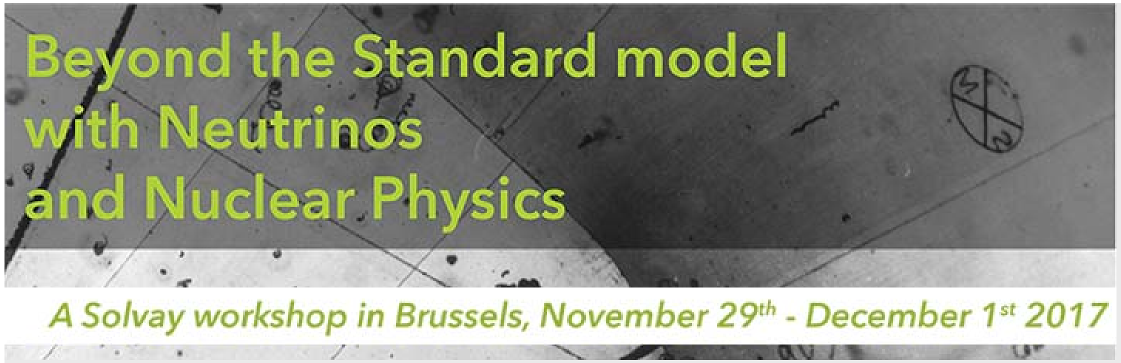

V_{ud} *from nuclear mirror transitions*

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National Superconducting Cyclotron Laboratory
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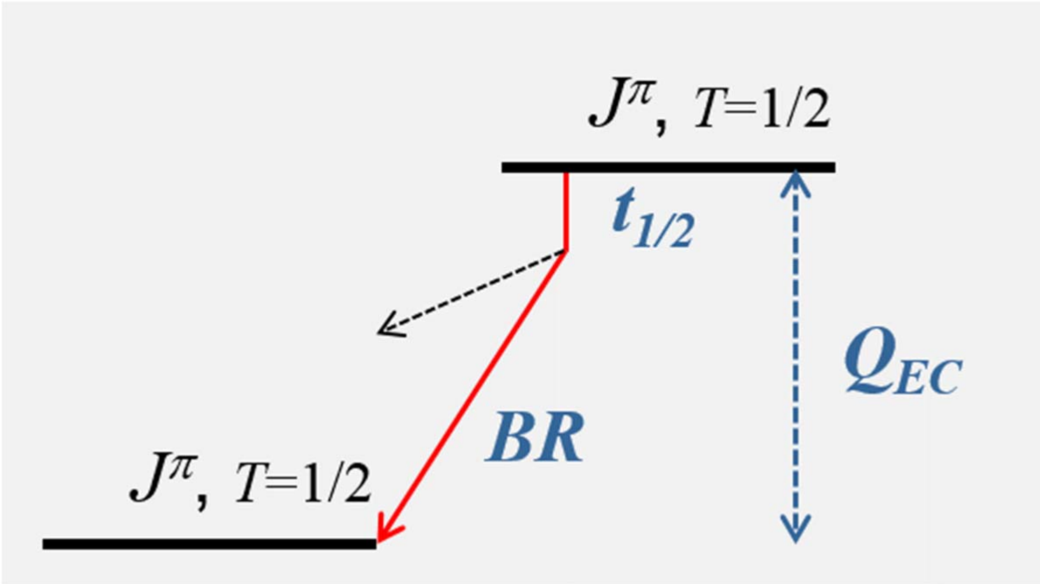
NSCL
NSF
MICHIGAN STATE UNIVERSITY

Outline

- Definitions, candidates, dynamic properties
- A short review of prior work
- Extraction of V_{ud}
- New results: spectroscopy and correlations
- Summary

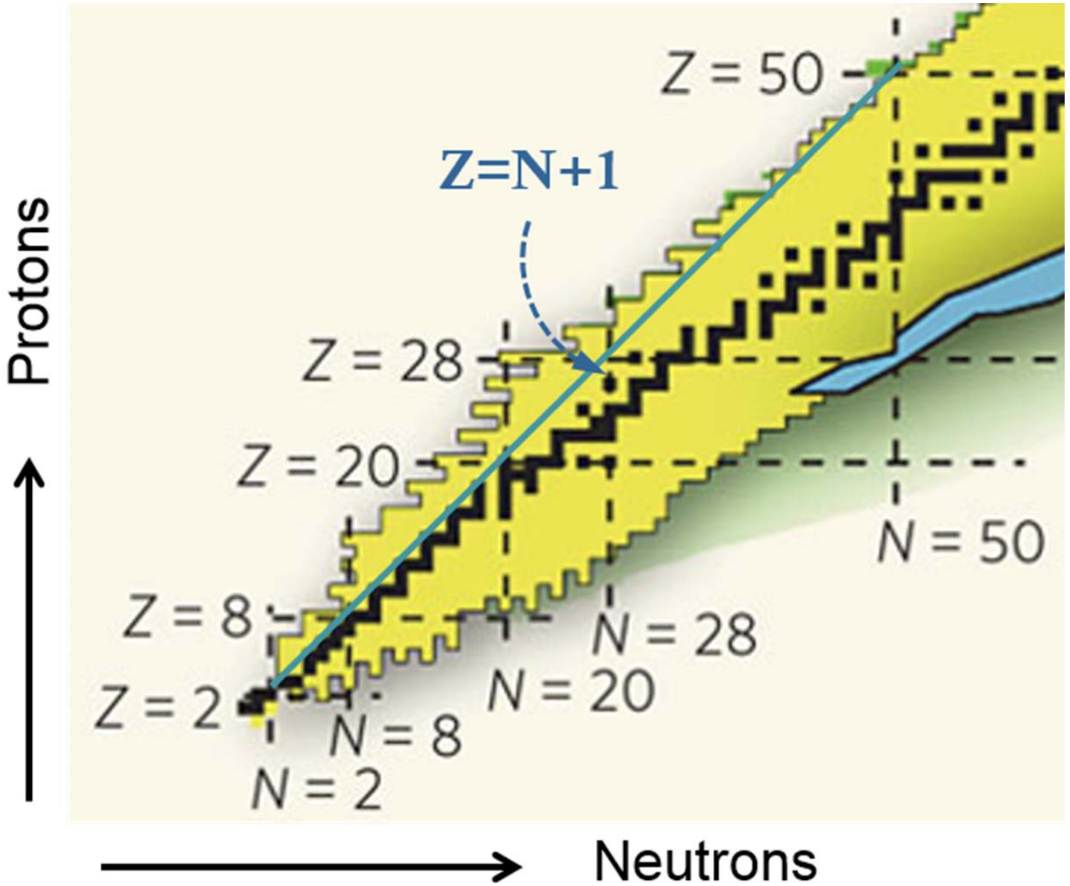
Nuclear mirror transitions in T=1/2 doublets

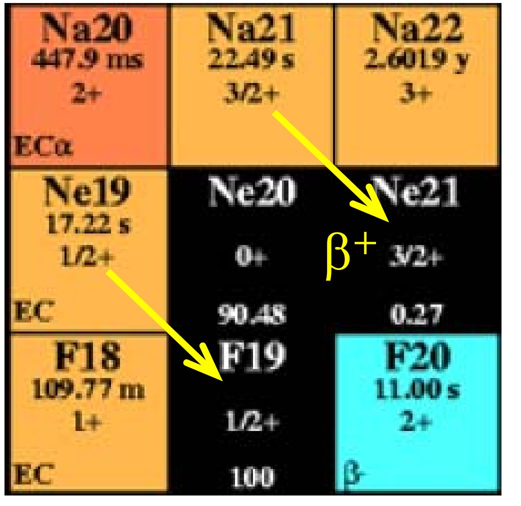


- Super-allowed transitions between isobaric analogue states with T=1/2 (doublets).
- Occur in mirror nuclei, between states with same spins and parities.

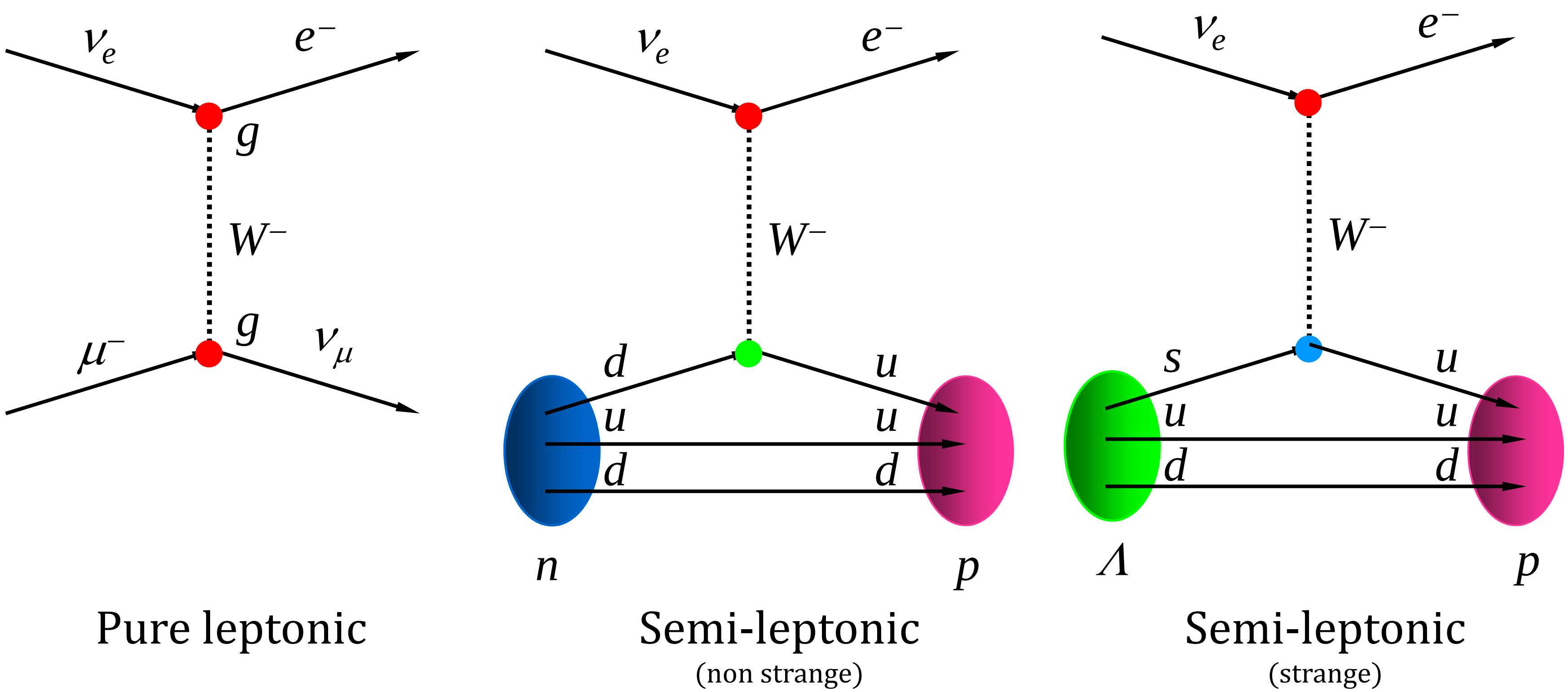
~30 potential candidates

- Parent nucleus located on the $Z=N+1$ line.
- All β^+ transitions except n and ^{3}H decays.





Vector strength in semi-leptonic decays



- Phenomenology within SM

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

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

$$G_\Lambda = G_F \sin\theta_C = G_F V_{us}$$

Michigan State University
National Science Foundation

Ft-value for a mirror transition

- Mirror decays include also the axial-vector interaction

$$\xi^2 = C_V^2 M_F^2 + C_A^2 M_{GT}^2 = C_V^2 M_F^2 (1+\rho^2)$$

M_F: Fermi matrix element
M_{GT}: Gamow-Teller matrix element
ρ: *GT/F* mixing ratio

- Corrected *Ft*-values

$$\mathcal{F}t^{\mathrm{mirror}} \left[1 + f_A \rho^2 / f_V\right] = 2\mathcal{F}t^{0^+ \to 0^+}$$

Same inputs (exp/theo) as $0^+ \to 0^+$ transitions

Additional term due to mixing

→ Can extract the vector strength, like with Fermi transitions

Review of prior work (1/3)

Volume 58B, number 3 PHYSICS LETTERS 15 September 1975

DOES THE CABIBBO ANGLE SOMETIMES VANISH IN NUCLEAR β-DECAY?

J.C. HARDY and I.S. TOWNER

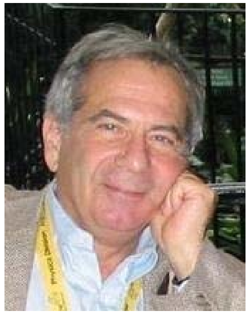
Atomic energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada, KOJ IJO

Table 1
Summary of Data.

	n	^{19}Ne	^{35}Ar
$\sin\theta_V$	0.27 ± 0.05	0.230 ± 0.014	0.03 ± 0.09

- 3 mirror transitions (including neutron decay)
- Indicates a CVC breaking in <u>nuclear</u> mirror decays
- Experimental error in ^{35}Ar decay lead to wrong conclusions

Review of prior work (2/3)



S.J. Freedman
(1944-2012)

4. Investigation of the β-Decay of Mirror Nuclei

S.J. Freedman and J. Napolitano (Argonne National Laboratory), with
M.A. Miller, P.A. Voytas, W. Haeberli, and P.A. Quin

Mirror nuclei provide us with several examples of weak transitions within isospin-1/2 multiplets. These transitions are particlularily simple and even the subtle contributions of induced currents are easy to classify. The size of the vector current anomaly (weak magnetism) is directly related to a combination of initial and final nucleus ground state magnetic moments and effects of possible "second class" currents can be isolated. The dominant contributions from allowed terms are the usual vector and axial vector strengths $C_V M_F$ and $C_A M_{GT}$, respectively. Because of the simple isospin

NSF proposal
(circa ~1996)

We propose to increase the number of experimental determinations of C_V by measuring the β asymmetry in several mirror nuclei, including ^{35}Ar. We will employ the method of producing stopped polarized nuclei with polarized beams. This method does not allow the nuclear polarization to be measured directly so we are limited to cases in which there are adequately strong, pure Gamow-Teller decay branches to excited states. In Gamow-Teller decays the β asymmetry parameter is easily calculated and the associated β asymmetry can be measured by counting deexcitation γ-rays in coincidence.

- Produced results in ^{29}P and ^{35}Ar decays (U. Wisconsin, PSI)

Review of prior work (3/3)

PHYSICAL REVIEW C **78**, 055501 (2008)

$\mathcal{F}t$ values of the $T = 1/2$ mirror β transitions

N. Severijns,[1,*] M. Tandecki,[1] T. Phalet,[1] and I. S. Towner[2]
[1] *K. U. Leuven, Instituut voor Kern-en Stralingsfysica, Celestijnenlaan 200D, B-3001 Leuven, Belgium*
[2] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
(Received 15 July 2008; published 5 November 2008)

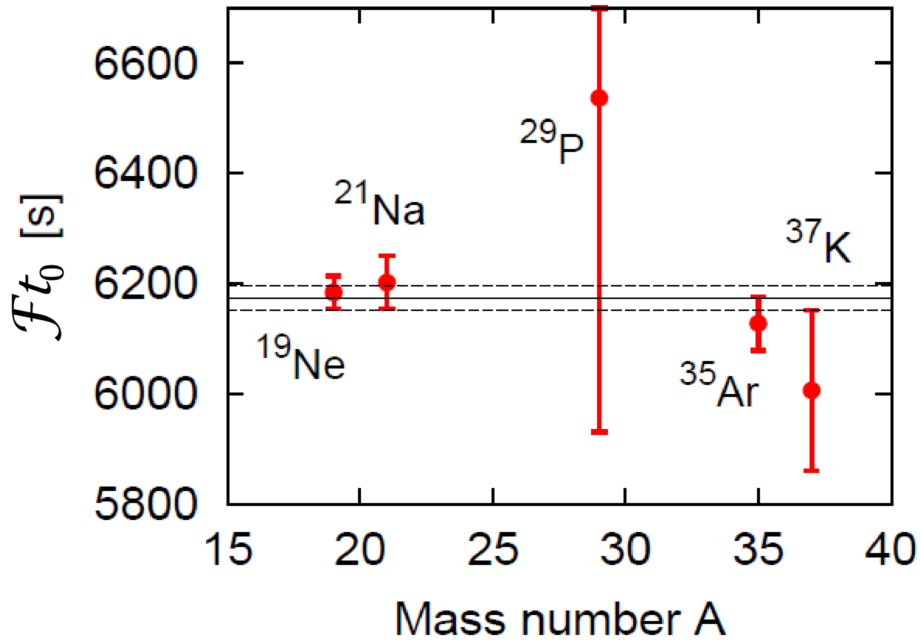
- Survey of available experimental data (half-lives, branching ratios, Q_{EC}-values)
- Provided theoretical corrections ($\delta_C^V - \delta_{NS}^V$)which are crucial for the determination of $\mathcal{F}t$ values
- No extraction of V_{ud}!

Extraction of V_{ud} (2009)

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

$$\mathcal{F}t_0 = \mathcal{F}t^{\text{mirror}}\left[1 + f_A\rho^2 / f_V\right]$$

- Use mixing ratios, ρ, extracted from experiments !!!



- Test of CVC in mirror transitions.
- Extract V_{ud}

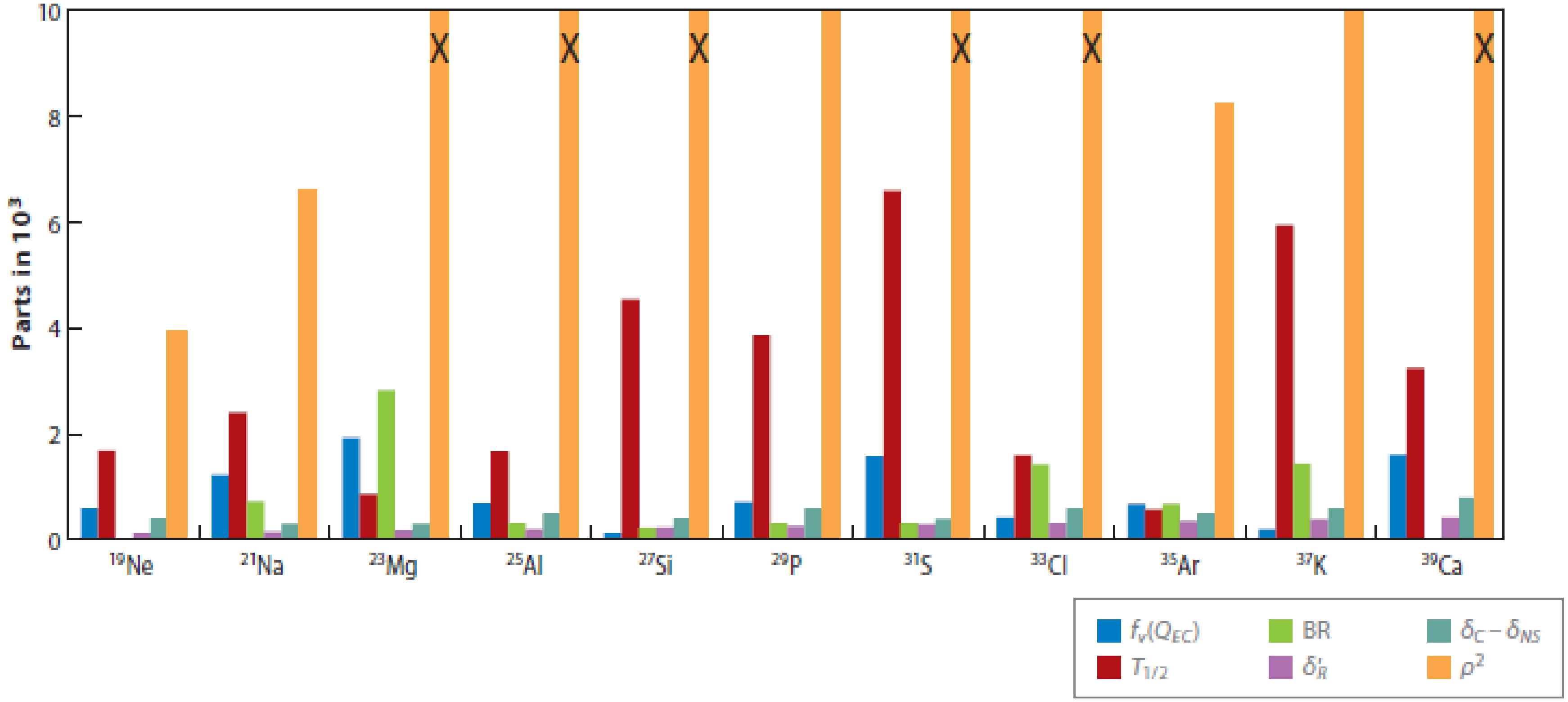
$$V_{ud}^2 = \frac{K}{\overline{\mathcal{F}t_0}\, G_F^2 (1 + \Delta_R^V)}$$

$$V_{ud}^{\text{mirror}} = 0.9719\,(17)$$

Error budget in mirror transitions - 2011

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

X ≡ never measured



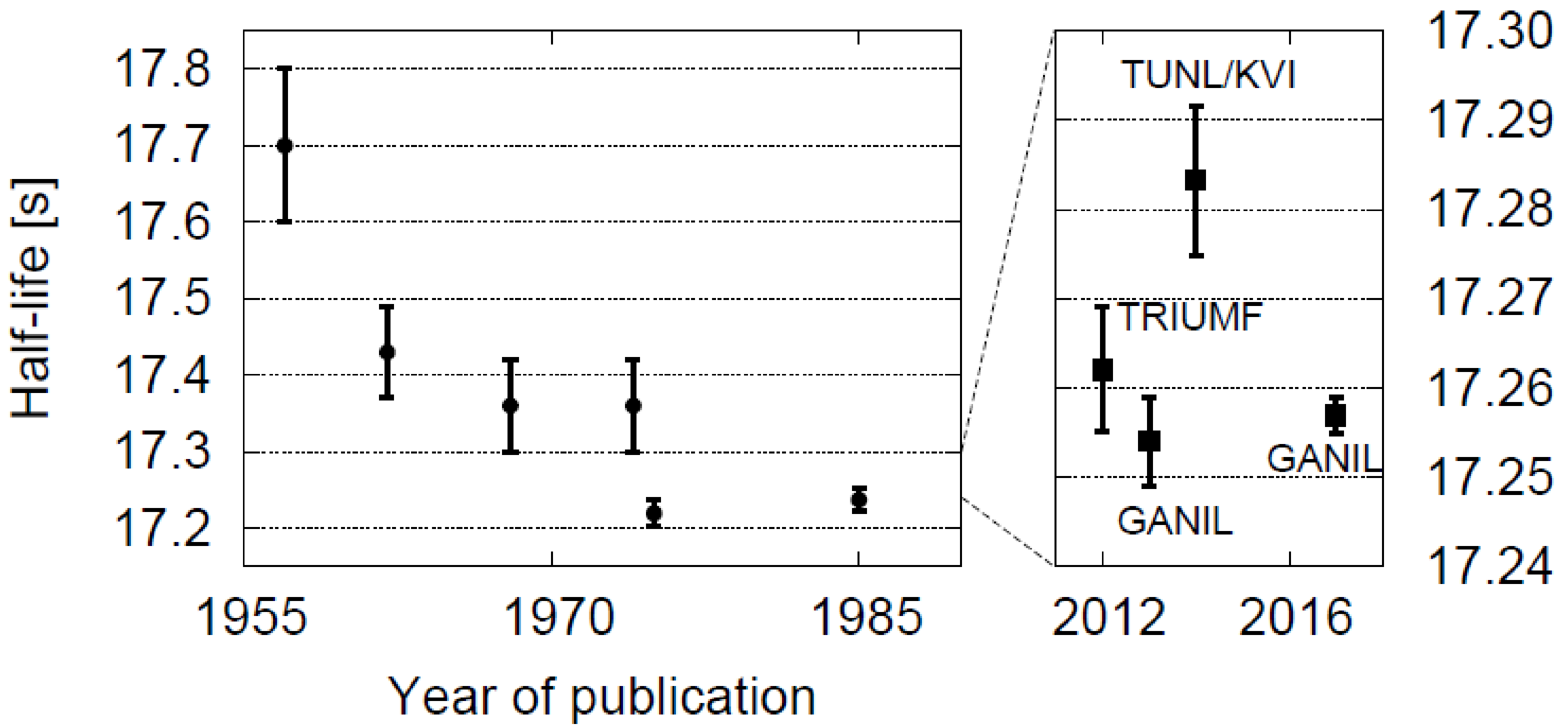
- Dominated by the uncertainty on GT/F mixing ratio, ρ
- Motivated also new measurements of spectroscopic quantities

Some new spectroscopy results

Parent	Property	Reference, Group(s)/Lab
^{11}C	Q_{EC}	Gulyuz et al. PRL **116** (2016) 012501
^{17}F	$t_{1/2}$	Grinyer et al. PRC **92** (2015) 045503
		Brodeur et al. PRC **93** (2016) 025503
^{19}Ne	$t_{1/2}$	TRIUMF; TUNL@KVI; GANIL
^{21}Na	$t_{1/2}$	Grinyer et al. PRC **91** (2015) 032401(R)
	$t_{1/2}$	Finlay et al. PRC **96** (2017) 025501
	Q_{EC}	Eibach et al. PRC **92** (2015)045502
^{25}Al	Q_{EC}	Canete et al. EPJA **52** (2016) 124
	$t_{1/2}$	Long et al. PRC **96** (2017) 015502
^{29}P	$t_{1/2}$	CENBG@JYFL
	Q_{EC}	Eibach et al. PRC **92** (2015)045502
^{31}S	$t_{1/2}$	Bacquias et al. EPJA **48** (2012) 155
	Q_{EC}	Kankainen et al. PRC **82** (2010) 052501(R)
^{33}Cl	$t_{1/2}$	Grinyer et al. PRC **92** (2015) 045503
^{37}K	$t_{1/2}$	Shidling et al. PRC **90** (2014) 032501(R)
^{39}Ca	$t_{1/2}$	Blank et al. EPJA **44** (2010) 363

- New compilation of *Ft* values under way [Severijns priv. com.]

Example: ^{19}Ne half-life

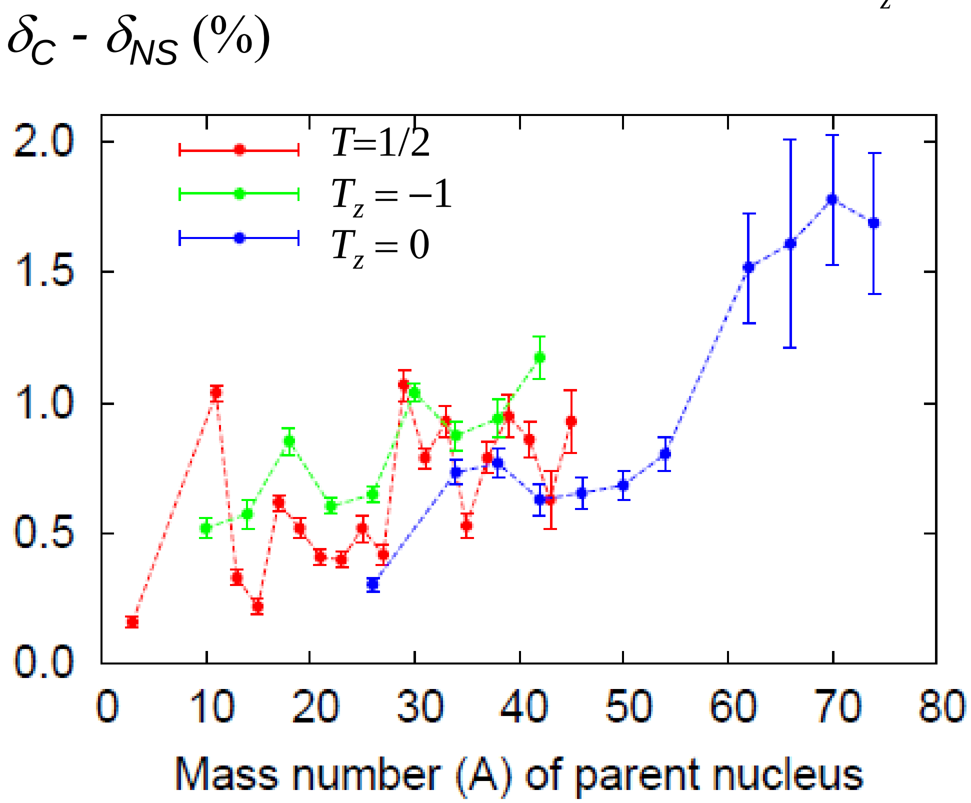


TRIUMF: Triambak et al. PRL **109** (2012) 042301
GANIL-1: Ujic et al. PRL **110** (2013) 032501
TUNL/KVI: Broussard et al. PRL **112** (2014) 212301
GANIL-2: Fontbonne et al. arXiv:1709.09415

- Measurement has now reached a precision of 1.2×10^{-4}

Theoretical corrections (shell model)

T=1/2: N. Severijns et al., PRC **78** (2008) 055501
$T_z = -1$ and $T_z = 0$: J. Hardy, I.S. Towner, PRC **91** (2015) 025501



- Corrections for $T_z = 0$ are systematically smaller than for $T_z = -1$.
- No systematic difference observed for mirror transitions:

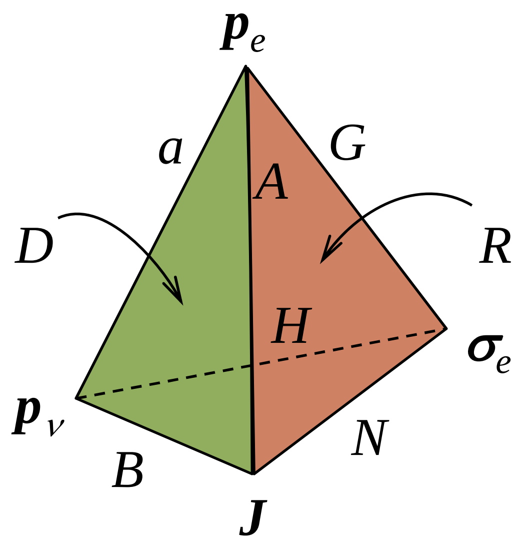
^{11}C is twice larger than ^{10}C
^{15}O is twice smaller than ^{14}O.

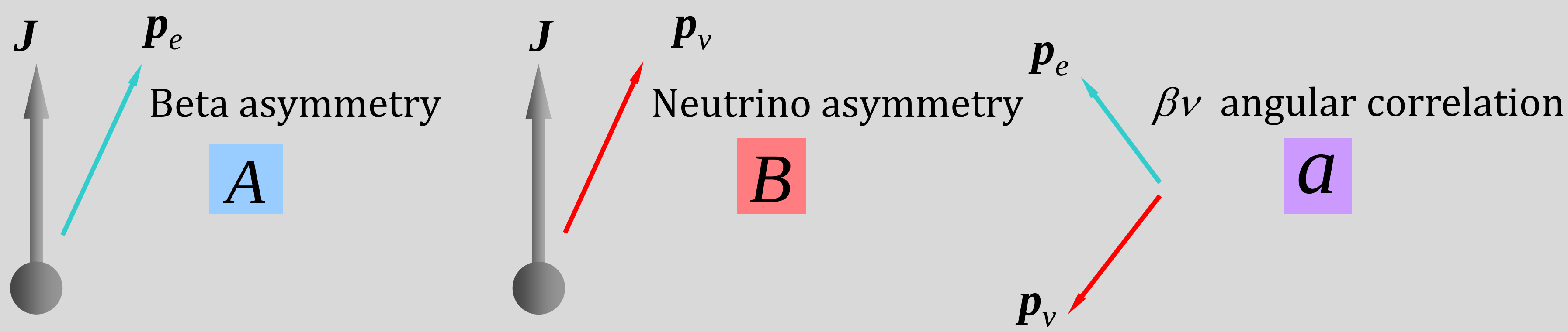
- Mirror transitions extend the range of nuclei to test theoretical corrections.

Mixing ratio and correlation coefficients

$$\mathcal{F}t_0 = \mathcal{F}t^{\text{mirror}}\left[1 + f_A\rho^2 / f_V\right]$$

- The most critical parameter: ρ
- A and B can determine ρ
- a can determine $|\rho|$



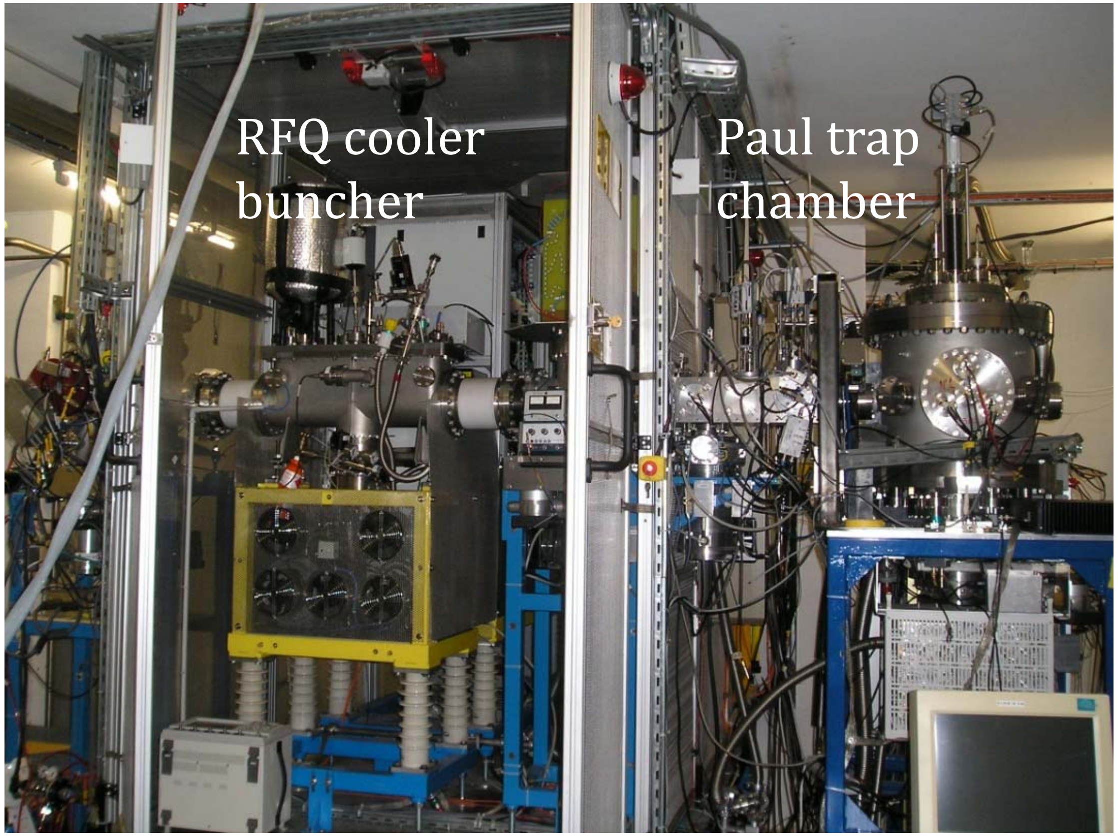


Measuring principle with LPC-Trap @ GANIL

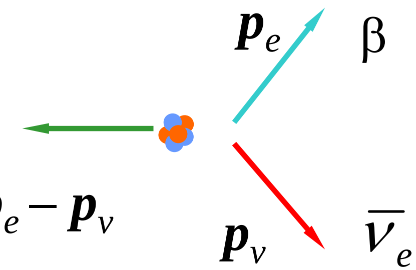
Production
of radioactive nuclei

Separate, slow down
cool, bunch

Trap ions and
observe their decay



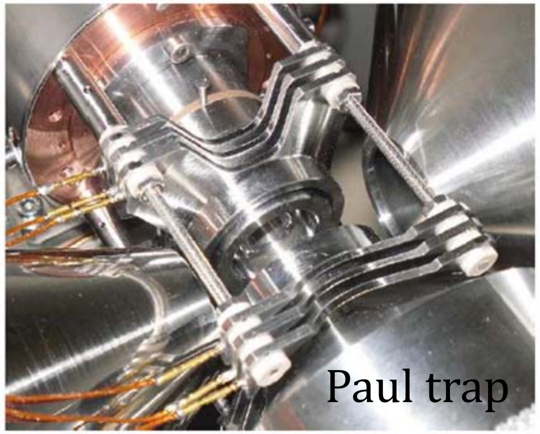
Deduce βν correlation from TOF spectrum of recoiling ions relative to b.

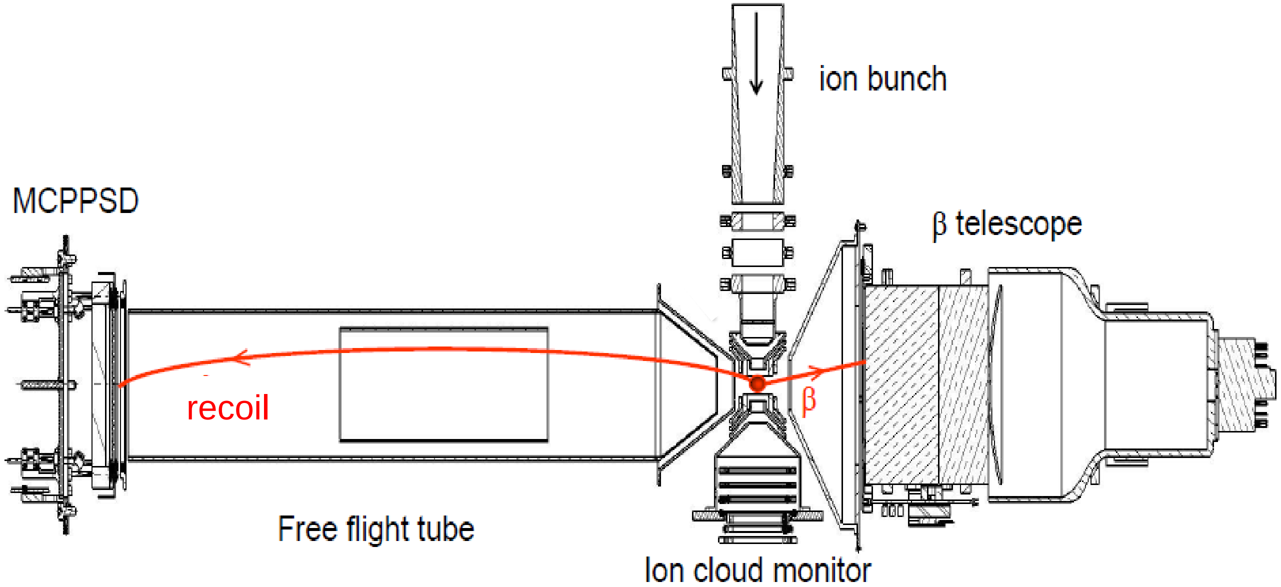


$$\boldsymbol{p}_R = -\boldsymbol{p}_e - \boldsymbol{p}_\nu$$

D. Rodriguez et al. NIMA **565** (2006) 876

Measurements of "a" with LPC-trap @ GANIL





- Continuous injection of bunches into the Paul trap.
- Measure energy and position of β particles (DSSSD and PVT).
- Measure TOF and position of recoil ions (over-determined kinematics).
- Continuous extraction and monitoring of remaining ions for each filling.

- "Free flight" ion recoil spectrometer enables to separate charge states.

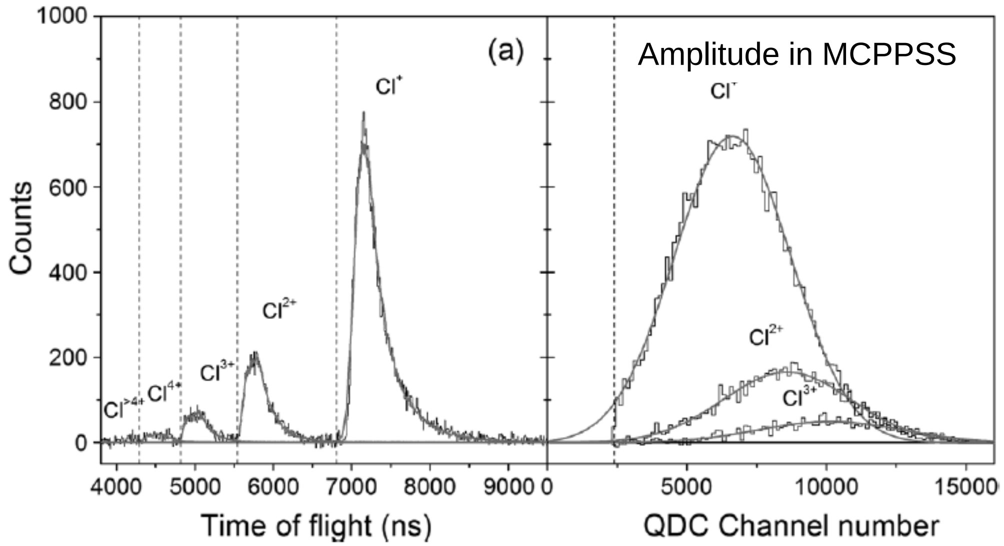
Results from LPC-trap

- Determine charge state distributions from shake-off (SO) following β decay.

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

- Theoretical calculations of SO reproduce results accurately.

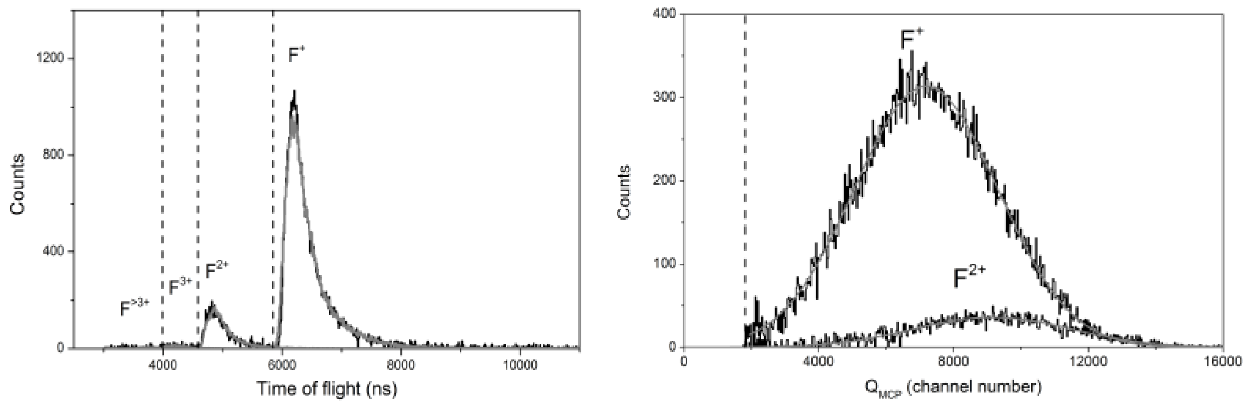
C. Couratin et al. PRA **88** (2013) 041403(R)



$$^{19}\mathrm{Ne}^{+} \rightarrow {}^{19}\mathrm{F}^{0} + e^{+} + \nu_e$$

- Theoretical calculations do not reproduce results.

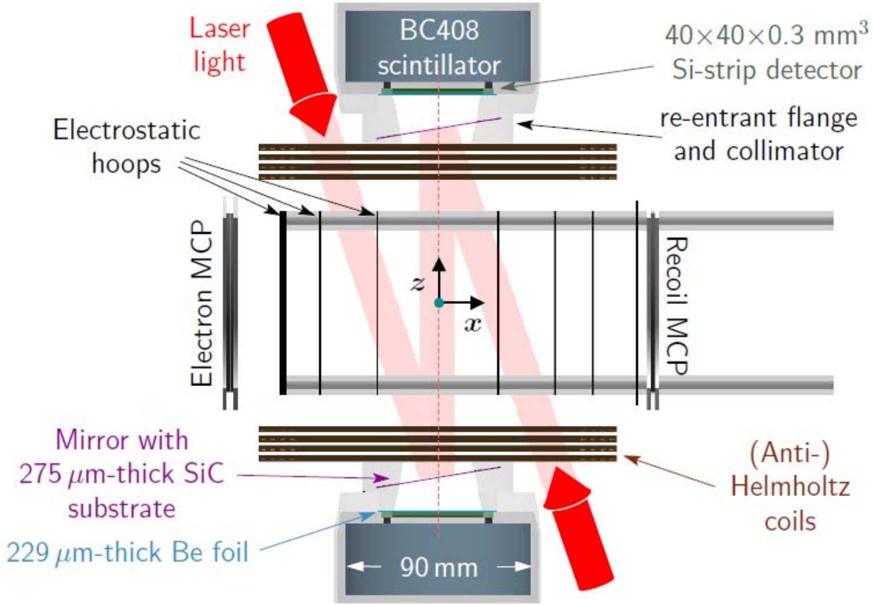
X. Fabian et al. submitted to PRA



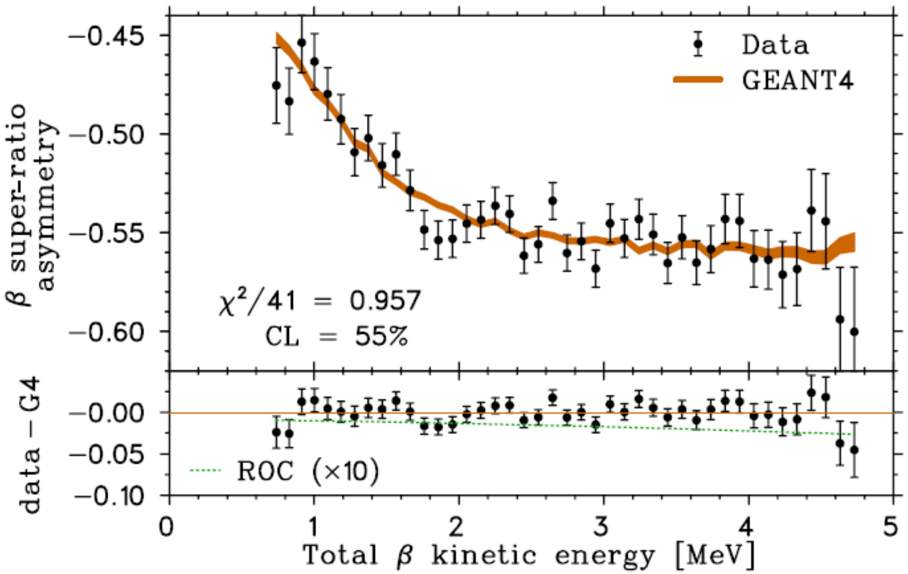
- Analysis of "a" under way [Flechard priv. com.]

Measurements of "A" in ^{37}K decay @ TRIUMF

- TRINAT detection chamber



B.B. Fenker et al. arXiv:1706.00414



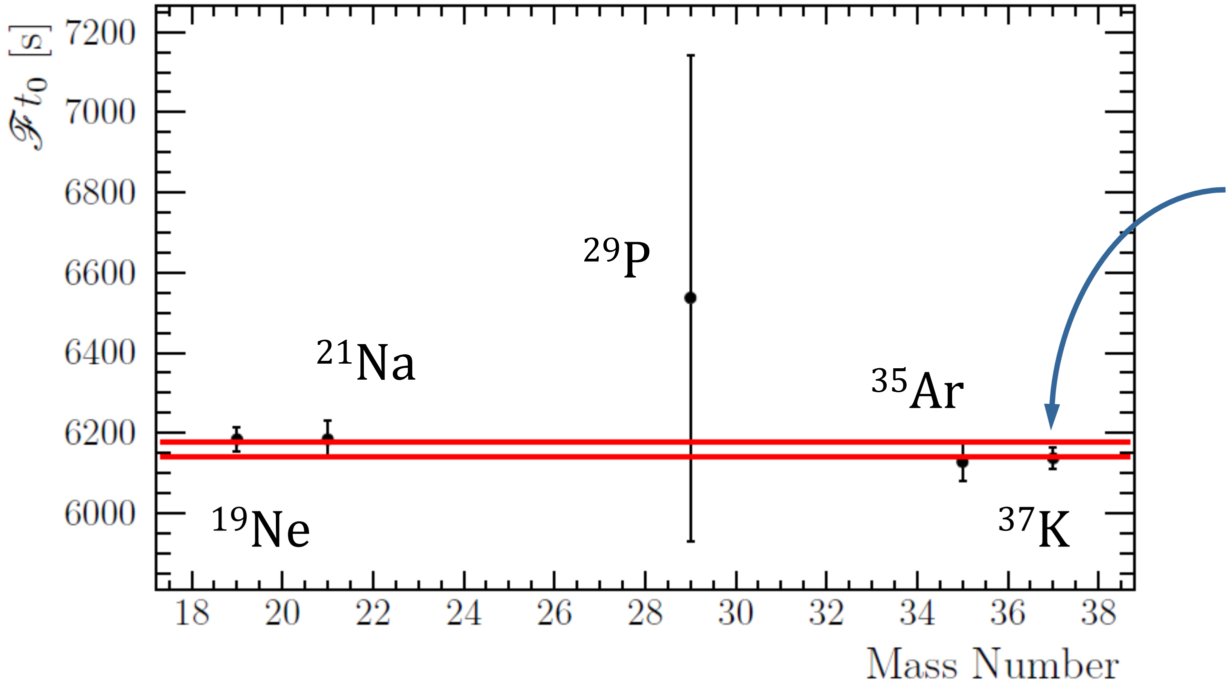
- Measure the degree of nuclear polarization by probing the atoms with a pulsed laser and detecting photo-ions with MCP.

- 0.1% precision of nuclear polarization!!!

$$A_\beta = -0.5707\,(18)$$
$$A_\beta^{SM} = -0.5706\,(7)$$

Current status

Adapted from B.B. Fenker, PhD Thesis, Texas A&M, 2016



- Ft value calculated with a weighted mean value of ρ deduced from measurements of B and A. Unique case!
- Includes also new value of $t_{1/2}$.

$$V_{ud}^{\text{mirror}} = 0.9728(14)$$

B.B. Fenker et al. arXiv:1706.00414

(a factor of 6.7 less precise than Fermi transitions)

Summary

• Nuclear mirror transitions have open a new window for the determination of V_{ud} .

• This extension requires a solid data set and has motivated numerous experiments in spectroscopy and correlation measurements.

• The uncertainties of GT/F mixing ratios will remain (for a while) the dominant source of uncertainty.

• Precision correlation measurements with ion and atom traps and with polarized low energy beams are crucial to this end.