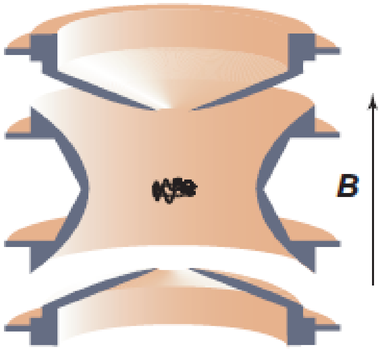
- K : constant (include fundamental constants)
- G'_V : effective vector coupling
- M_V : matrix element

$$G'^2_V = G_F^2 V_{ud}^2 (1 + \Delta_R)$$

$$\left|M_V\right|^2 = \left|\langle f \left| T_- \right| i \rangle\right|^2 = \left[T(T+1) - T_3(T_3 - 1)\right] = 2$$

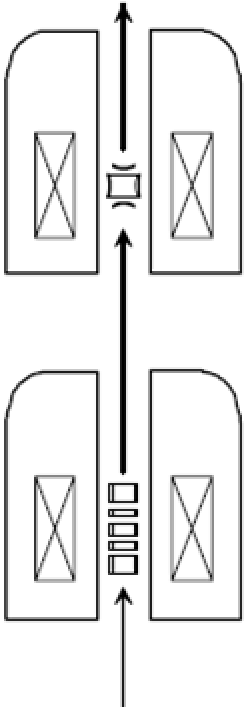
- $f = f(Z, Q_{EC})$ → Measure masses of initial/final states
- t → Measure half-life of initial g.s. and branching ratio

Penning trap mass spectrometers



- Radial confinement: *B*
- Axial confinement: *E*
- Apply external RF field around cyclotron frequency

$$f_c = \frac{q}{2\pi m} B$$



Precision Penning trap: measurement of cyclotron frequency

Preparation Penning trap: removal of contaminants

See details during hands-on activities

For Fundamental Interactions:
ANL, ISOLDE, JYFL, NSCL, TRIUMF

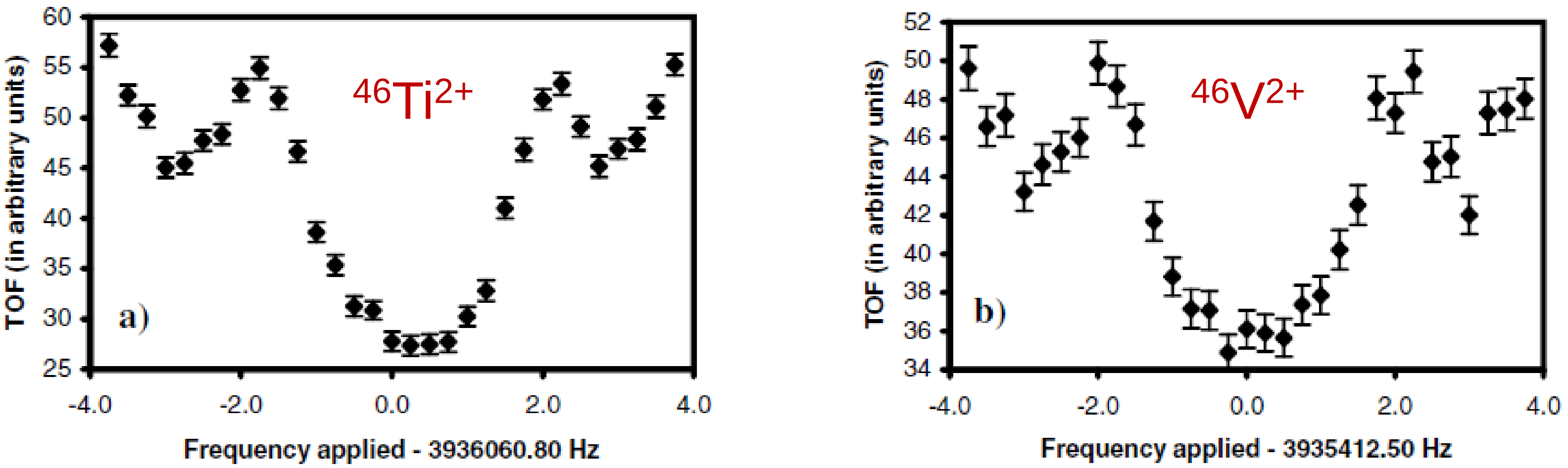
Example ^{46}V

ANL

G. Savard et al. PRL 95 (2005) 102501

- Measure simultaneously parent (^{46}V) and daughter (^{46}Ti) masses to extract Q_{EC} (reduced systematic effects)

Time of flight of extracted ions vs external RF



- Measured masses to 10^{-8} precision
- Solved a standing discrepancy excluding 7 previous measurements

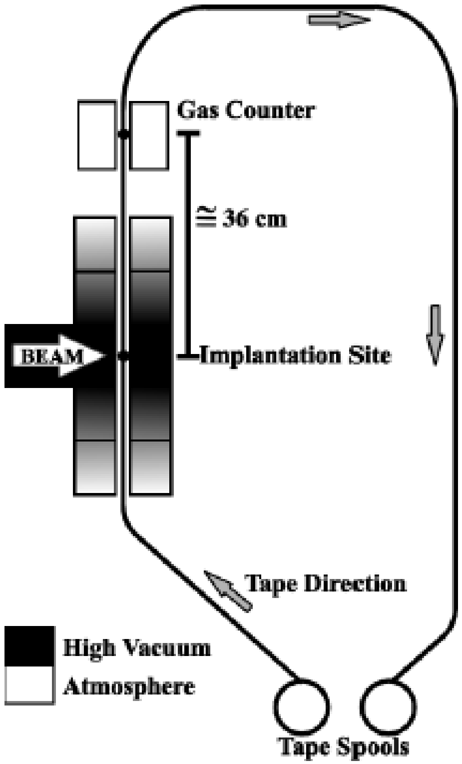
Example of precision lifetime measurement

TRIUMF

$^{26}Al^{m}$ decay

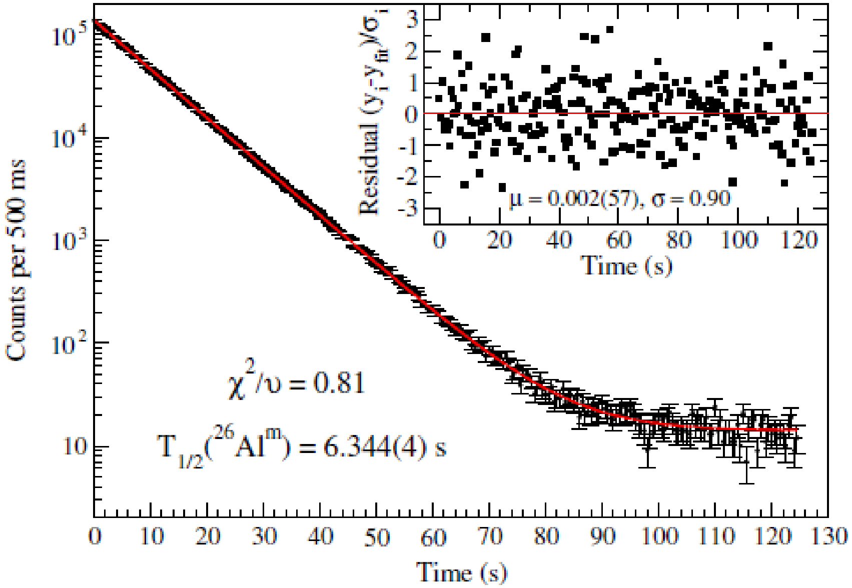
P. Finlay et al. PRL 106 (2011) 032501

$^{26}Al^{m}$ selectively separated by laser ionization and implanted into tape



(P. Finlay PhD, U. Guelph 2012)

Count β+ particles integrated over energy.

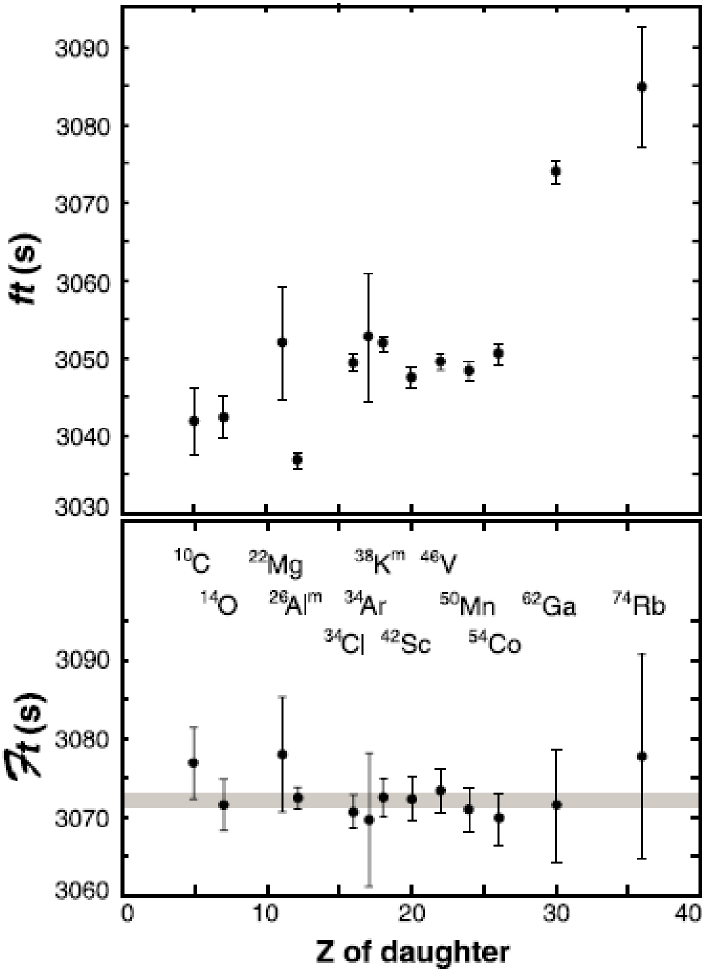


- Final precision of 1.2×10^{-4}
- The most precisely determined *ft*-value

(see Alex Laffoley poster for ^{14}O)

Systematic of pure Fermi transitions

Towner and Hardy, Rep.Prog.Phys. 73 (2010) 046301



$$ft = \frac{K}{G'^2_V \left|M_V\right|^2}$$

should be constant

Corrections need: nuclear theory crucial!

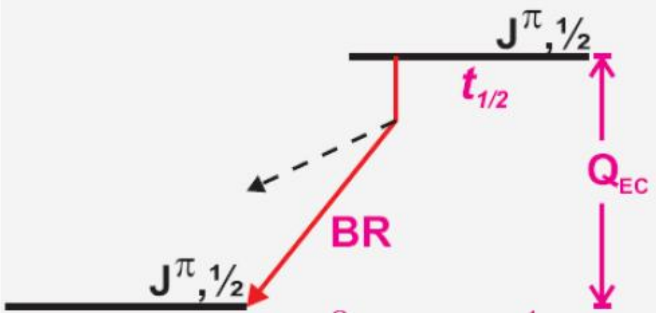
$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

- δ'_R : nucleus dependent radiative correction (QED) (Z, Q_{EC})
- δ_c : Isospin symmetry breaking correction
- δ_{NS} : Nuclear structure correction (small)

(All terms in the lhs refer to a given transition; all those in the rhs are constants)

Constancy of Ft-values verified at few 10^{-4} level

Experimental inputs for mirror transitions



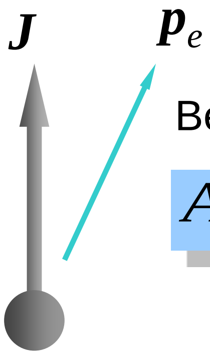
- In contrast to pure Fermi transitions, mirror transitions are mixed (V and A)

$$\mathcal{F}t_0 = \underbrace{\mathcal{F}t C_V^2 |M_F^0|^2}_{\text{Similar to } 0^+\to0^+ \text{ transitions}} [1 + (f_A/f_V)\rho^2],$$

“Mixing ratio”

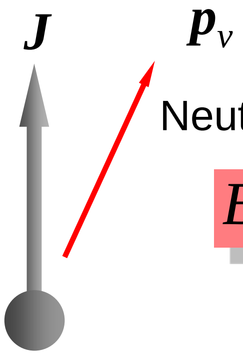
$$\rho \approx C_A M_{GT} / C_V M_F$$

- The GT/F mixing ratio cannot be determined accurately from theory
- Needs an additional experimental input



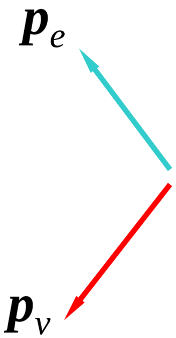
Beta asymmetry

$A_\beta \to \rho$



Neutrino asymmetry

$B_\upsilon \to \rho$



$\beta\nu$ angular correlation

$a_{\beta\upsilon} \to |\rho|$

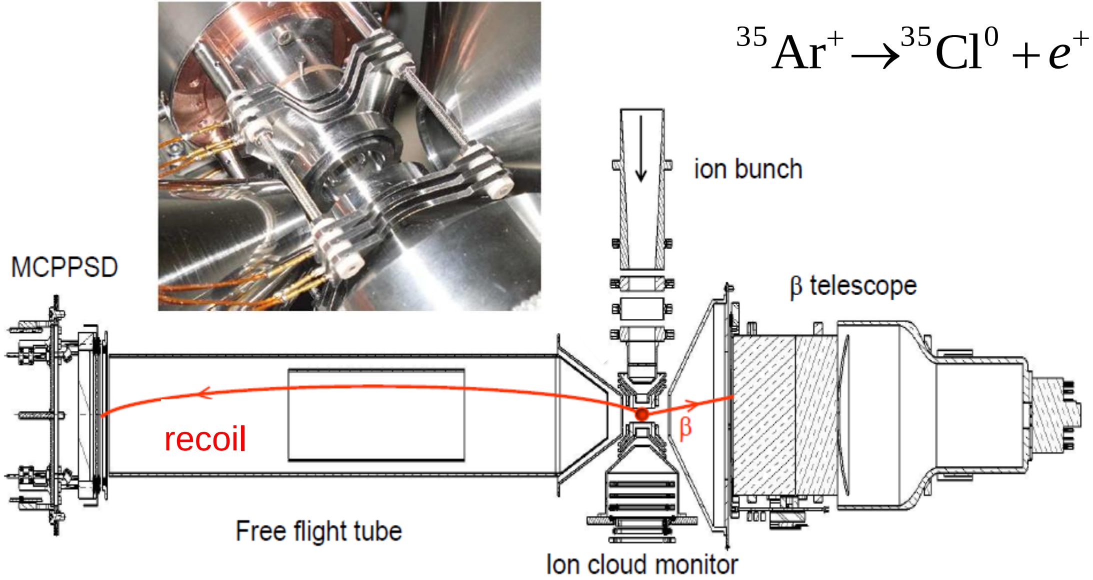
Measurement of *a* in ^{35}Ar decay

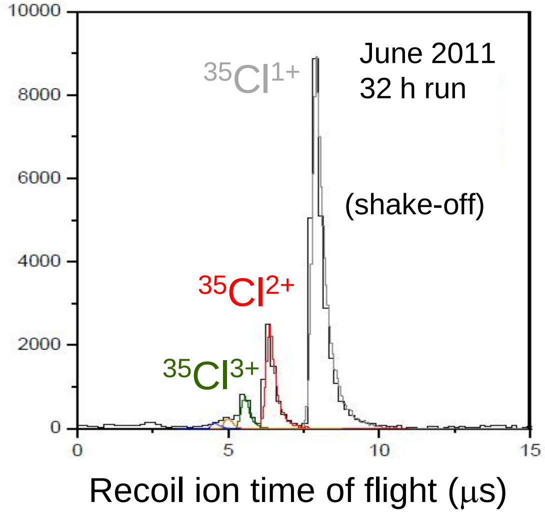
- Deduce βν correlation from detection of recoil ions in coincidence with β particles, from $^{35}Ar^{+}$ decays in a Paul trap.

$$a\left(\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_eE_\nu}\right)$$

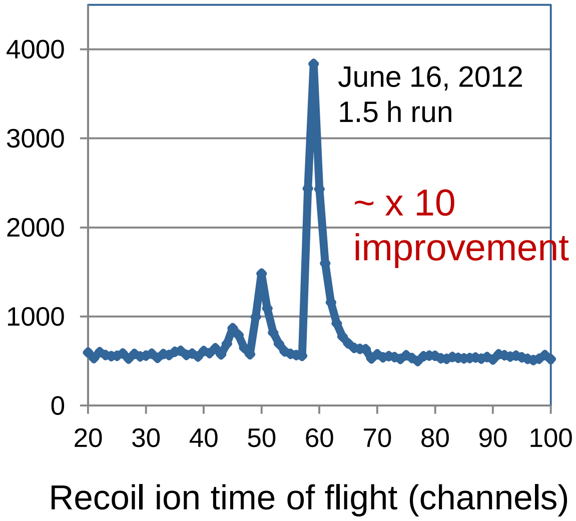
$$^{35}\mathrm{Ar}^{+}\rightarrow{}^{35}\mathrm{Cl}^{0}+e^{+}+\nu_e$$

LPCTrap@GANIL





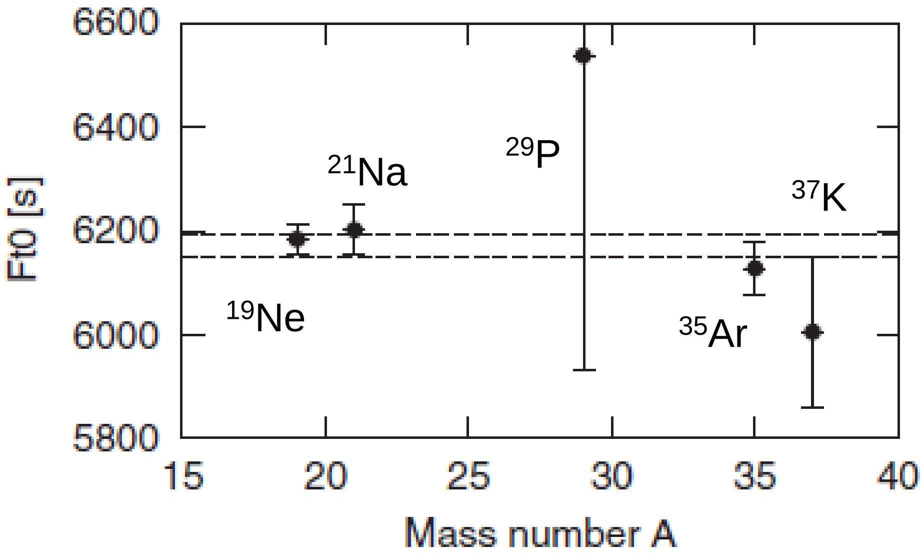
Courtesy: E. Lienard



Total collected statistics corresponds to $\Delta a/a$ < 0.5 %

Systematic of mirror transitions

O. N-C and N. Severijns, PRL 102 (2009) 142302

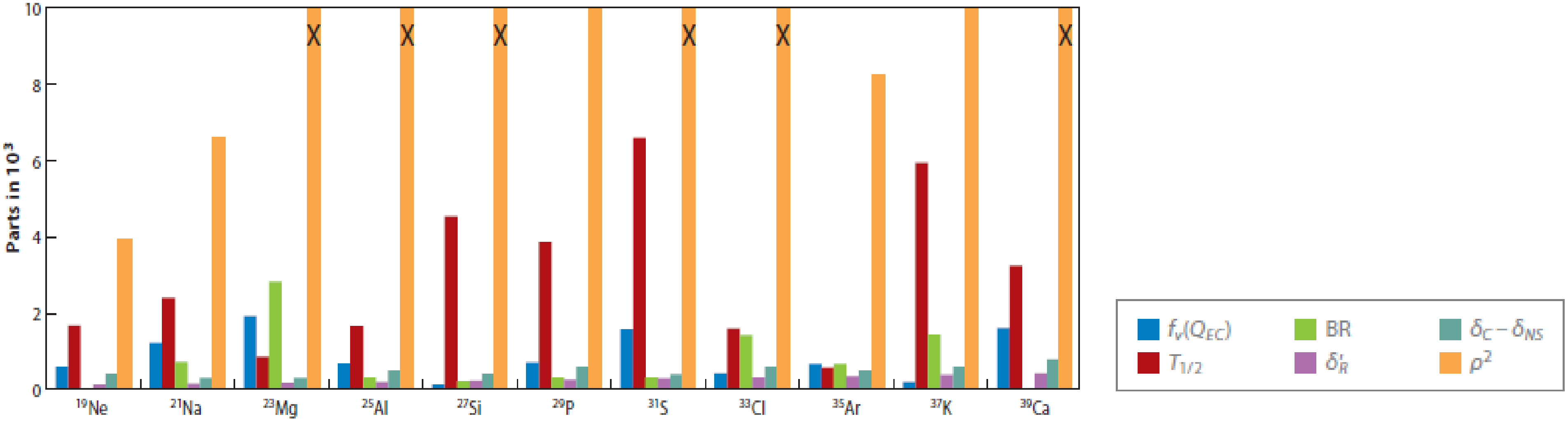


$$Ft_0 = 2Ft(\,0^+ \rightarrow 0^+\,)$$

- First consistent test of the constancy of Ft-values in a set of nuclear transitions other than super-allowed pure Fermi

Error budget and new efforts

N. Severijns and O.N-C, Annu.Rev.Nucl.Part.Sci. 61 (2011) 23



- ^{19}Ne: τ, a TUNL@KVI, TRIUMF, LPC-Caen
- ^{21}Na: τ, A TUNL@KVI, NSCL
- ^{29}P: τ CENBG@JYFL
- ^{31}S: τ, Br CENBG@JYFL
- ^{35}Ar: a LPC-Caen
- ^{37}K: τ, A TUNL@KVI, NSCL
- ^{39}Ca: τ CENBG@ISOLDE

Status of CKM unitarity

- With V_{ud} from nuclear transitions and V_{us} from *K* decays one tests the CKM unitarity on the first row

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990(60)$$

Towner and Hardy, Rep.Prog.Phys. 73 (2010) 046301

- Is the most stringent test of unitarity of CKM, (although it does not probe the imaginary phases)

- Provides tight constraints on “new physics” beyond SM

Take away

- Nuclear transitions offer many advantages for the determination of V_{ud} as compared to n and π decays:

  - Very high precision experiments are possible (Penning trap mass spectrometers; high efficiency γ multi-detectors arrays; high selectivity sources for lifetime measurements,…)
  - Many candidates available: consistency checks

- A robust data set has been collected for pure Fermi transitions: provides the most stringent test of CKM unitarity.

- Mirror transitions opened a new window extending the set of nuclei. New, high quality, data started to be collected recently.

- Input from theory is crucial (corrections) for further progress.

Readings

- *Weak Interactions of Leptons and Quarks*,
E.D. Commins and P.H. Bucksbaum,
Cambridge University Press, 1983

- *Tests of the standard electroweak model in nuclear beta decay,*
N. Severijns, M. Beck, O. Naviliat-Cuncic,
Rev. Mod. Phys. 78 (2006) 991

- *The evaluation of V_{ud} and its impact on the unitarity of the Cabibbo–Kobayashi–Maskawa quark-mixing matrix,*
I.S. Towner and J.C. Hardy,
Rep. Prog. Phys. 73 (2010) 046301