Low-energy tests of the CVC-hypothesis and the unitarity of the CKM-matrix by means of precision mass measurements in a Penning trap

Ari Jokinen
Department of Physics
University of Jyväskylä

Physics of superallowed beta decay

Conserved vector current hypothesis:
ft should be constant

$$Ft \equiv ft(1+\delta_R)\left[1-\left(\delta_C-\delta_{NS}\right)\right]=\frac{K}{2G_V^2(1+\Delta_R)}$$

δ_R radiative correction
f(Z,Q_{EC}) ~1.5 %

δ_C-δ_{NC} isospin symmetry breaking correction
f(nuclear structure), 0.3-0.7%

Δ_R nucleus-independent radiative correction
f(interactions), ~2.4%

Exp. parameters to be determined:
Beta decay half-life $T_{1/2}$
Beta decay branching ratio I_b
Decay energy Q_{EC}

Single nucleus: determination of $G_V^2(1+\Delta_R)$

Many transitions: Check if Ft is constant
→ Test of the CVC

One can deduce V_{ud} by combining beta decay and muon decay data

$$V_{ud}^2=\frac{G_V^2}{G_\mu^2}$$

Cabibbo-Kobayashi-Maskawa quark mixing matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity test of CKM-matrix

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

> 99 %

small

very small

B meson decays

Kaon decay

Superallowed pure Fermi transitions
Neutron decay
Pion beta decay

World data 2005

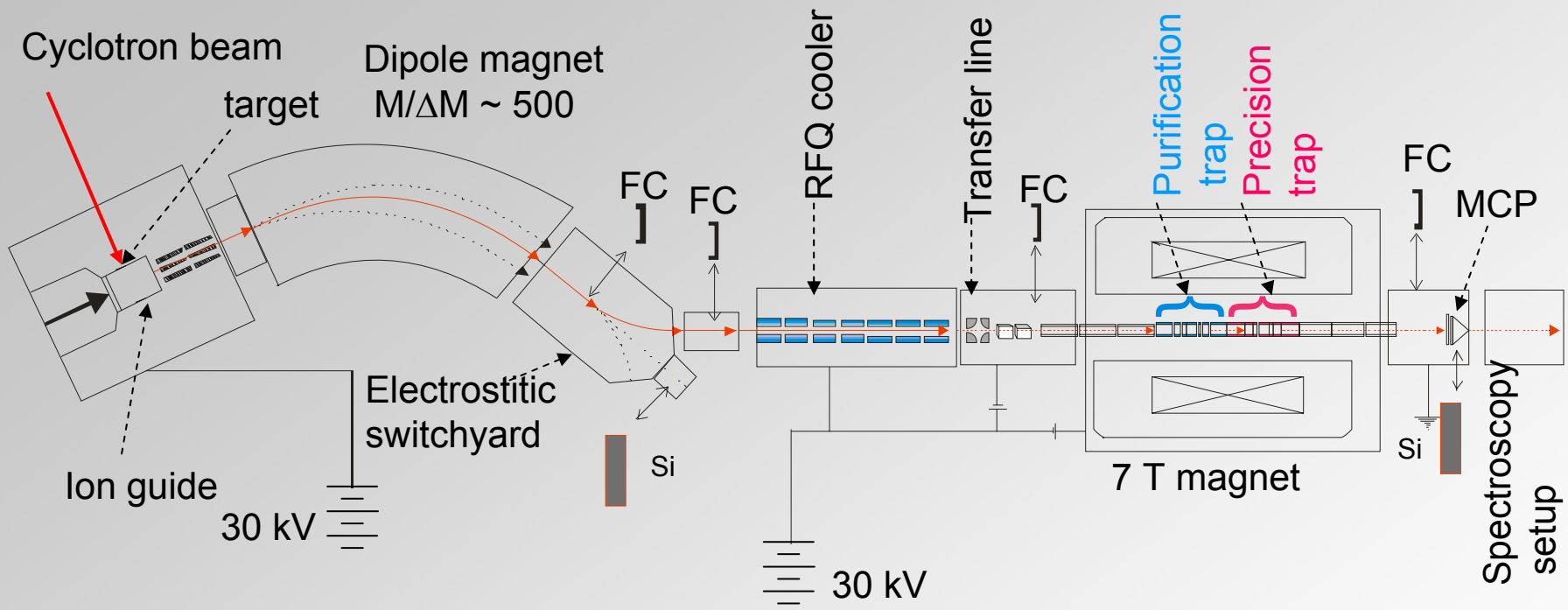
J. Hardy and I. Towner, Phys. Rev. C 71 (2005) 055501

- Nine best known cases: ^{10}C, ^{14}O, $^{26}Al^m$, ^{34}Cl, $^{38}K^m$, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co (ft value known to a precision of ~0.1 %)
- Together with new data on ^{22}Mg, ^{34}Ar and ^{74}Rb (ft value known to a precision < 0.40 %)
- The average Ft from survey; $Ft = 3072.7(8)$ → $3073.5(12)$ δ_C from OB or TH
- G_V constant verified to 0.013%
- Precise value determined for $V_{ud} = G_V/G\mu = 0.9738(4)$
- Unitarity of the CKM-matrix $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014$

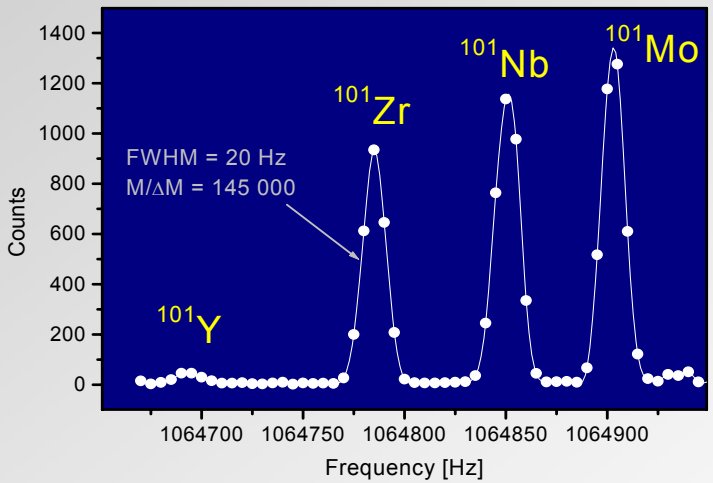
NEW TRENDS:

- Improve the precision of the nine cases
- Add new cases with larger corrections → to test corrections and improve them
- New cases with A=18-42 (T_z=-1)
- New cases with A≥62 (T_z=0)

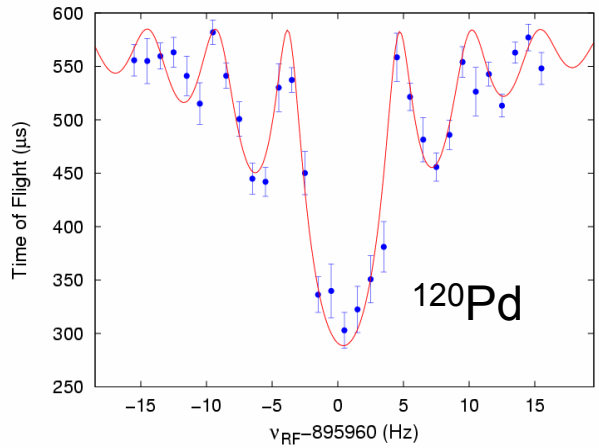
JYFLTRAP at IGISOL-facility



Purification scan



TOF-resonance in Precision trap



Basic equations for mass determination

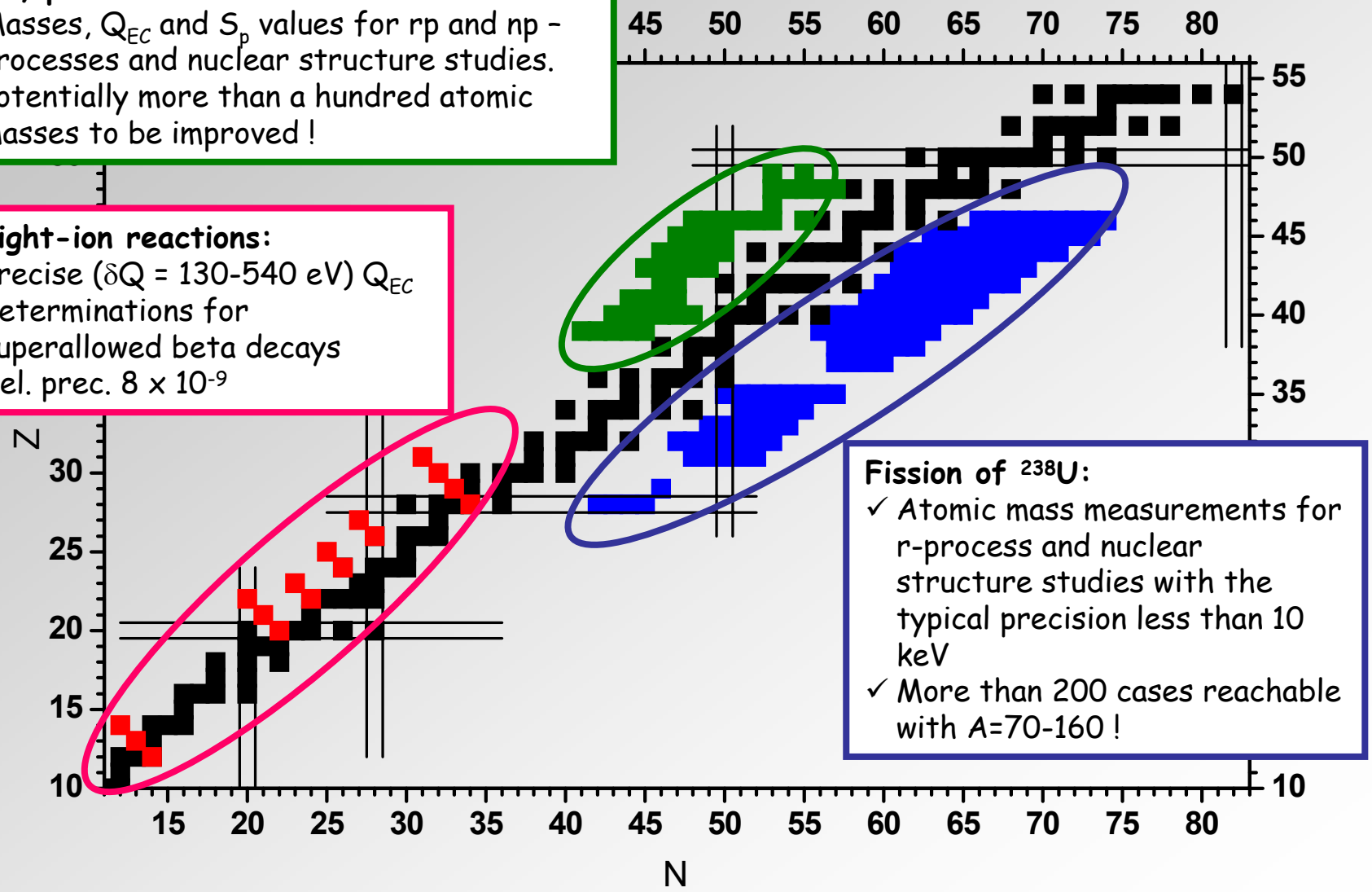
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

$$\frac{f_{c,\mathrm{ref}}}{f_c} = \frac{m - m_e}{m_{\mathrm{ref}} - m_e}$$

Overview of JYFLTRAP mass program

HI, p- and ^{3}He-induced reactions:
Masses, Q_{EC} and S_p values for rp and np – processes and nuclear structure studies.
Potentially more than a hundred atomic masses to be improved !

Light-ion reactions:
Precise (δQ = 130-540 eV) Q_{EC} determinations for superallowed beta decays
Rel. prec. 8 x 10^{-9}



Fission of ^{238}U:
- ✓ Atomic mass measurements for r-process and nuclear structure studies with the typical precision less than 10 keV
- ✓ More than 200 cases reachable with A=70-160 !

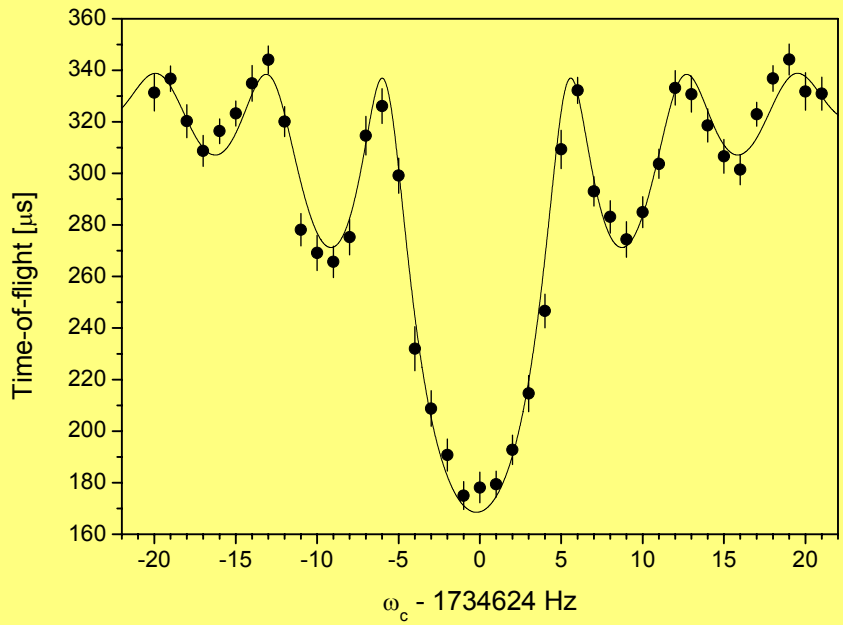
^{62}Ga – extension to higher Z

JYFLTRAP:

- ✓ 48 MeV p-beam on ^{64}Zn-target
- ✓ 600 ions/s ^{62}Ga, 7x10^5 ions/s ^{62}Zn
- ✓ Direct comparison between mother and daughter isotopes

$$Q_{EC} = M_p - M_d = \underbrace{\left(\frac{f_d}{f_p} - 1\right)}_{\leq 10^{-3}} M_d \quad \rightarrow \quad \Delta M_d \text{ negligible !}$$

- ✓ Q_{EC} = 9181.07(54) keV
- ✓ Rel. mass precision 1.8 x 10^{-8}
- ✓ Additional check for ^{62}Ni and ^{62}Cu



T. Eronen et al., Phys. Lett. B 636 (2006) 191

TRIUMF:
High precision branching ratio measurement:
B. Hyland et al., PRL 97 (2006) 102501

19 gamma-rays → superallowed branching ratio 99.861(11) %

→ ft = 3075.6(14) s (purely experimental)

Q_{EC} = 9181.07(54) keV
$T_{1/2}$ = 116.175(38) ms
I_b = 99.861(11) %
Uncertainty of (δ_{NS}-δ_C) dominates

Deduced δ_C = 1.47(+0.13)(-0.18)

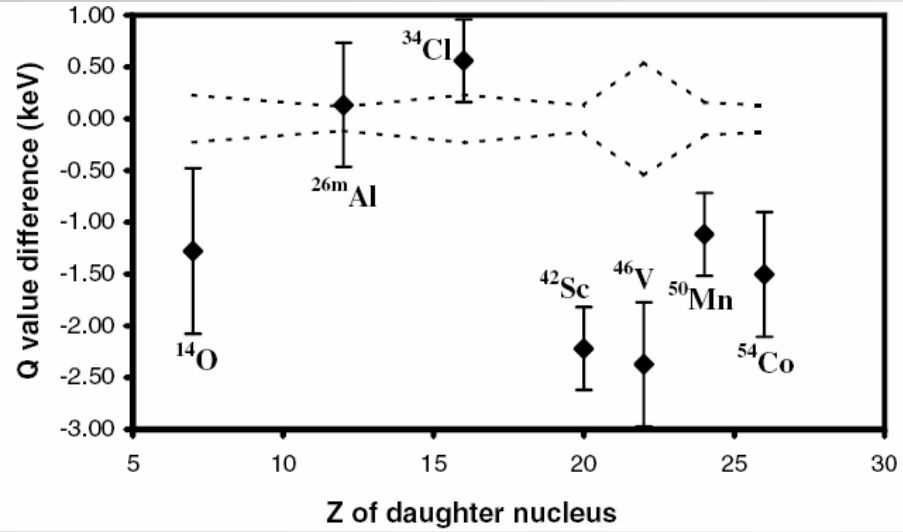
Towner&Hardy:	1.38(16)
Sagawa:	1.42
Ormand-Brown:	1.30/1.69 (HF)/(WS)

Q_{EC}-values of $^{26}Al^m$, ^{42}Sc and ^{46}V

Canadian Penning Trap at Argonne:

G. Savard et al., Phys. Rev. Lett. 95 (2005) 102501

- → $Q_{EC}(^{46}V)$ = 7052.90(40) keV, which differed by 2.19 keV from the previous compilation
- → Detailed analysis of the existing new data against earlier data
- → Data set of H. Vonach et al., [Nucl. Phys. A278 (1977) 189], which affects 7 of the best nine cases was found to be systematically off compared to other measurements



→ "Penning trap revolution ?!"
(W. Marciano, NUPAC at CERN, Nov-2005)

JYFLTRAP:

$^{46}Ti(p,n)^{46}V$, E(p) = 20 MeV

$^{26}Mg(p,n)^{26}Al$, E(p) = 15 MeV

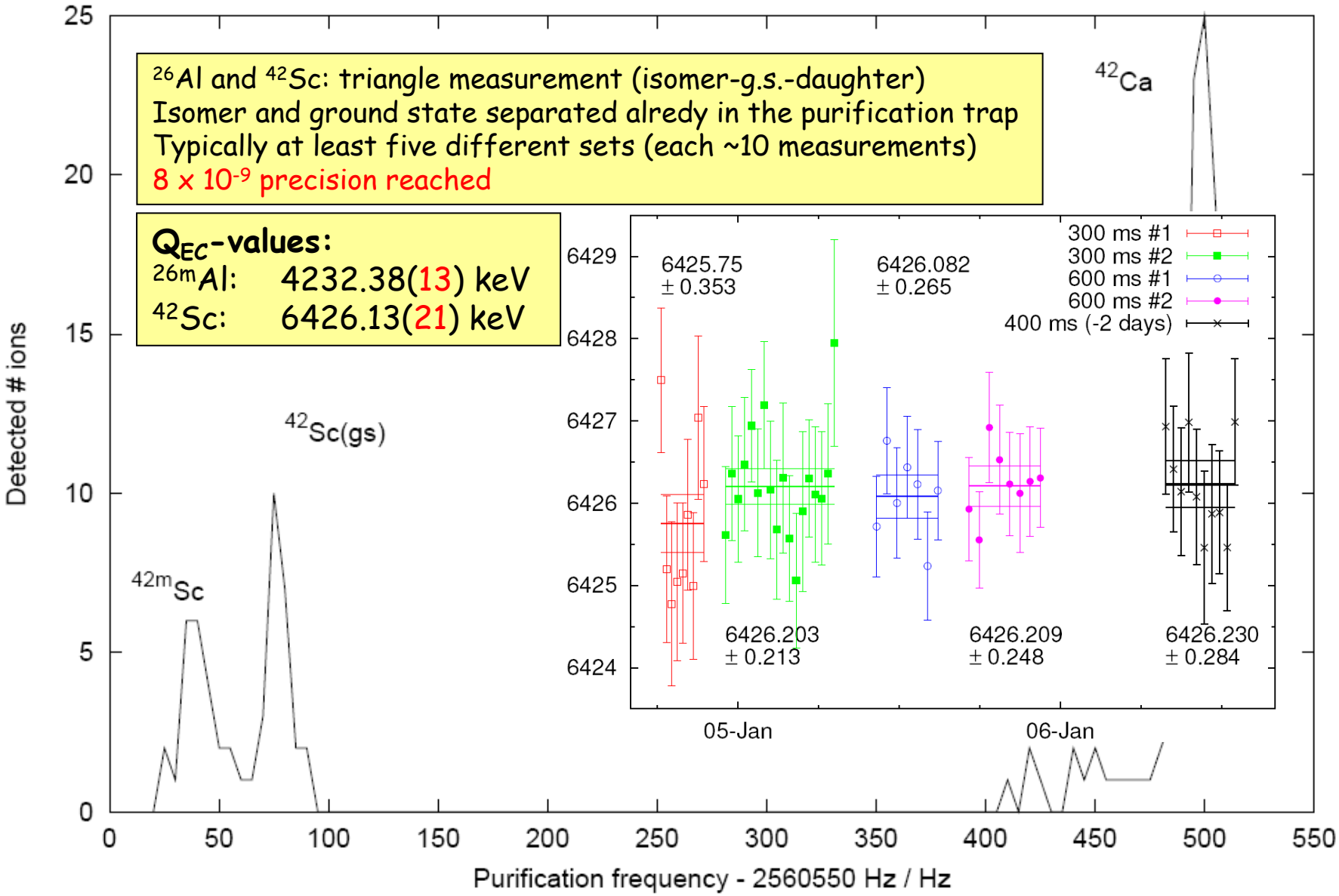
$^{40}Ca(^3He,p)^{42}Sc$, E(^{3}He) = 20 MeV

Conclusions:

- ✓ $Q_{EC}(^{46}V)$= 7052.72(31) keV in agreement with CPT
- ✓ Anomalous Q_{EC}-value of ^{46}V measured by G. Savard et al., was confirmed

T. Eronen et al., PRL97 (2006) 232501

Consistency checks: $^{26}Al^{m}$ and ^{42}Sc



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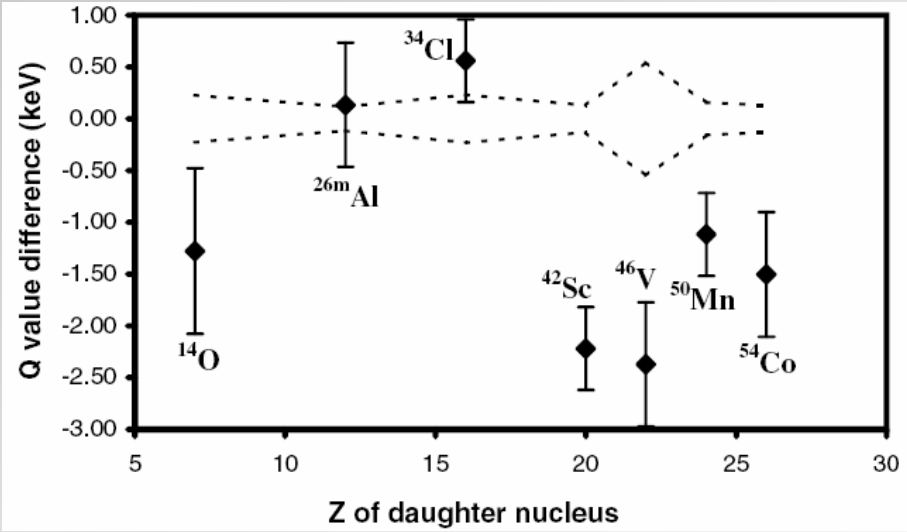

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Conclusions:

- ✓ $Q_{EC}(^{46}V)$= 7052.72(31) keV in agreement with CPT
- ✓ Anomalous Q_{EC}-value of ^{46}V measured by G. Savard et al., was confirmed
- ✓ Extended systematic deviation between reaction data and PT measurements is ruled out in 100 eV limit.
- ✓ There is no significant change in V_{ud} value
  - ✓ V_{ud}(new) = 0.9737(3)
  - ✓ V_{ud}(old) = 0.9738(4)

T. Eronen et al., PRL97 (2006) 232501

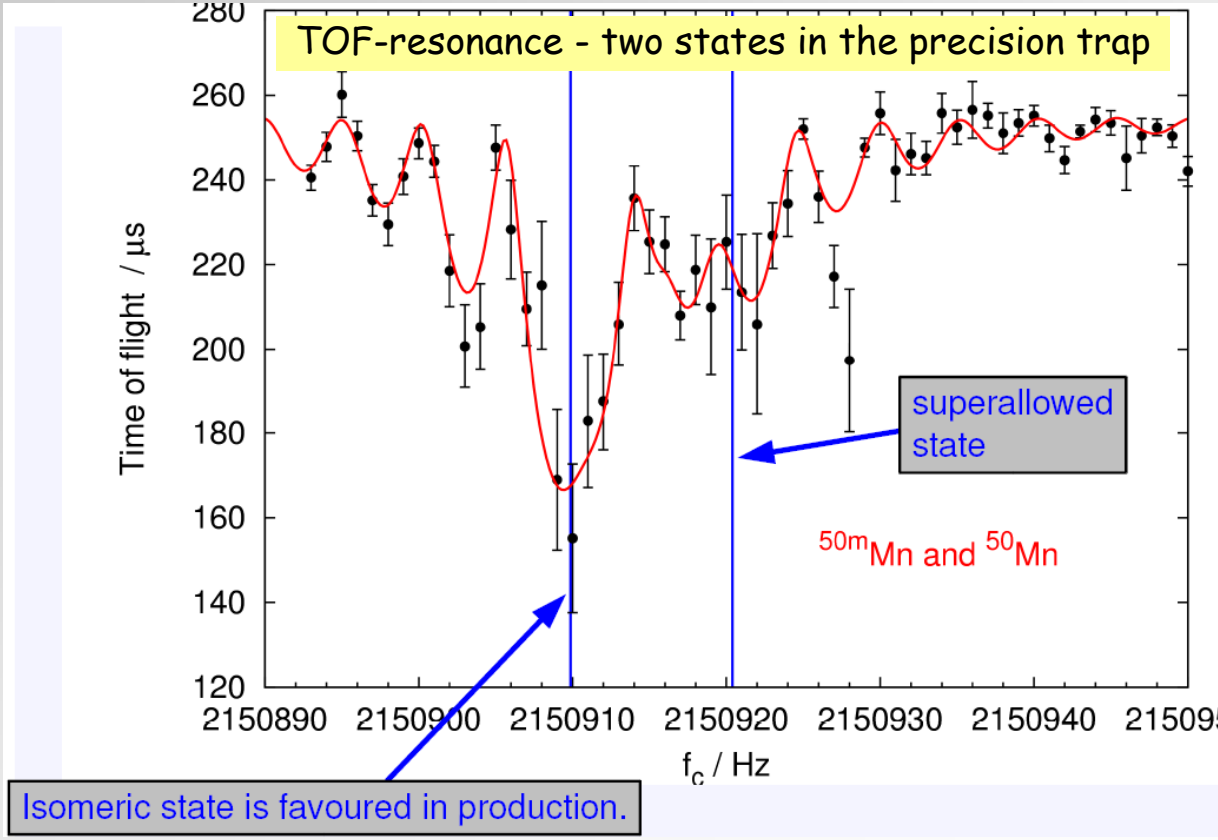
Further studies and challenges …

^{50}Mn and ^{54}Co Q_{EC}-values, measured last week at JYFLTRAP

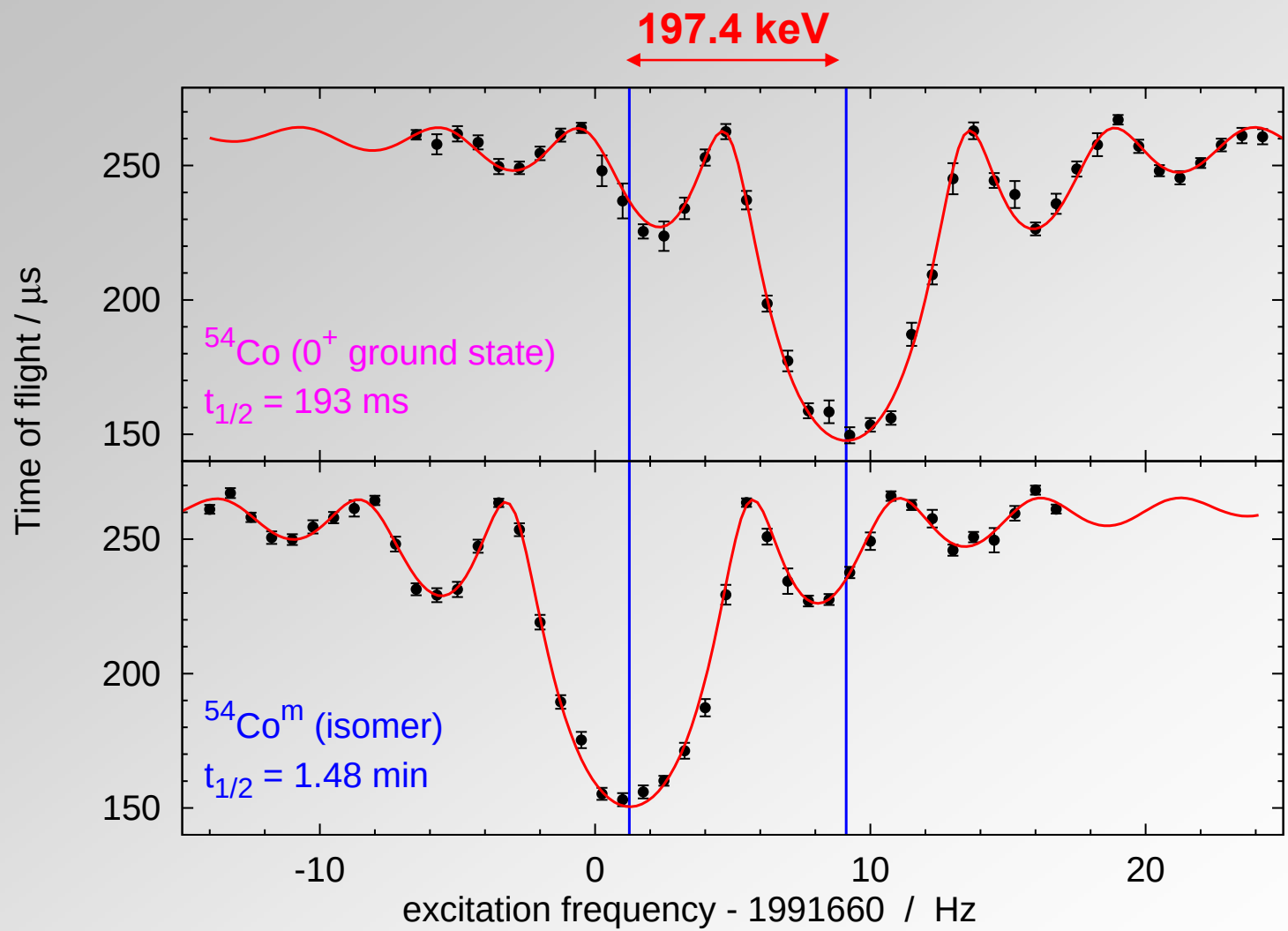
Both isomeric and ground state populated

ΔE(g.s.-m) small and $T_{1/2}$ short

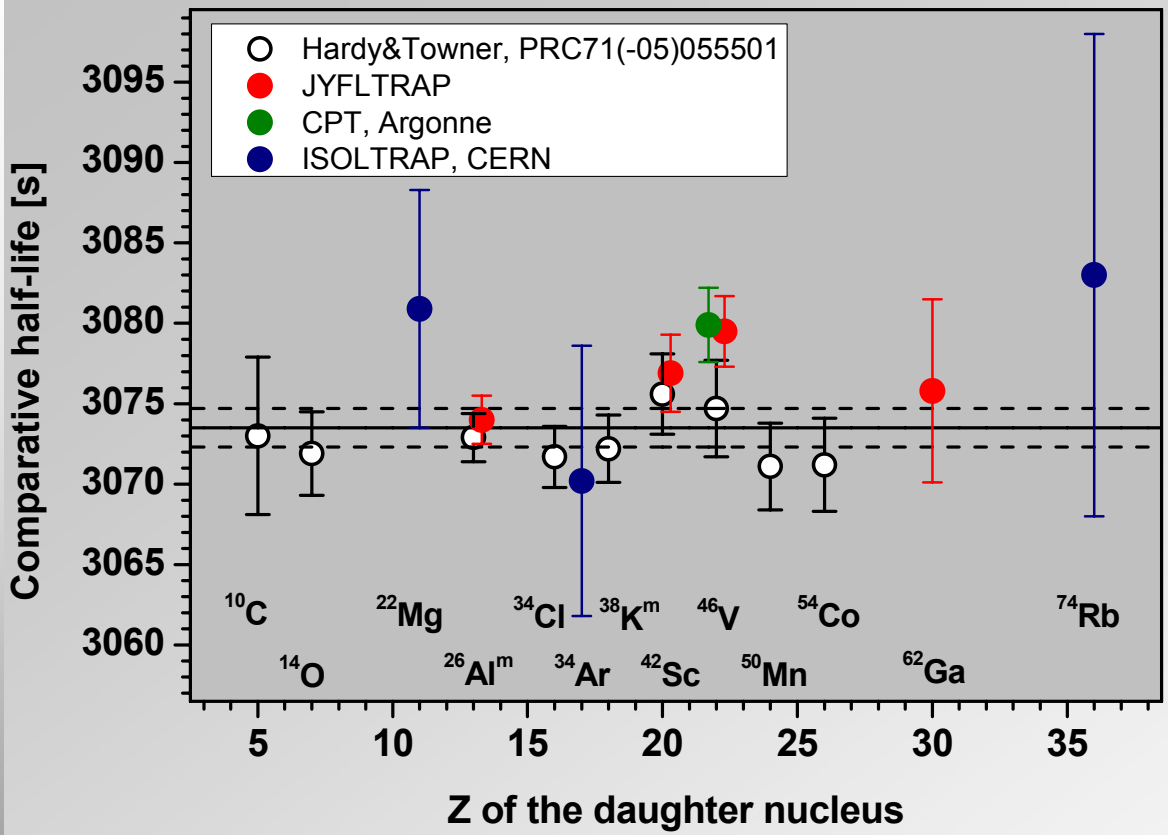
→ conventional isobaric purification does not work → Ramsey cleaning



Ramsey cleaning at work



Experimental status June-2007



New Q_{EC}-value determinations (Penning Trap):

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^{74}Rb	A. Kellerbauer *et al.*, Phys. Rev. Lett. 93 (2004) 072502

^{22}Mg, ^{34}Ar, ^{62}Ga and ^{74}Rb: Error bars in Ft dos not reflect the accuracy of Q_{EC}-determination

JYFLTRAP:

^{50}Mn and ^{54}Co Q_{EC}-values checked and improved in the last week.

Slight deviation in Q_{EC}-value.

Will slightly increase Ft-values

Q_{EC}-values of ^{26}Si and ^{42}Ti in progress

Half-lives:

^{34}Ar and ^{34}Cl, Texas A&M

V.E. Iacob et al., PRC 74 (2006) 055502

^{50}Mn, Auckland/Canberra

Barker & Byrne, PRC 73 (2006) 064306

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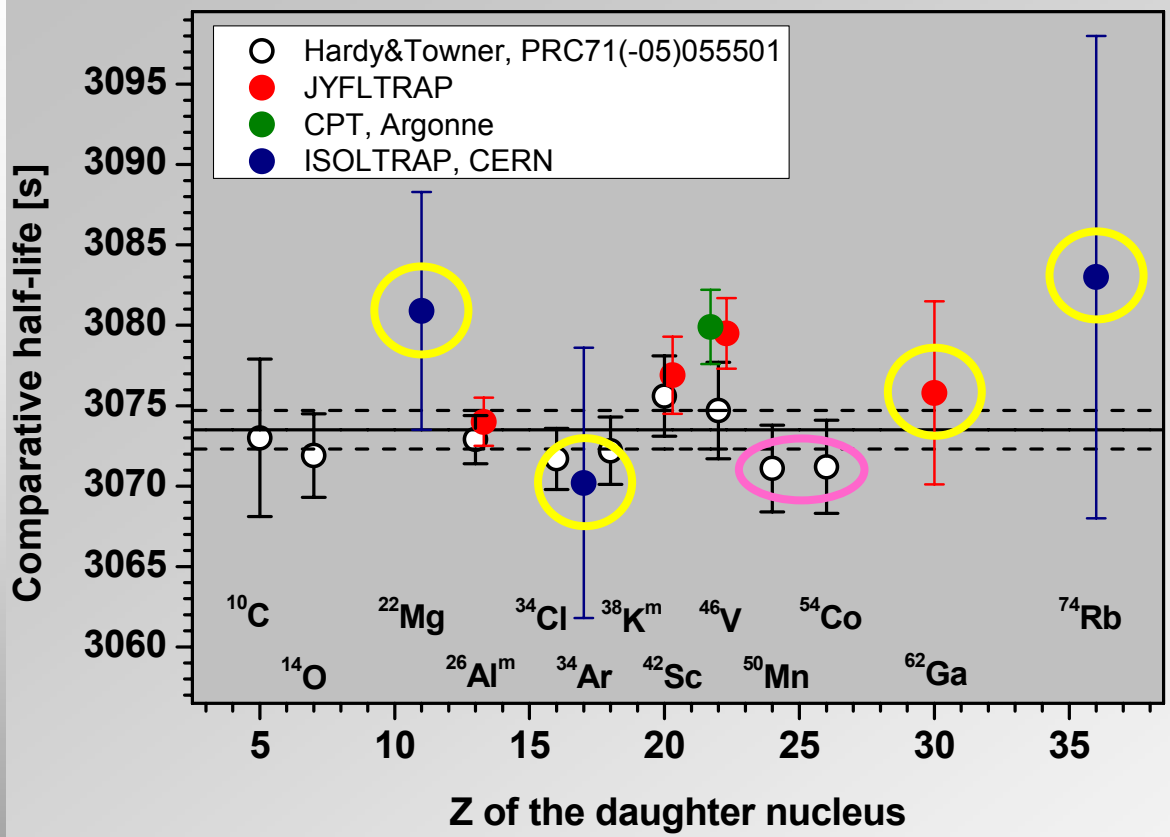

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Implications on V_{ud} and the unitarity of CKM

Situation as now:
J. Hardy CKM2006 + priv. comm.

Ft = 3073.9(8)

V_{ud} = 0.97378(27) ⟷

Compare to 2005 survey
Hardy & Towner, PRC71 (2005) 055501

V_{ud} = 0.97380(40)

Improved precision mainly due to improved radiative correction ΔR
Marciano & Sirlin, PRL96 (2006) 032001

$V_{ud}^2 + V_{us}^2 + V_{ub}^2$ = 0.9992(11)

< 0.0001

0.0509(9) ⟷

M. Moulson, CKM2006:
V_{us} from *Kl3* 0.2257 ± 0.0020

0.9483(5) ⟷

Nuclear 0+ → 0+ 0.9738 ± 0.0003
Neutron decay 0.9745 ± 0.0018
Pion beta decay 0.9751 ± 0.0027

Acknowledgements:

IGISOL-crew:

V.-V. Elomaa
T. Eronen
U. Hager
J. Hakala
A. Jokinen
A. Kankainen
I. Moore
H. Penttilä
S. Rahaman
S. Rinta-Antila
J. Rissanen
T. Sonoda
C. Weber
J. Äystö

Department of Physics,
P.O.Box 35 (YFL)
FIN-40014 University of Jyväskylä

M. Oinonen, Helsinki Institute of Physics, Finland
V. Kolhinen and J. Szerypo, LMU, Munchen, Germany
J. Hardy, Texas A&M, USA