Precision measurements in nuclear beta decay

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Scope and Outline

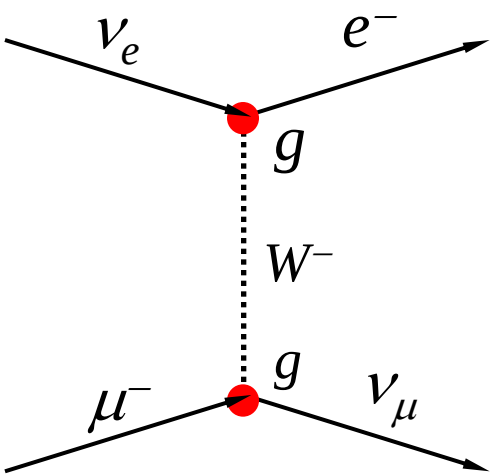
• Present recent results and discuss new projects in beta decay motivated by tests of fundamental symmetries and the searches for new interactions.

1. Determination of the effective weak coupling (V_{ud}) from nuclear mirror transitions
2. T-violating correlations in nuclear and neutron decays

V_{ud} from nuclear mirror transitions

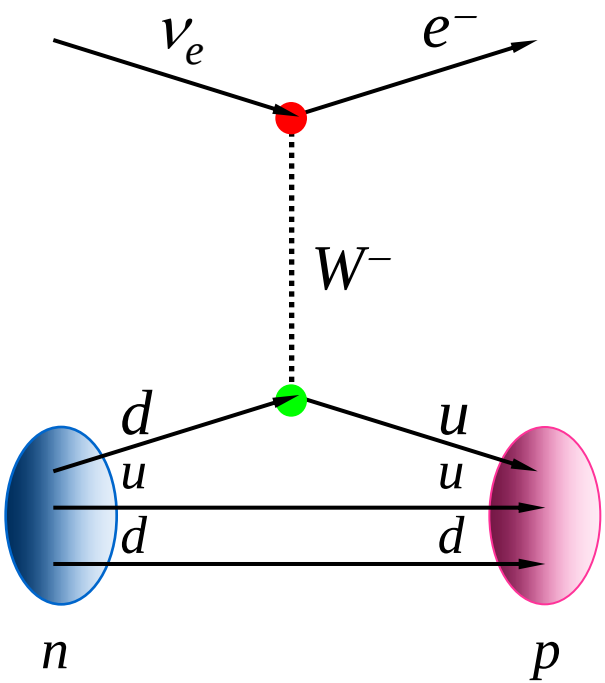
The strength of the weak interaction

μ-decay



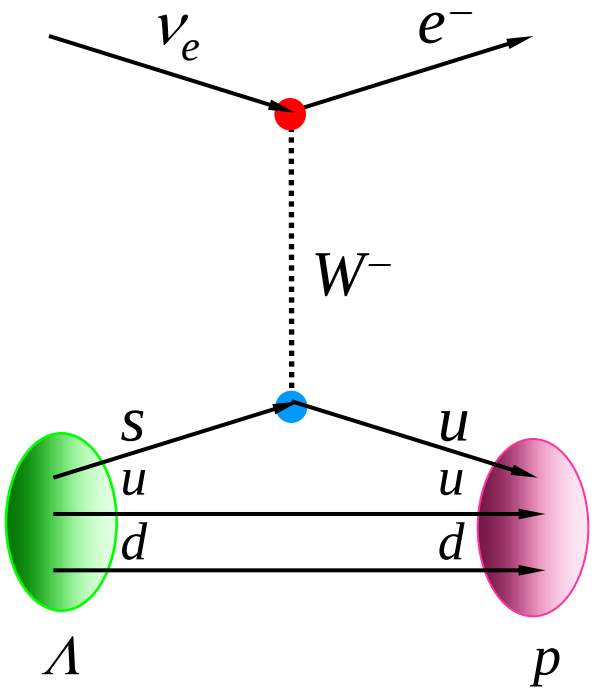
Pure leptonic

neutron decay



Semi-leptonic
(non strange)

Λ-decay



Semi-leptonic
(strange)

- Quark mixing with 2 generations → one new parameter: θ_C (Cabibbo angle)

$$G_\mu = G_F \propto g^2 \qquad G_V = G_F \cos\theta_C \qquad G_\Lambda = G_F \sin\theta_C$$

$(\theta_C \approx 13°)$

Quark mixing within the Standard Model

- 3 quark generations; weak interacting states are mixtures of mass eigen-states (CKM matrix):

$$\cos\theta_C = V_{ud} = G_V/G_F$$

- Determination of $|V_{ud}|$ from experiments (systems with *ud* quarks):

  - Nuclear super-allowed pure Fermi ($0^+ \rightarrow 0^+$) transitions (Vector)

  - Neutron decay (Vector and Axial) $n \rightarrow p + e^- + \bar{\nu}_e$

  - Pion beta decay (Vector) $\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$

  - Nuclear super-allowed isospin doublets (Vector and Axial)

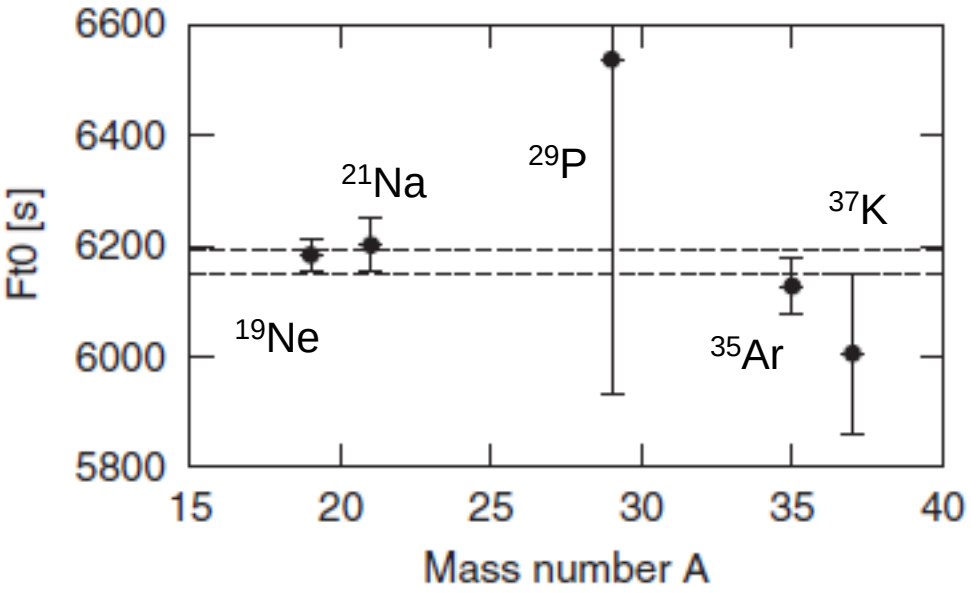
V_{ud} from T=1/2 mirror transitions

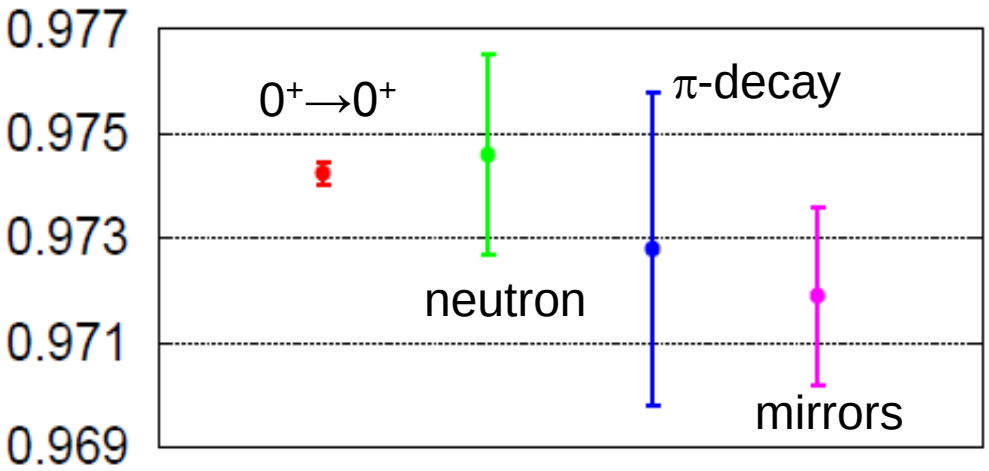
Decay rate corrected for:
- Phase space; branching ratio
- Radiative effects (EM and weak)
- Isospin and nuclear structure effects

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

- First consistent test of CVC in a set of nuclear transitions other than super-allowed pure Fermi

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





$$|V_{ud}| = 0.9719(17)$$

- Comparable precision to neutron for which dedicated experimental activity has been going on for more than 20 years.

Experimental difficulty

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

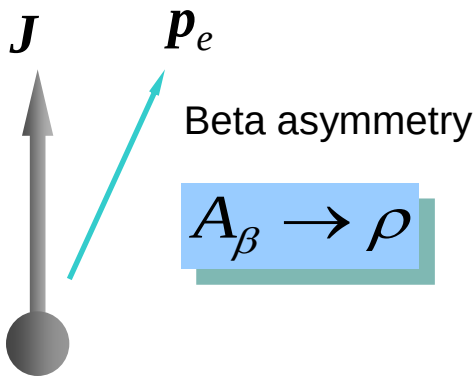
$$\mathcal{F}t_0 = \mathcal{F}tC_V^2|M_F^0|^2[1+(f_A/f_V)\rho^2],$$

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

Similar to $0^+ \rightarrow 0^+$ transitions

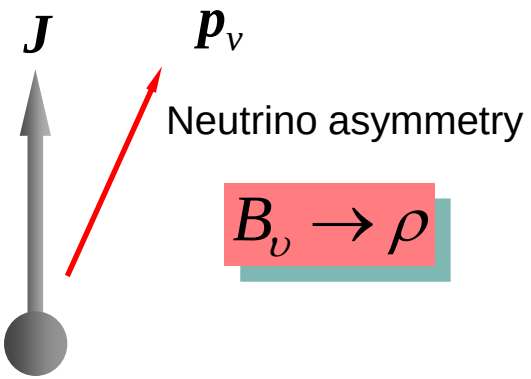
- Factorize the Vector contribution
- Determine the mixing ratio from experiments

- The GT/F mixing ratio has to be determined experimentally (correlations)



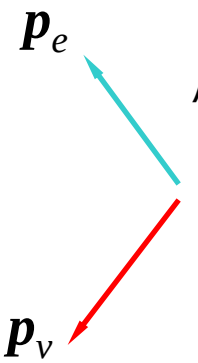
Beta asymmetry

$A_\beta \rightarrow \rho$



Neutrino asymmetry

$B_\upsilon \rightarrow \rho$

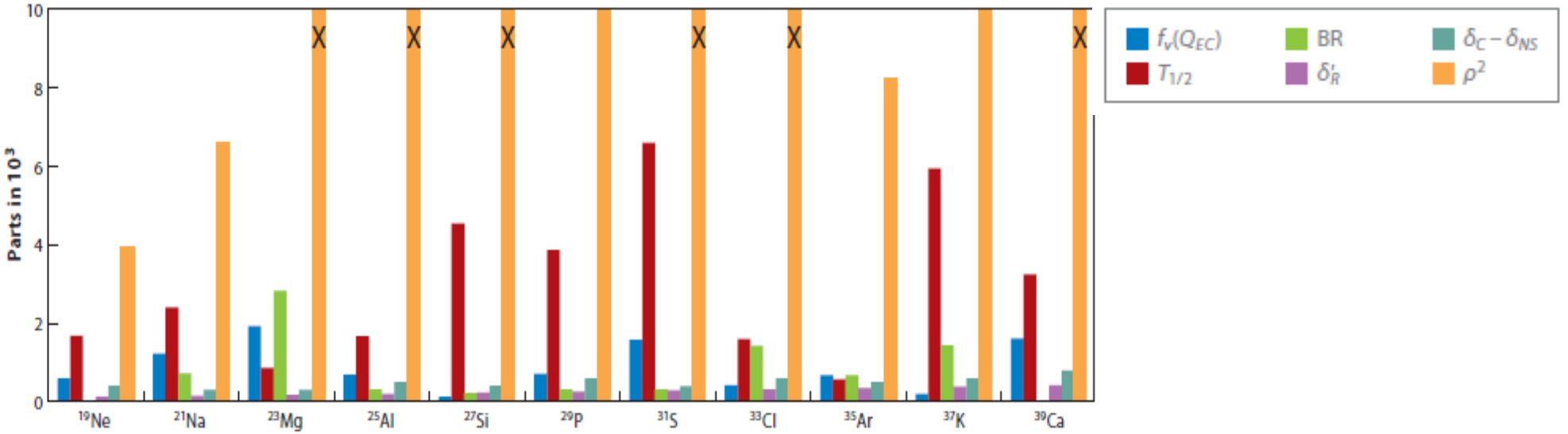


$\beta\nu$ angular correlation

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

Error budget and new efforts

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



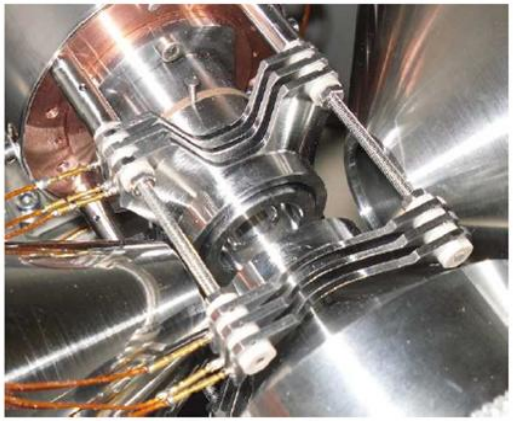
1st candidate in program

- ^{19}Ne: τ, TUNL@KVI and TRIUMF
- ^{21}Na: τ, TUNL@KVI
- ^{29}P: τ, CENBG@JYFL
- ^{31}S: τ, Br, CENBG@JYFL
- ^{37}K: τ, TUNL@KVI
- ^{39}Ca: τ, CENBG@ISOLDE
- …/…

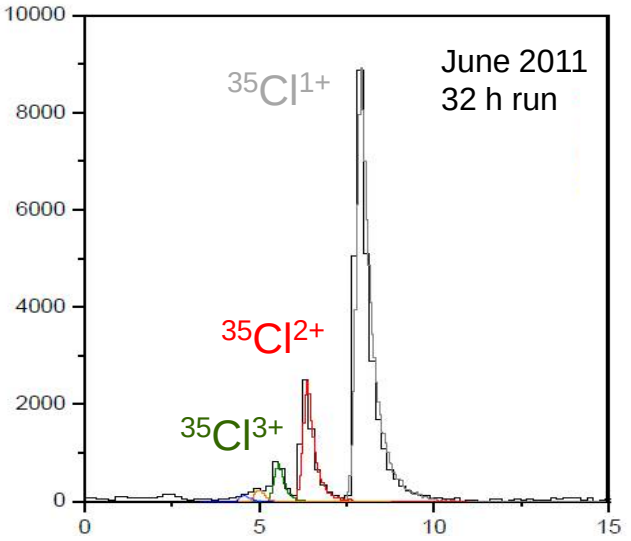
Measurement of a in ^{35}Ar decay

- Detection of β particles in coincidence with recoil ions, from decays in a Paul trap.

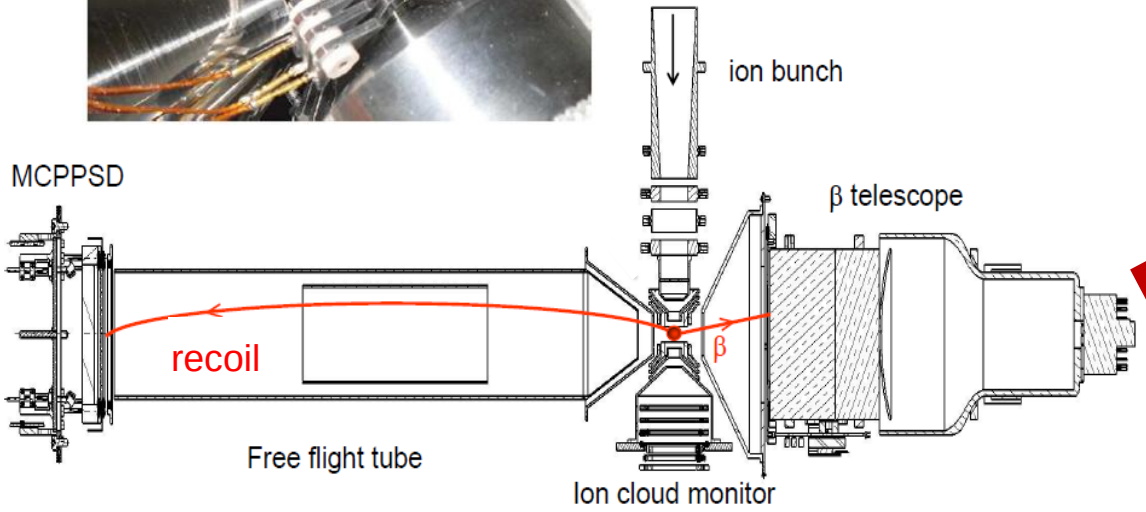
LPCTrap@GANIL



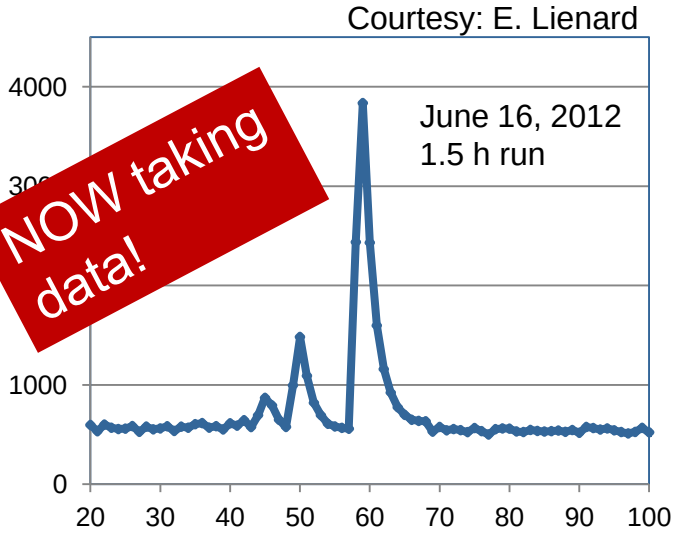
Statistics corresponds to $\Delta a/a$ ~1-2 %



Recoil ion time of flight (μs)



Courtesy: E. Lienard



Recoil ion time of flight (channels)

Searches for Time Reversal Violation (triple correlations)

TRV correlations in beta decay

P-even, T-odd correlation: $D\,\vec{J}\cdot(\vec{p}_e\times\vec{p}_\upsilon)/E_eE_\upsilon$

P-odd, T-odd correlation: $R\,\vec{\sigma}_e\cdot(\vec{J}\times\vec{p}_e)/E_e$

Do not probe the same physics

Phenomenology and complementarity with EDMs: T. Chupp talk (… now wait until Wednesday)

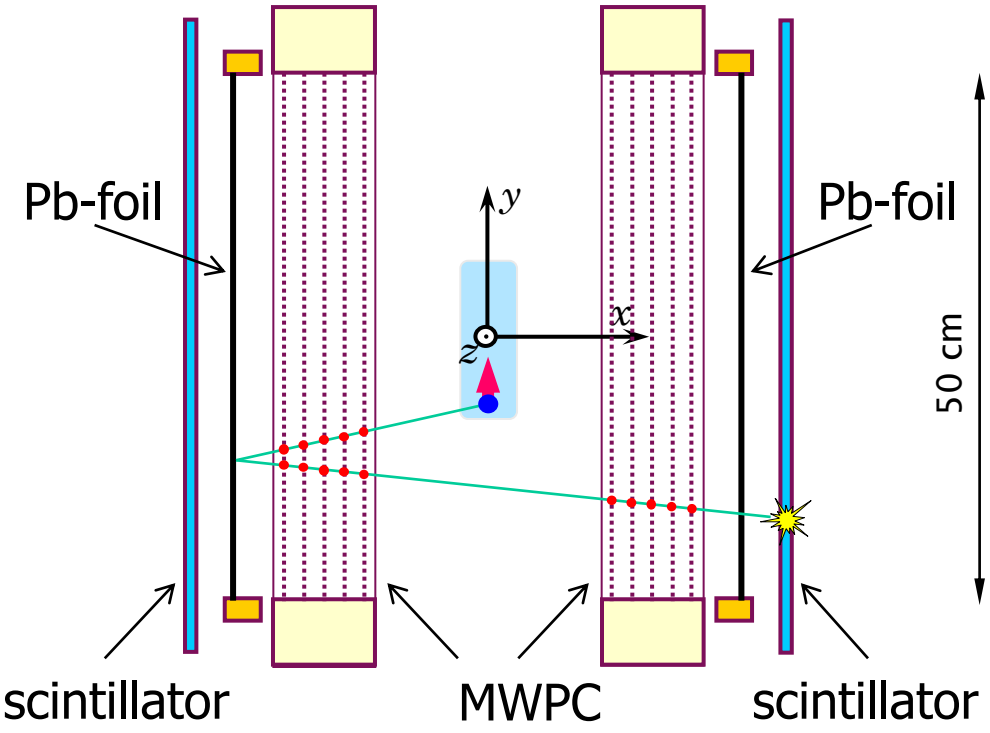
Outline

- Final result of the measurement of R in neutron decay at PSI
- Ongoing measurement of R in ^{8}Li decay at TRIUMF
- A new triple momentum correlation

Measurement of R in neutron decay

Cracow, PSI, LPC-Caen, KU-Leuven, ETH-Zurich, NSCL, Katowice

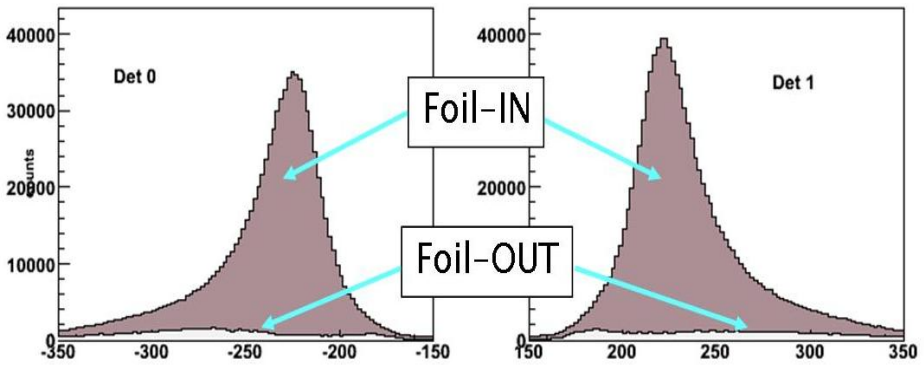
$R\,\vec{\sigma}_e \cdot \left(\vec{J} \times \vec{p}_e\right) / E_e$ Maximal sensitivity for mutually perpendicular vectors



- Tracking of electrons in low-mass, low-Z MWPC
- Identification of Mott events by vertex
- Frequent neutron spin flipping
- Foil IN/OUT measurements

- Polarized cold neutron beam FUNSPIN/PSI.
- Transverse electron polarization analysis by Mott scattering on Pb-foil

- Vertex identification

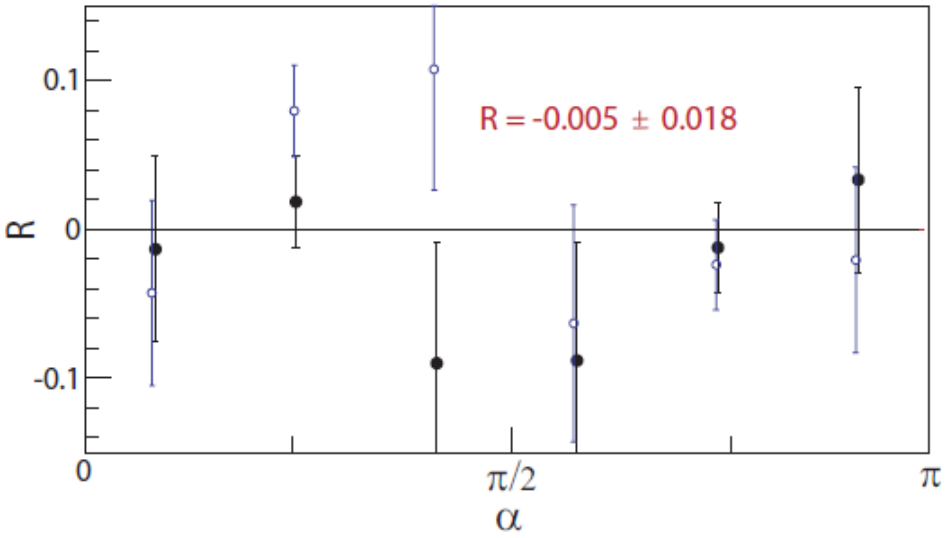


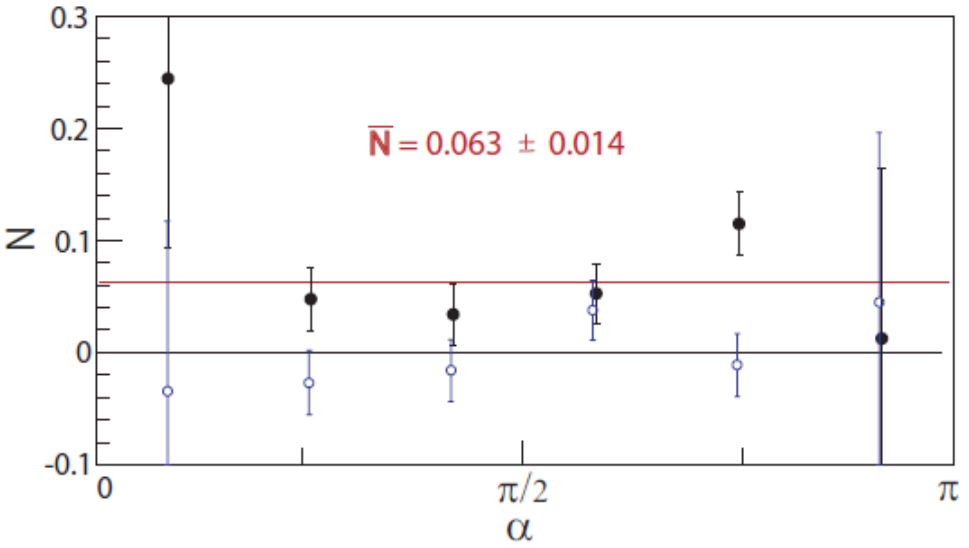
Final result

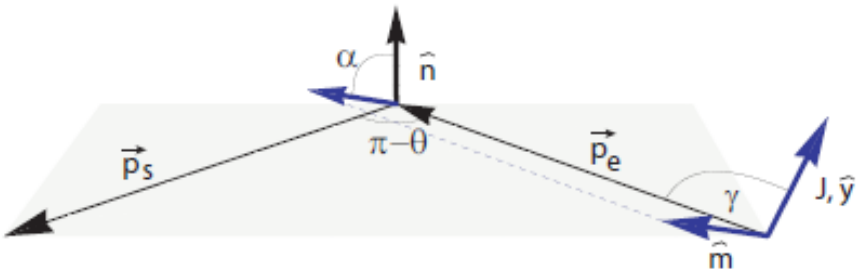
A. Kozela *et al.*, PRC **85** (2012) 045501

The setup enables also to determine the N correlation (P and T even) that provides a control of the polarimeter

- 2007 data







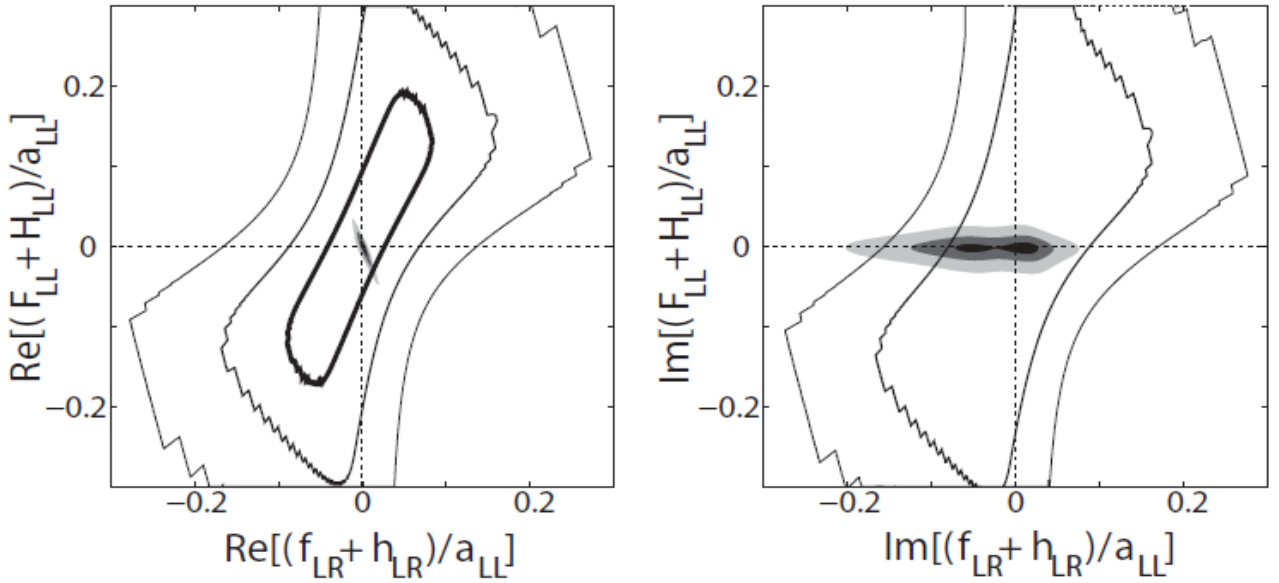
- All data

R_{exp} = 0.004(12+5) N_{exp} = 0.067(11+4)

R_{FSI} = 0.0006(2) N_{FSI} = 0.068(1)

Constraints on leptoquark exchange model

Exclusion plots from nuclear beta decay (gray areas), and from the measurements of N and R in neutron decay (lines at 1, 2 and 3σ)



Helicity projection amplitudes

	Q=1/3	Q=2/3
Scalar	H_{ij}	F_{ij}
Vector	h_{ij}	f_{ij}

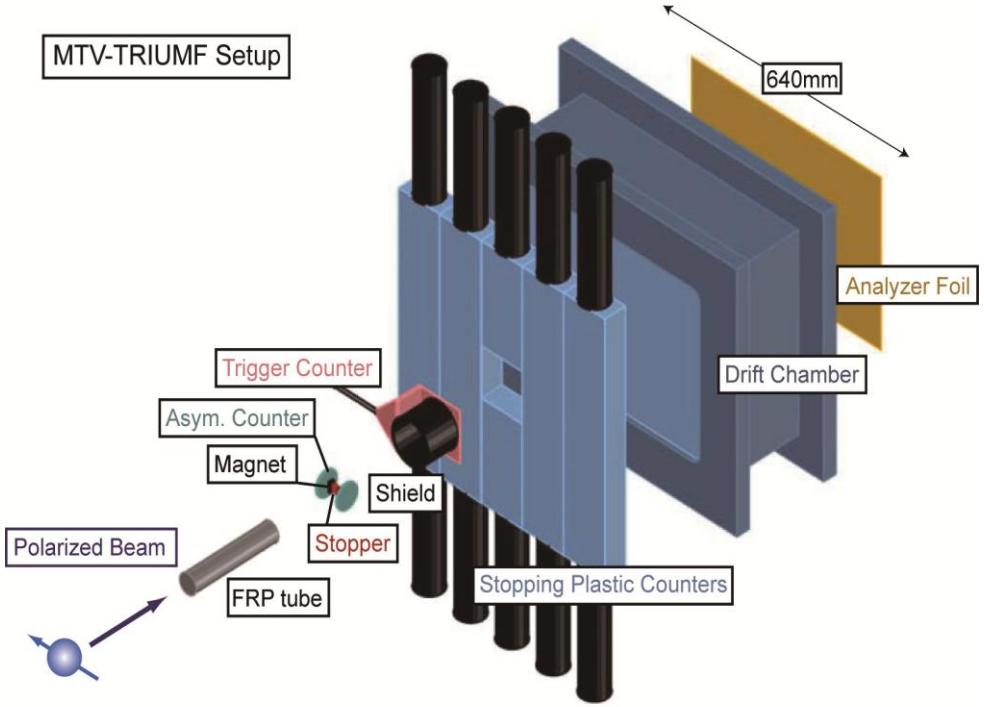
A. Kozela *et al.,* PRC **85** (2012) 045501

Measurement of R in ^{8}Li decay

Rikkyo-U, KEK/TRIMF(Jiro Murata et al.): Started at KEK-TRIAC (2008), moved to ISAC-TRIUMF (2009)

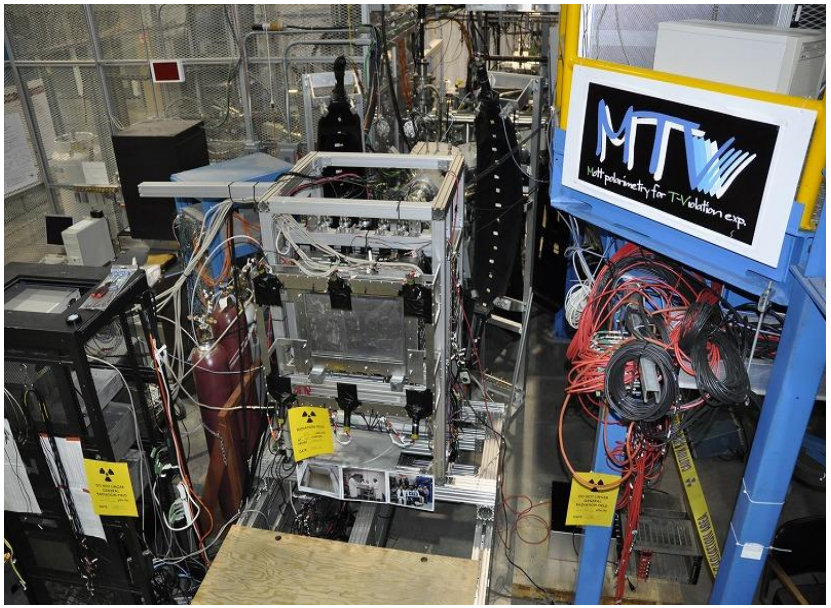
Determines the transverse polarization of electron emitted from polarized nuclei

$$R\,\vec{\sigma}_e \cdot \left(\vec{J} \times \vec{p}_e\right) / E_e$$



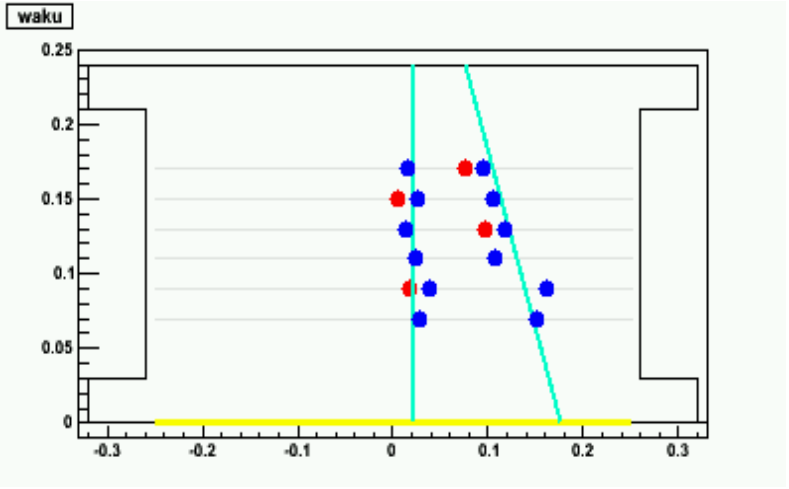
^{8}Li from ISAC

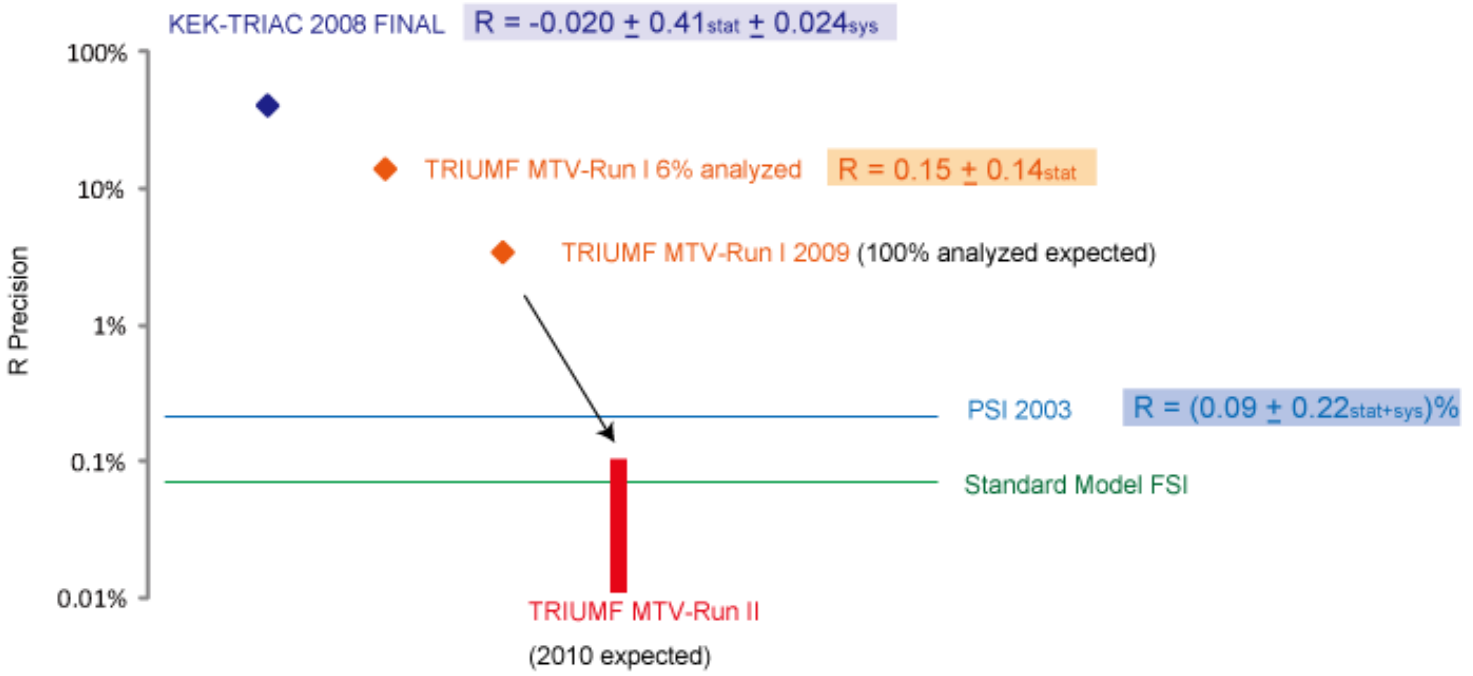
- Beam 10^7 pps @ 28 keV
- 80% polarization (optically pomped)
- 10 μm Al in 500 G



Status and projected sensitivity

- Production run Nov.2010



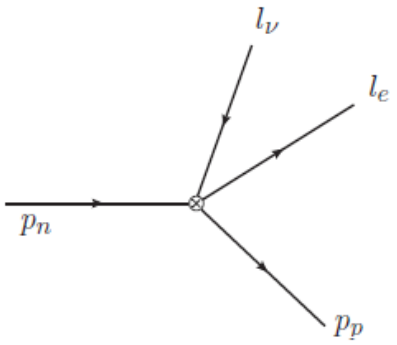


A new triple correlation in β-decay

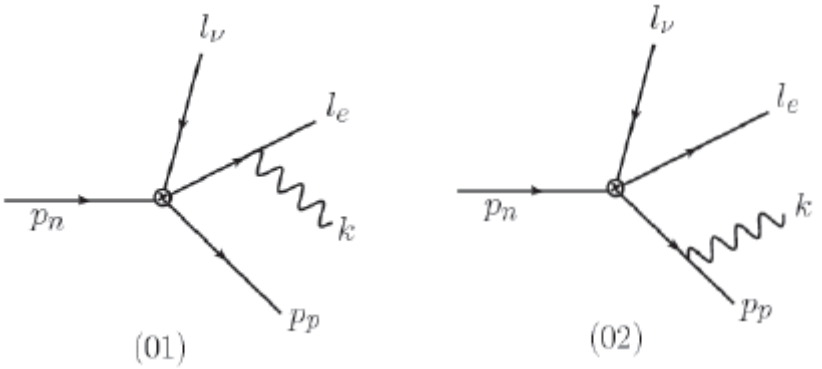
- *"A T-odd momentum correlation in radiatve β-decay"*

S.Gardner & Daheng He, arXiv:hep-ph/1202.5239

Normal decay



Radiative decay



$$W \approx W_0\left[1 + A_\xi^{SM}\,\vec{p}_\gamma \cdot \left(\vec{p}_e \times \vec{p}_R\right)\right]$$

See S. Gardner's talk for contributions to the T-odd asymmetry.

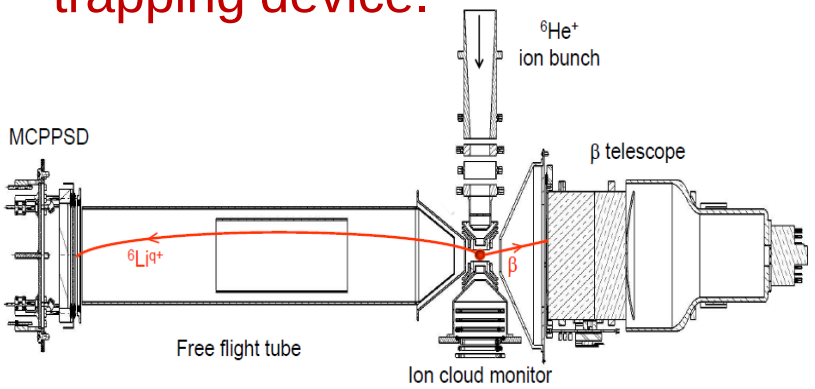
T-odd 3-momentum correlation

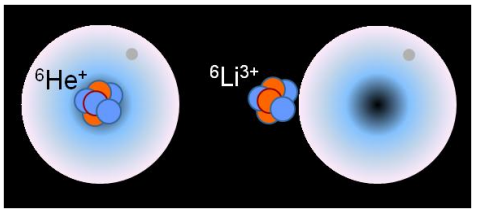
SM "background" (calculated within QED)

"A triple mementum correlation should be sensitive to other T-violating mechanisms than correlations involving spins." (not obvious)

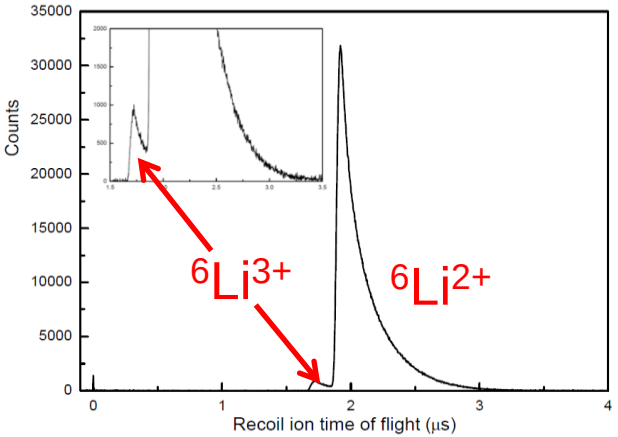
Experimental conditions and first step

- β^- decay to avoid annihilation background.
- gs → gs transition to avoid subsequent γ background.
- Ion/atom trapping to detect the recoil (along with e and γ)
- Nuclear decay candidate: $^6\mathrm{He}^+ \rightarrow {}^6\mathrm{Li}^{2+} + \beta^- + \bar{\nu}_e + \gamma$
- First step: measure the radiative decay mode (~1%) with a high sensitivity trapping device.





$P_{so} = 0.02348(35)$



C. Couratin *et al.*, PRL **108** (2012) 243201

This week highlight (Physics Synopsis) at physics.aps.org

Requires addition of γ detectors around trap

Summary

- The determination of V_{ud} from nuclear mirror transitions requires the measurement of correlation parameters to deduce the GT/F mixing ρ. An ongoing program at GANIL will measure several such transitions.

- The *R* and *N* coefficients have been measured in neutron decay for the first time. The results are consistent with SM predictions.

- A new measurement of *R* in going at TRIUMF in ^{8}Li decay that will possibly reach the level of the FSI for this decay.

- The first step towards the measurement of a new triple momentum correlation considers the detection of the radiative decay mode from trapped $^{6}He^{+}$ by detecting all measurable particles in the final state.