Correlation measurements in nuclear β-decay

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context and scope

context

• searches for signatures of new physics at low energies (any place where improvements of sensitivity are possible and SM "backgrounds" are small)

• tests of the SM ? …foundations: discrete symmetries

scope

• review selected achievements and ongoing projects worldwide

• consider only nuclear beta decay experiments (exclude neutron decay: same physics ! ↔ other production techniques / ISOLDE; exclude muon decay)

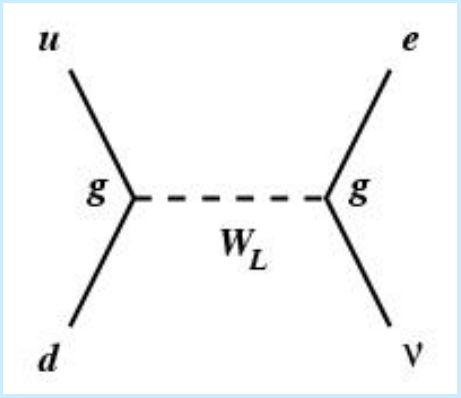
plan

1. phenomenology
2. searches for TRI exotic interactions
3. searches for TRV interactions

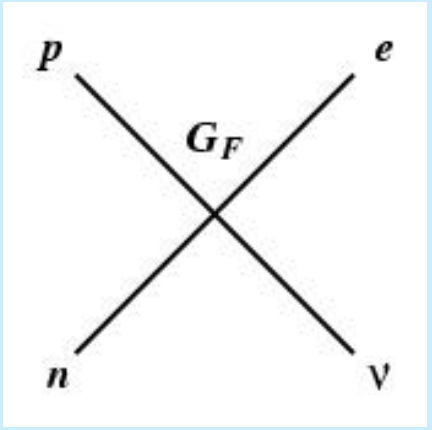
1. phenomenology of allowed β-decay

- within the SM $d \rightarrow u + e^- + \bar{\nu}_e$

(tree level)



at low momentum transfer: 4 fermion interaction



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

- beyond the SM

$$\mathcal{H}_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \sum_i (\bar{\psi}_p \mathcal{O}_i \psi_n)(\bar{\psi}_e \mathcal{O}_i (C_i + \gamma_5 C_i') \psi_\nu) \; + \; hc.$$

i = *S*, *P*, *V*, *A*, *T* Lorentz invariants

C_i and C'_i : relative amplitudes
(determined by experiments)

- standard couplings: Vector, Axial
- "exotic" couplings: Scalar, Tensor

signatures of new physics:

- presence of exotic couplings
- symmetry violations

constraints on exotic couplings

- within the SM

$$C_A/C_V \approx -1.27$$

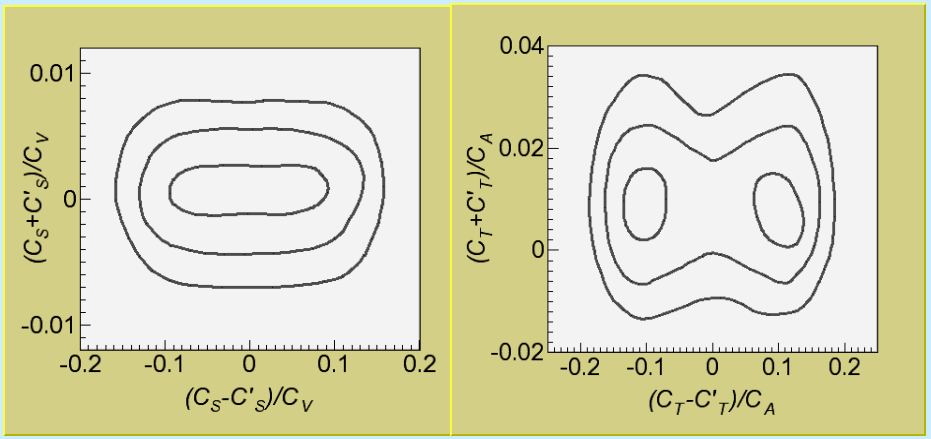
$$C_S = C'_S = C_T = C'_T = 0$$

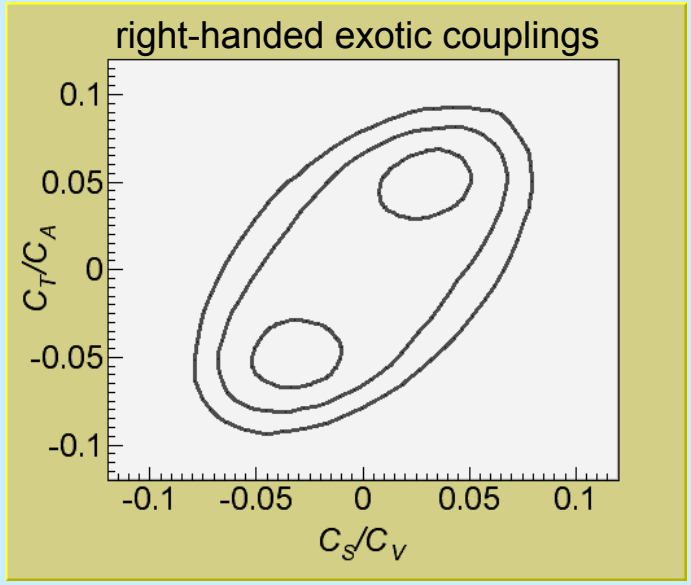
- constraints from precision experiments

N. Severijns, M. Beck, O. Naviliat-Cuncic, submitted to Rev.Mod.Phys.

(excluding neutron lifetime measurement by A. Serebrov *et al.* 2005)

sums and differences of couplings





sizable room to accommodate exotic interactions without affecting SM conclusions

2. time reversal invariant exotic interactions

- β–ν angular correlation

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

requires to measure the recoil ion

- within the SM

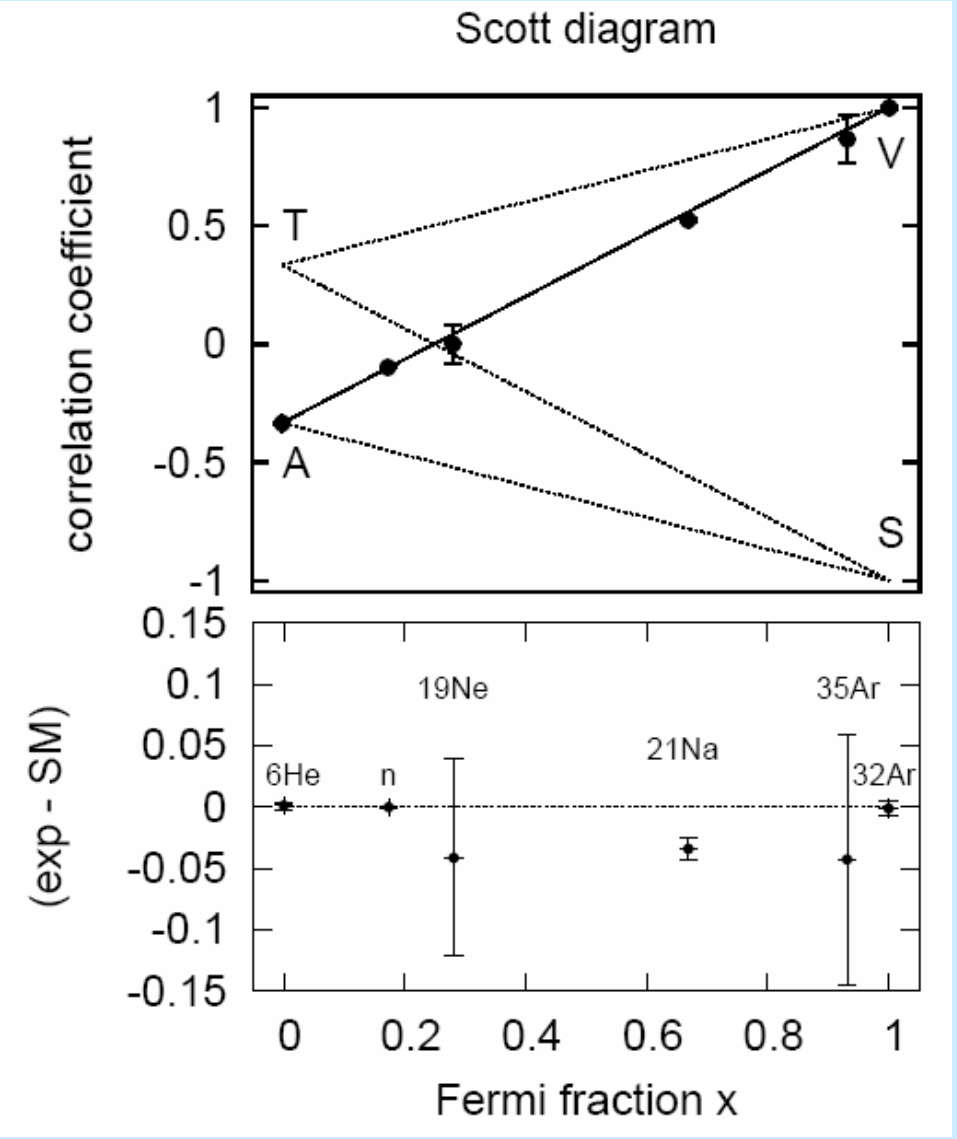
$$a_0 = \frac{1}{3}\left(\frac{3-\rho^2}{1+\rho^2}\right) = \frac{1}{3}(4x-1)$$

x : Fermi fraction; ρ : GT/F mixing ratio

- beyond the SM

$$a \approx a_0(1-\alpha)$$

α contains quadratic *S* and *T* contributions



scalar couplings…

ISOLDE achievements: ^{32}Ar

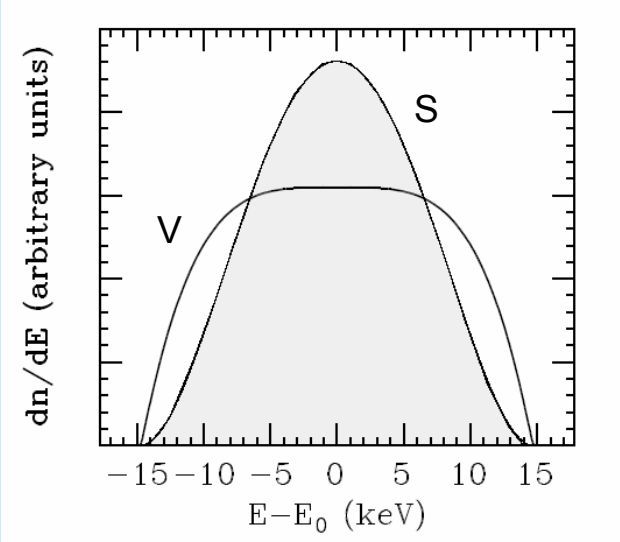
- principle

$$^{32}Ar \rightarrow {}^{32}Cl^{*} + \beta^{+} + \nu_e$$

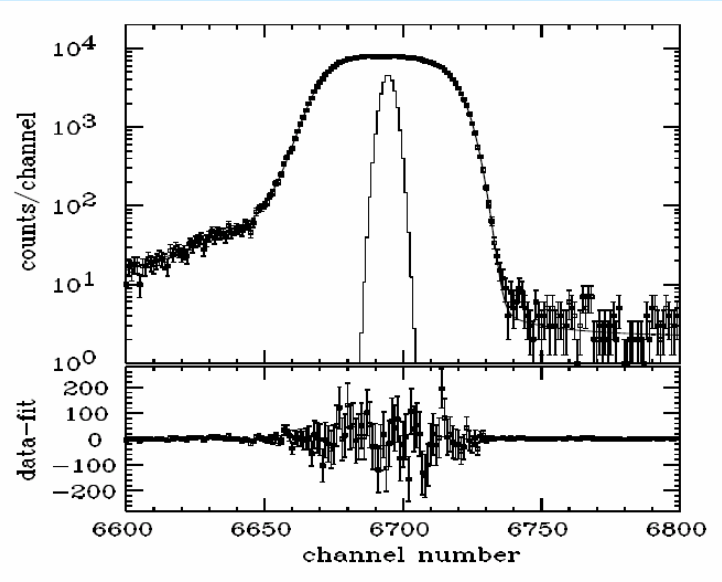
$$^{32}Cl^{*} \rightarrow {}^{31}S + p$$

the information on the recoil is transferred to the proton

kinematic broadening of β-delayed proton



- experimental proton energy spectrum



$\tilde{a}$ = 0.9989(65) consistent with a_0 = 1

Adelberger *et al.*, PRL **83** (1999) 1299

required precision mass measurement of ^{32}Ar to extract robust limits on scalar couplings

ISOLTRAP ($\Delta m/m = 6.0\times10^{-8}$)

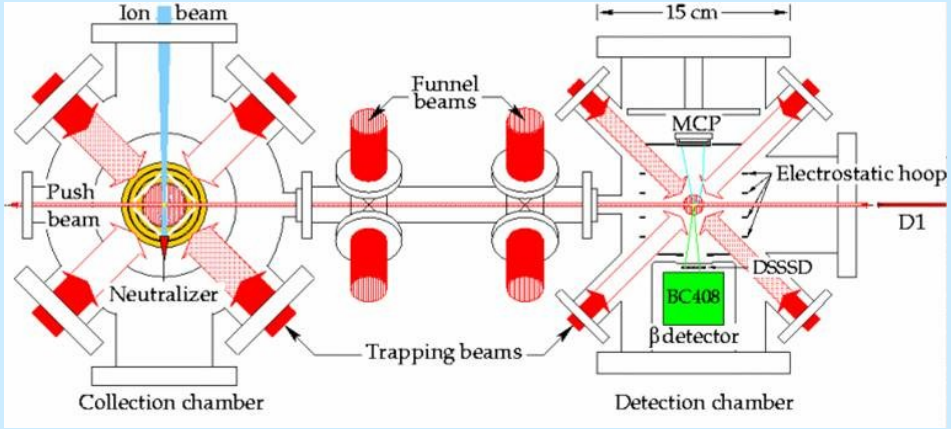
Blaum *et al.*, PRL **91**(2003) 260801

^{38m}K in a MOT (TRIUMF)

- new generation experiments

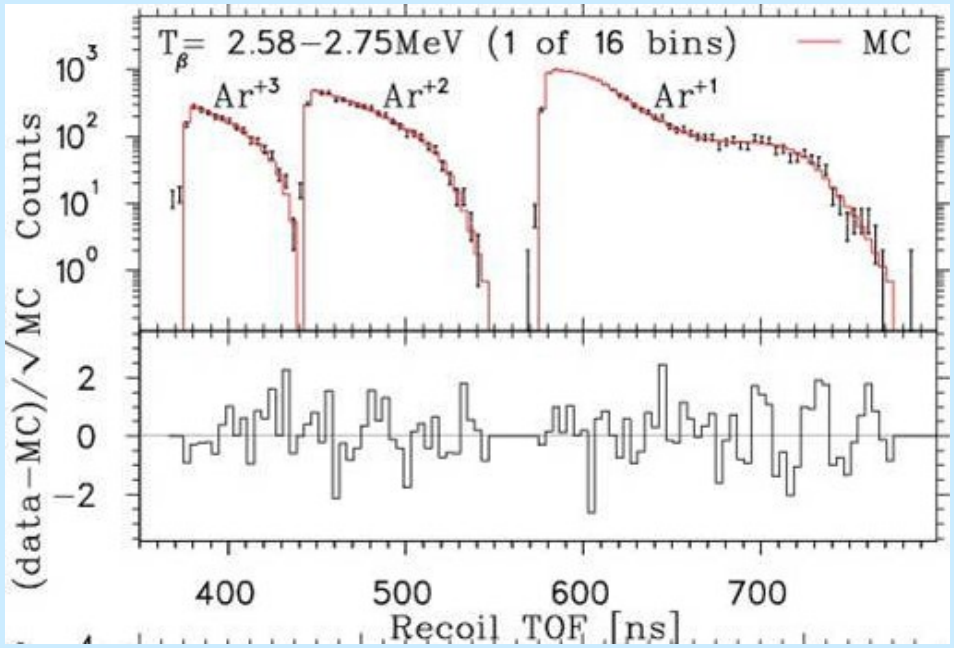
  direct detection of recoils (traps)

  TRIUMF Neutral Atom Trap at ISAC



- preparation MOT
  - implantation in Zr foil neutralizer
  - 900 C heating, release
  - 10^{-3} capture efficiency; 75% transfer efficiency
- measurement MOT
  - beta and ion detectors

- measured β-ion TOF spectra / MC



Gorelov *et al.*, PRL **93** (2005) 142501

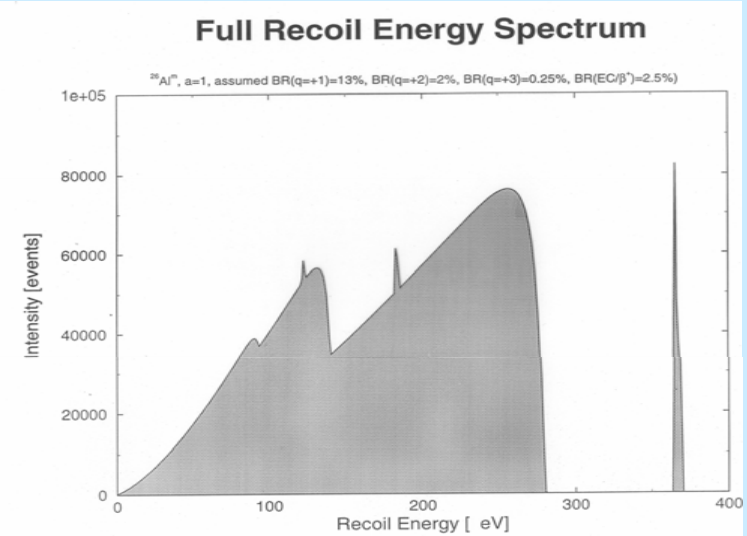
$\tilde{a}$ = 0.9978 (48) consistent with a_0 = 1

(also included in the 2005 review)

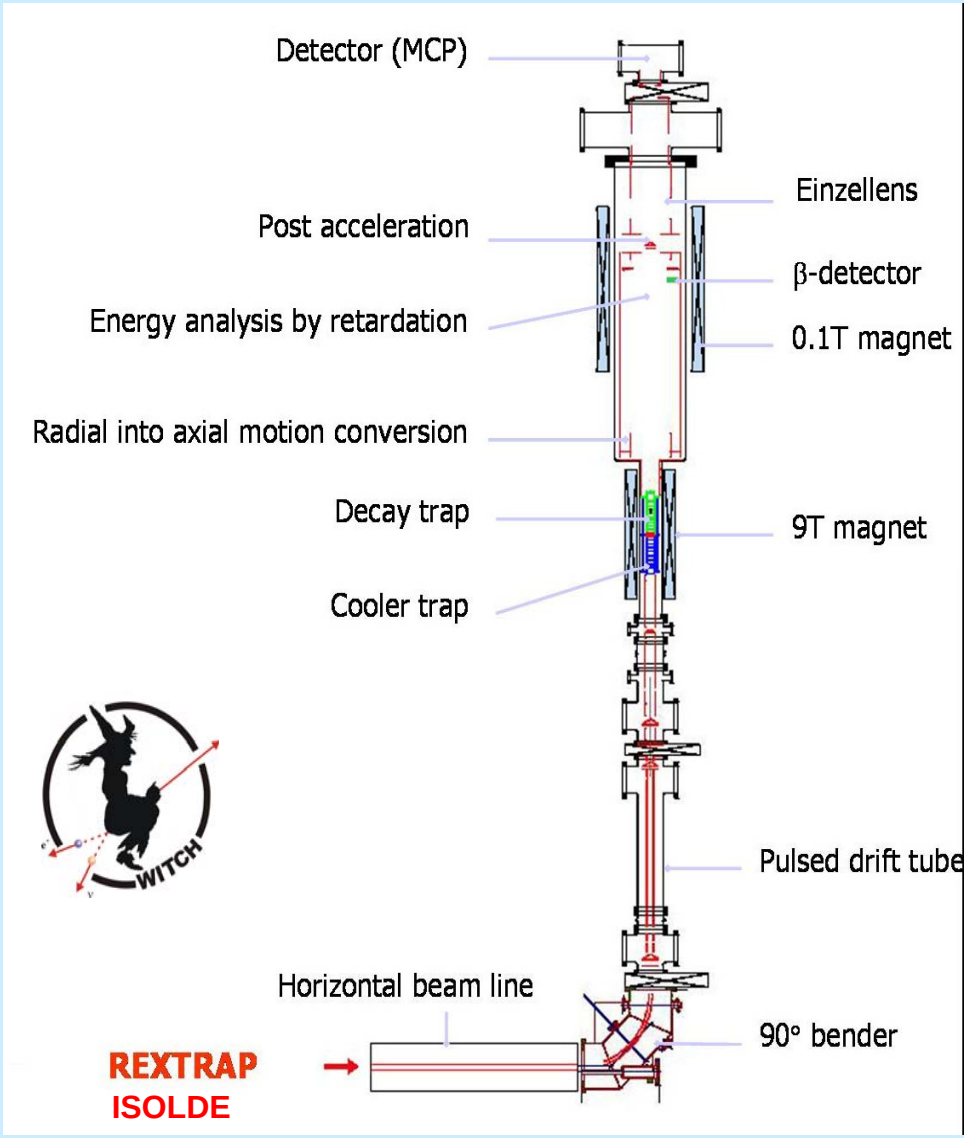
^{35}Ar in a Penning trap (ISOLDE)

- WITCH (Leuven)
  - cooler and decay Penning traps
  - retardation spectrometer

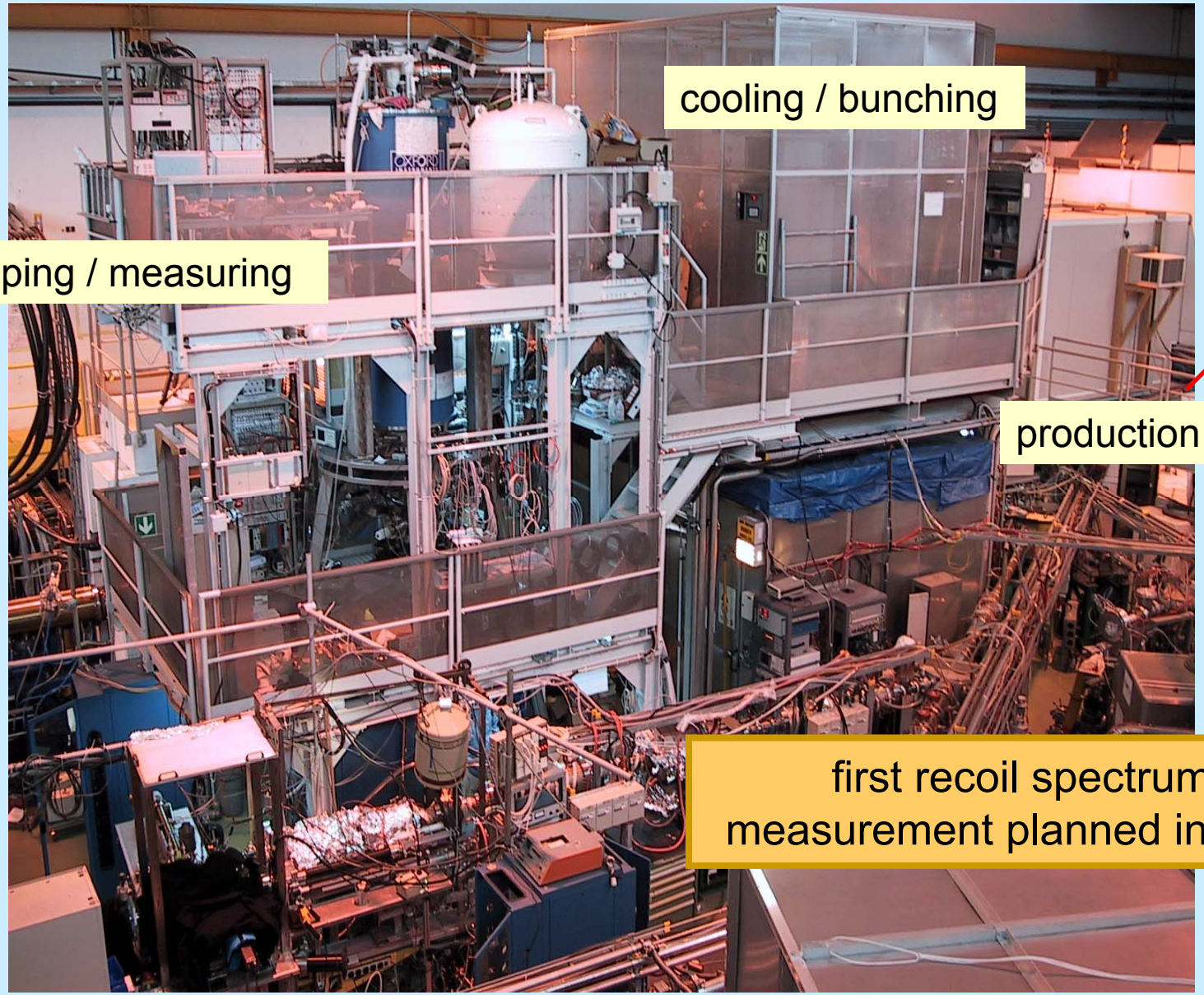
will measure recoil ions
in singles; in sequence



a deduced from shape of energy spectrum



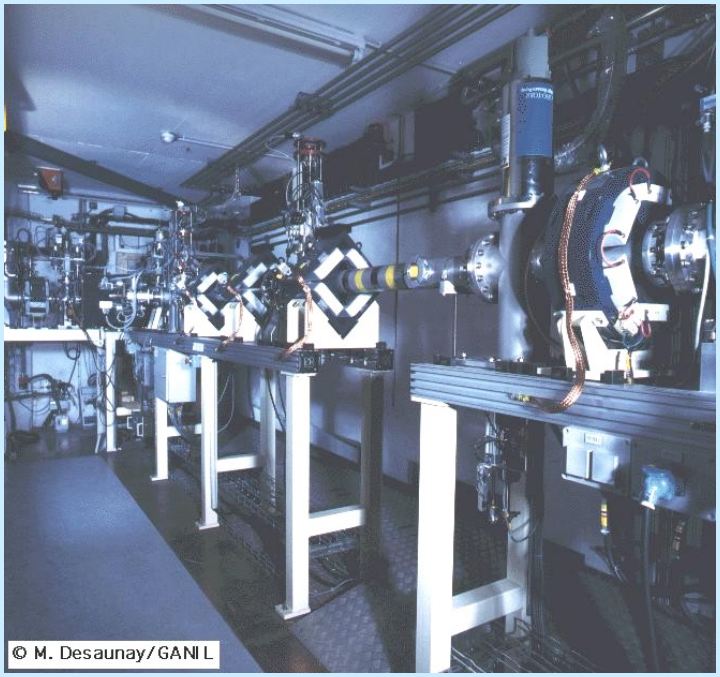
^{35}Ar in a Penning trap (ISOLDE)



tensor couplings…

^{6}He in a Paul trap (GANIL)

production of ^{6}He (SPIRAL TSS)



LIRAT low energy line

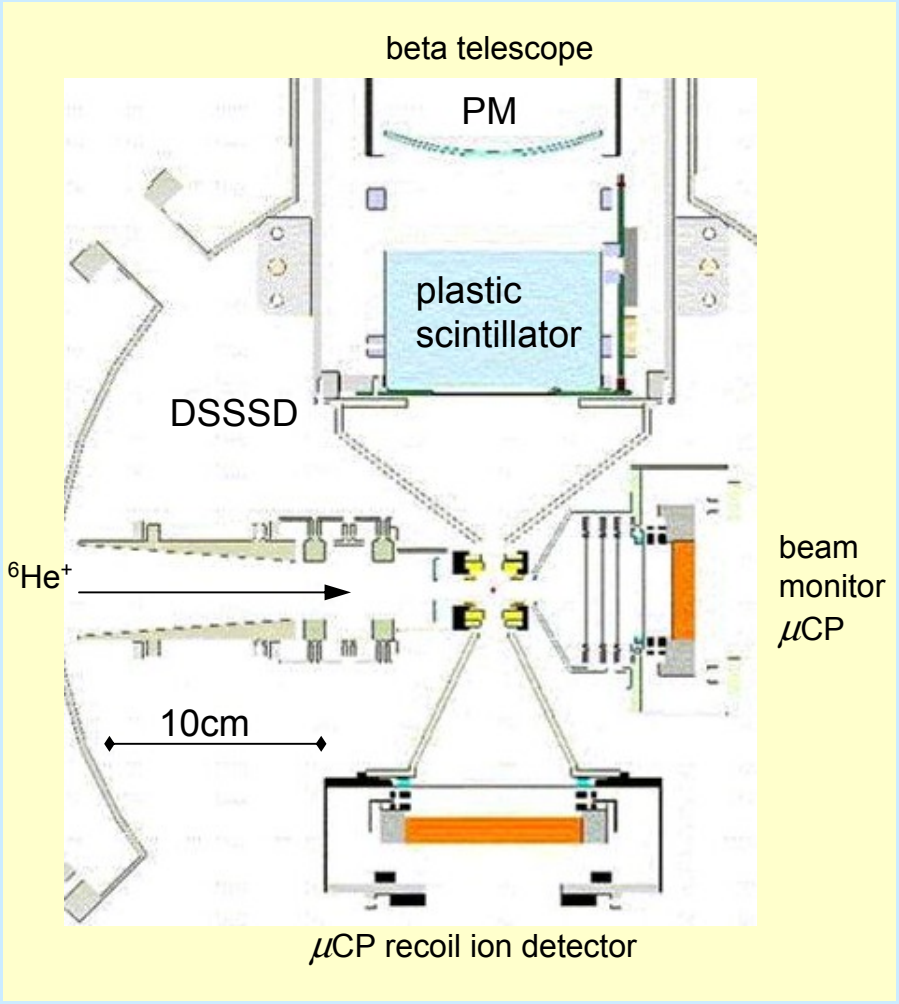
cooling (H_2)/ bunching

trapping / measuring

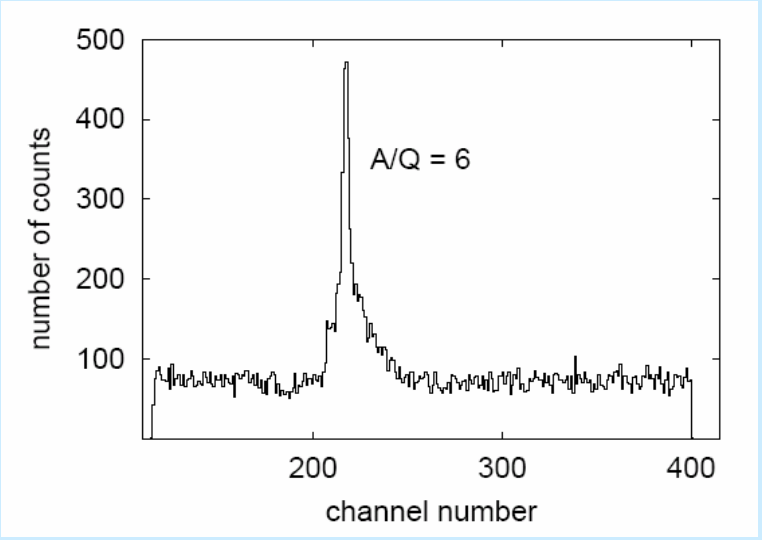
table top experiment

^{6}He in a Paul trap (GANIL)

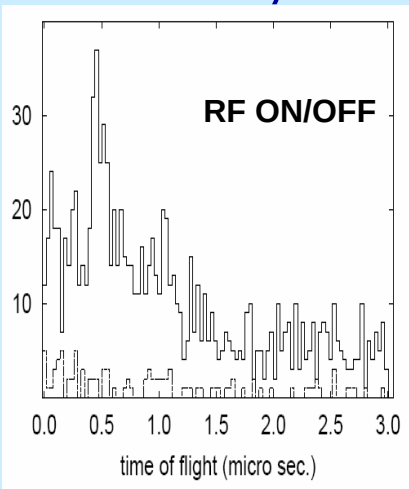
$$^6\mathrm{He} \rightarrow {}^6\mathrm{Li} + e^- + \bar{\nu}_e$$

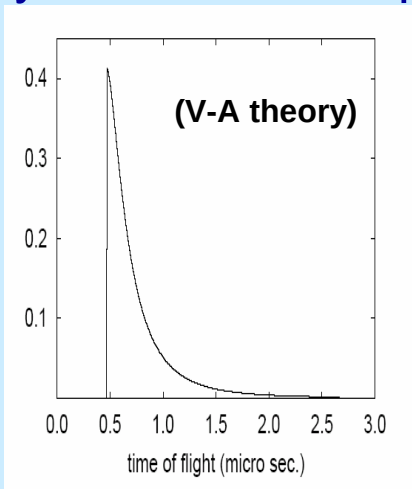


- TOF of ions extracted from the trap



- First direct β-decay from an ion trap



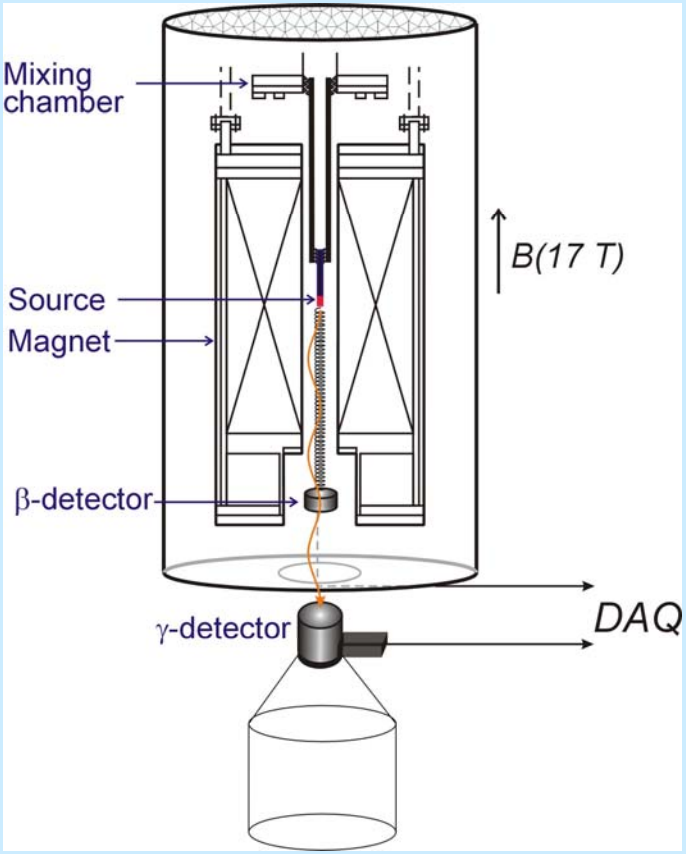


GT decays implanted (KUL/ISOLDE)

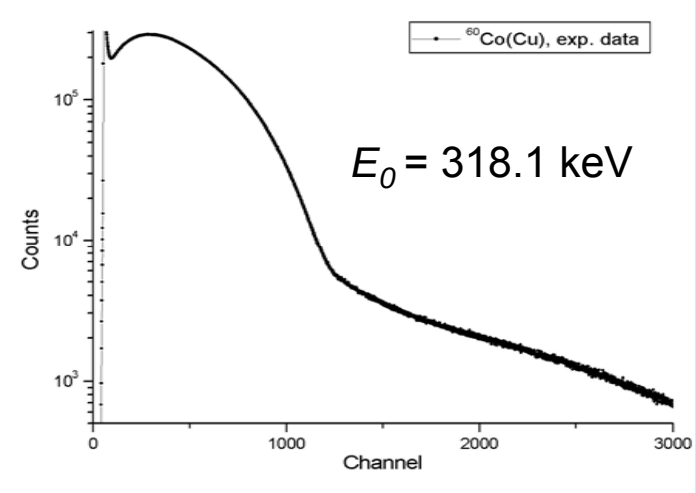
modern variants of Mme Wu experiment $A\ (\mathbf{J}\cdot\mathbf{p_e})/E_e$ needs polarized nuclei

Low Temperature Nuclear Orientation

- Long-lived nuclei (KUL setup)



control/study of apparatus with ^{60}Co source



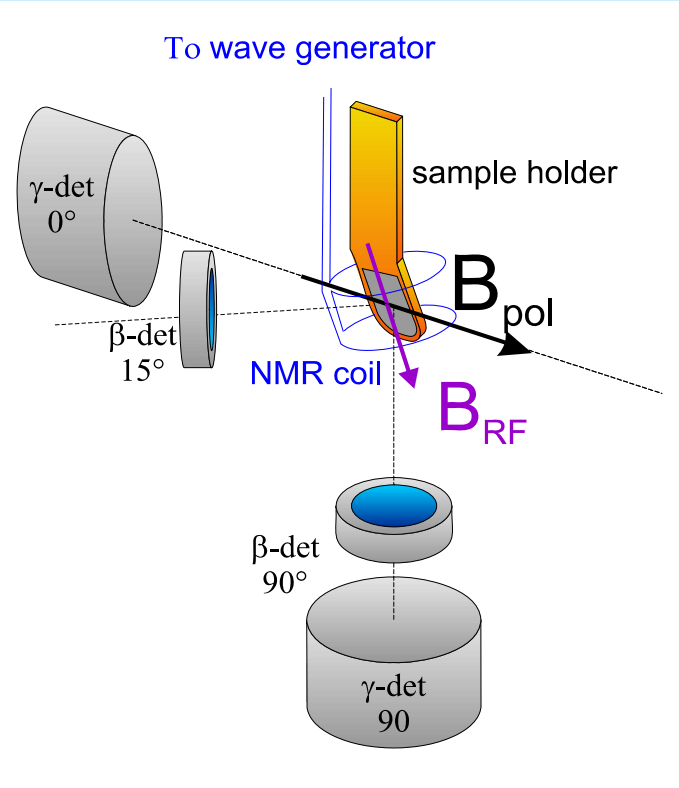
proposal for a measurement in ^{133}Xe decay with < 0.01 precision

GT decays implanted (KUL/ISOLDE)

Low Temperature Nuclear Orientation

- Short-lived nuclei

needs implantation on-line: NICOLE station



proposal for **relative** and **absolute** measurements in several decays:

^{79}Kr, ^{85m}Kr / ^{67}Cu, ^{82g}Br, ^{83}Br

with < 0.01 precision

requires careful control of nuclear polarization and/or experimental geometry

^{82}Rb, ^{118}Sb and GEANT4 simulations

others

- ^{6}He decay in flight (RIKEN)
- polarized ^{82}Rb decay in MOT (LANL)

rich diversity of tools and techniques
worldwide in small size experiments

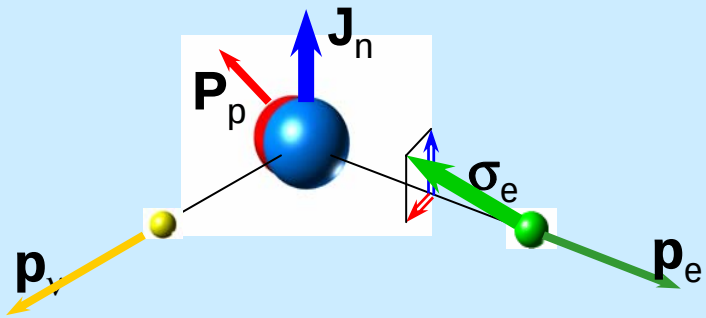
3. time reversal violating interactions

- CP is known to be violated (*K* and *B* decays) and the results appear to be accommodated within the SM: flavor mixing
- new mechanism of CP-violation appear in several SM extensions
- in CPT invariant models: CP-violation = T-violation
- in systems or processes without strangeness, the effects due to the CKM CP-violation are strongly suppressed (nEDM < 10^{-31}; beta decay correlations <10^{-10})
- **Large window to search for new physics**

  ...provided that other SM backgrounds are under control (FSI)

TRV correlations in β-decay

kinematic vectors



R : P-odd T-odd

D : P-even T-odd

$$R\ \boldsymbol{\sigma}_e \cdot (\mathbf{J} \times \mathbf{p_e})/E_e$$

$$D\ \mathbf{J} \cdot (\mathbf{p_e} \times \mathbf{p}_\nu)/E_e E_\nu$$

probe different interactions

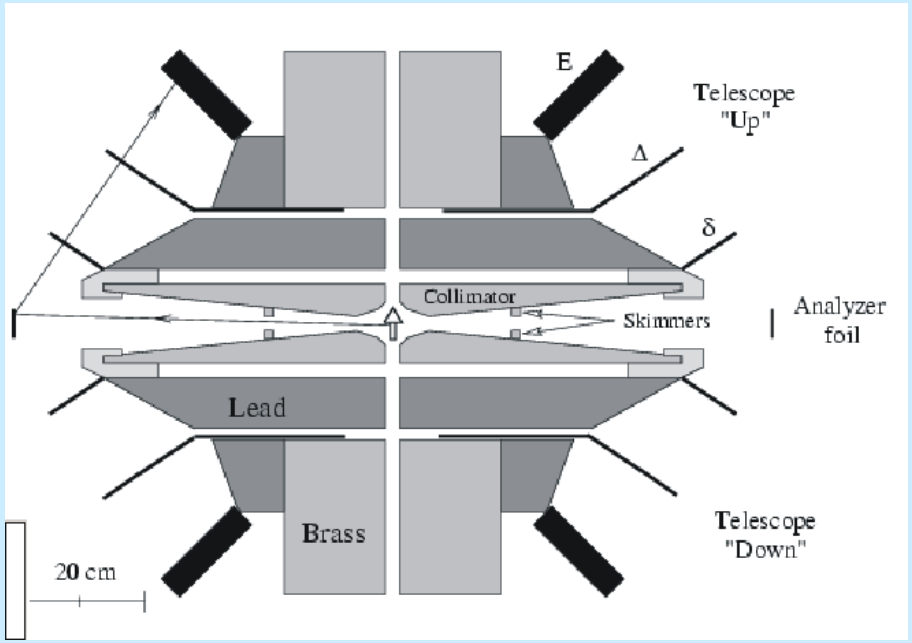
$R_{exp} = R_{TRV} + R_{FSI}$

$D_{exp} = D_{TRV} + D_{FSI}$

^{8}Li implanted (PSI)

$$R_{TRV}^{GT} \propto Im(C_T C_A'^* + C_T' C_A^*)$$

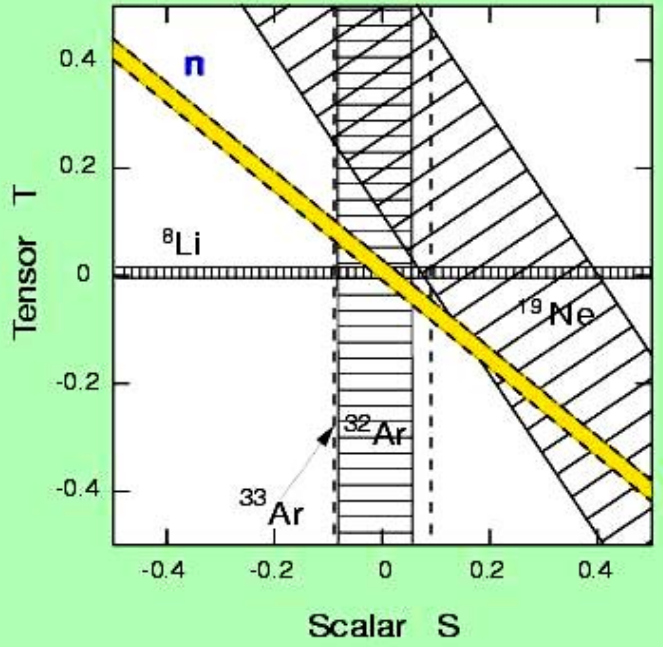
$$R\,\boldsymbol{\sigma}_e \cdot (\mathbf{J} \times \mathbf{p_e})/E_e$$



- polarized ^{8}Li produced by polarization transfer from a polarized *d* beam
- LHe cooled target in low magnetic field
- analyze transverse electron polarization by Mott scattering on Pb
- measure asymmetries under beam spin flip

- **Result** Huber *et al.*, PRL **90** (2003) 202301

$$R_{TRV} = (0.9 \pm 2.2) \times 10^{-3}$$

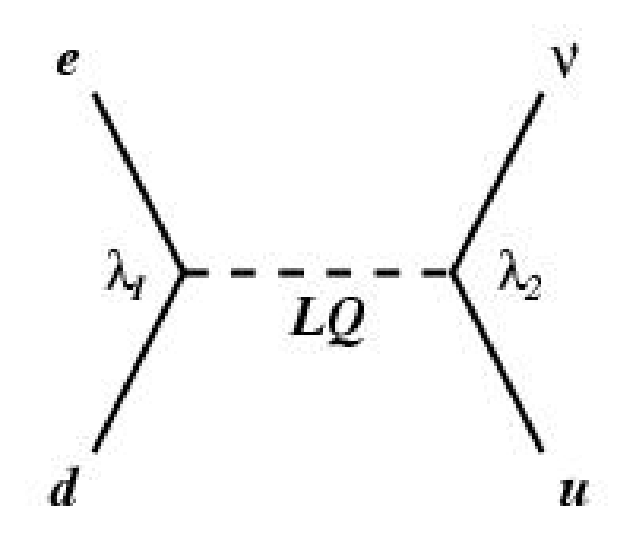


constraint on LQ mass scale

- leptoquark exchange

  bosons which induce quark-lepton transitions

  - carry lepton and baryon numbers
  - have fractional |Q| = 1/3, 2/3 charges
  - have spin J = 0,1 (in minimal extensions)



- assuming standard couplings:

$$\lambda_1 = \lambda_2 = g_{LQ} \text{ and } g_{LQ}^2/4\pi = 1/137$$

M_{LQ} > 560 GeV (90% CL)

Huber *et al.*, PRL **90** (2003) 202301

- direct searches:

M_{LQ} > 200-300 GeV

Eidelman *et al.* , (PDG) PLB **592** (2004) 1

complementarity between low energy experiments and direct searches

^{21}Na plans in MOT (KVI)

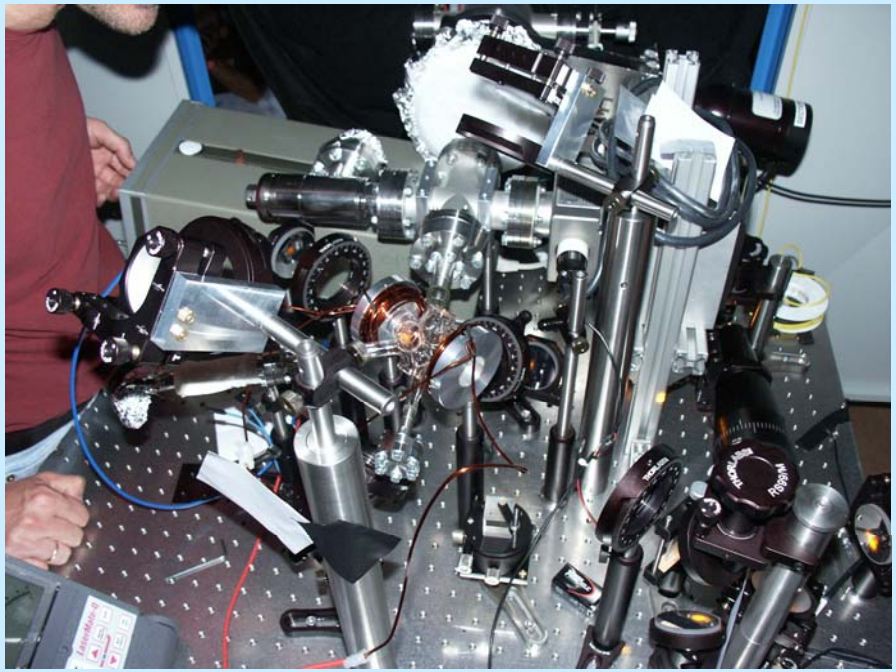
$$D_{TRV} \propto Im(C_V C_A^* + C_V' C_A'^*)$$

- reference measurement: ^{19}Ne

$$D_{TRV} = (0.4 \pm 0.8) \times 10^{-3}$$

(Hallin *et al.*, PRL **52** (1984) 337)

- preparation of a double MOT setup (KVI)



Phase 1: unpolarized nuclei
- measure *a* at ≈ 10^{-3}

Phase 2: polarized nuclei
- measure *D*
- observe momentum dependence

to study FSI (≈ 10^{-4})

summary and outlook

- precision measurements at low energies offer a window to search for new physics, complementary to direct searches at high energies

- experiments at ISOLDE have significantly contributed to provide new constraints on exotic couplings

- the diversity of isotopes/intensities available near RIBs has resulted in a rich spectrum of tools/techniques worldwide

- the improvement/understanding of new tools (traps) require preparations over long time scales, with frequent access to the beam