Superallowed β-Decay Studies at TRIUMF-ISAC: New Precision Measurements at the Limits of Nuclear Stability

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TITAN Workshop, TRIUMF June 11, 2005

- **overview of superallowed Fermi $0^+ \rightarrow 0^+$ β-decay**
  - *- present status of V_{ud} and the CKM unitarity problem*
- **the search for 'trivial explanations' to resolve the problem**
  - *focus on nuclear structure dependent corrections*
  - *where are new measurements are needed*
- **New developments in superallowed β-decay studies at ISAC**
  - *high precision lifetime and branching ratio measurements with the 8π gamma-ray spectrometer and SCEPTAR*
  - *high precision mass measurements of highly-charged ions(TITAN)*
- **Need for improved Q_{EC} measurements**
- **Summary**

Probing for Physics beyond the Standard Model via the Cabibbo-Kobayashi-Maskawa (CKM) matrix

- **The CKM matrix plays a central role in the Standard Model**
  - it is a matrix that describes mixing of different quark families because of the weak interaction

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

- The CKM matrix must satisfy unitary condition

  $\Rightarrow$ sum of squares on each row must add to 1, i.e.,

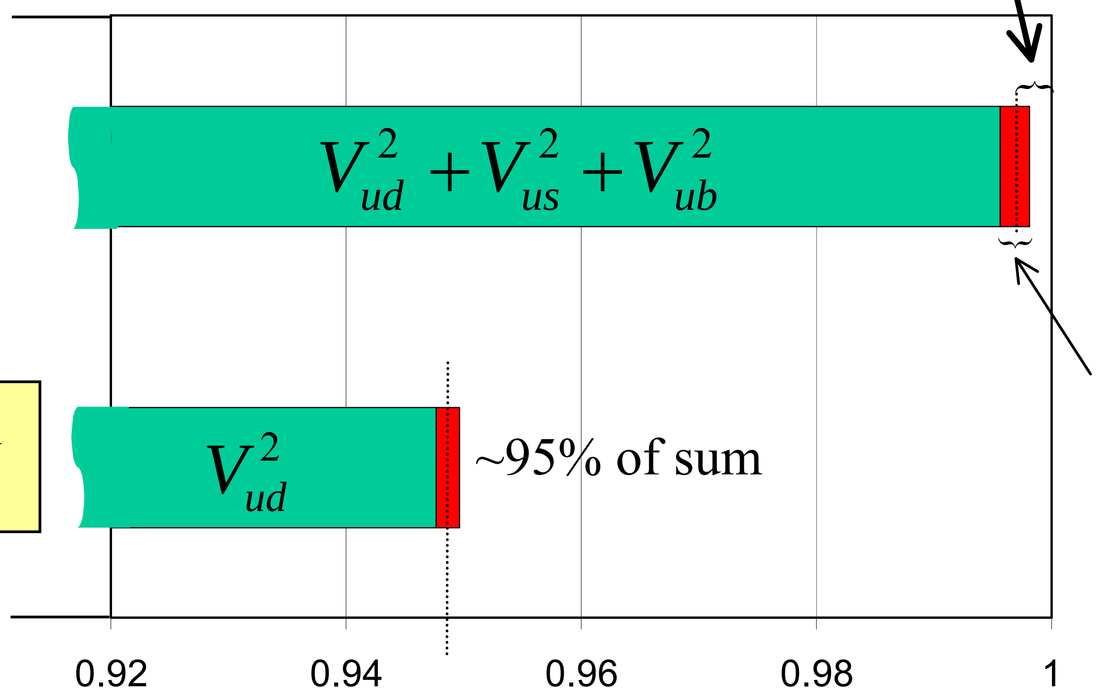
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

The first row of the CKM matrix provides the most demanding experimental test of the unitarity condition.

Current Status of Experimental Test of CKM Unitarity

- **For CKM unitarity, length of bar ≡ 1**
- **Violation of unitarity *at any level* has profound consequences**

Different from Unitarity condition at 98% confidence level



Contribution from nuclear physics

Note scale!

Present status of V_{us}

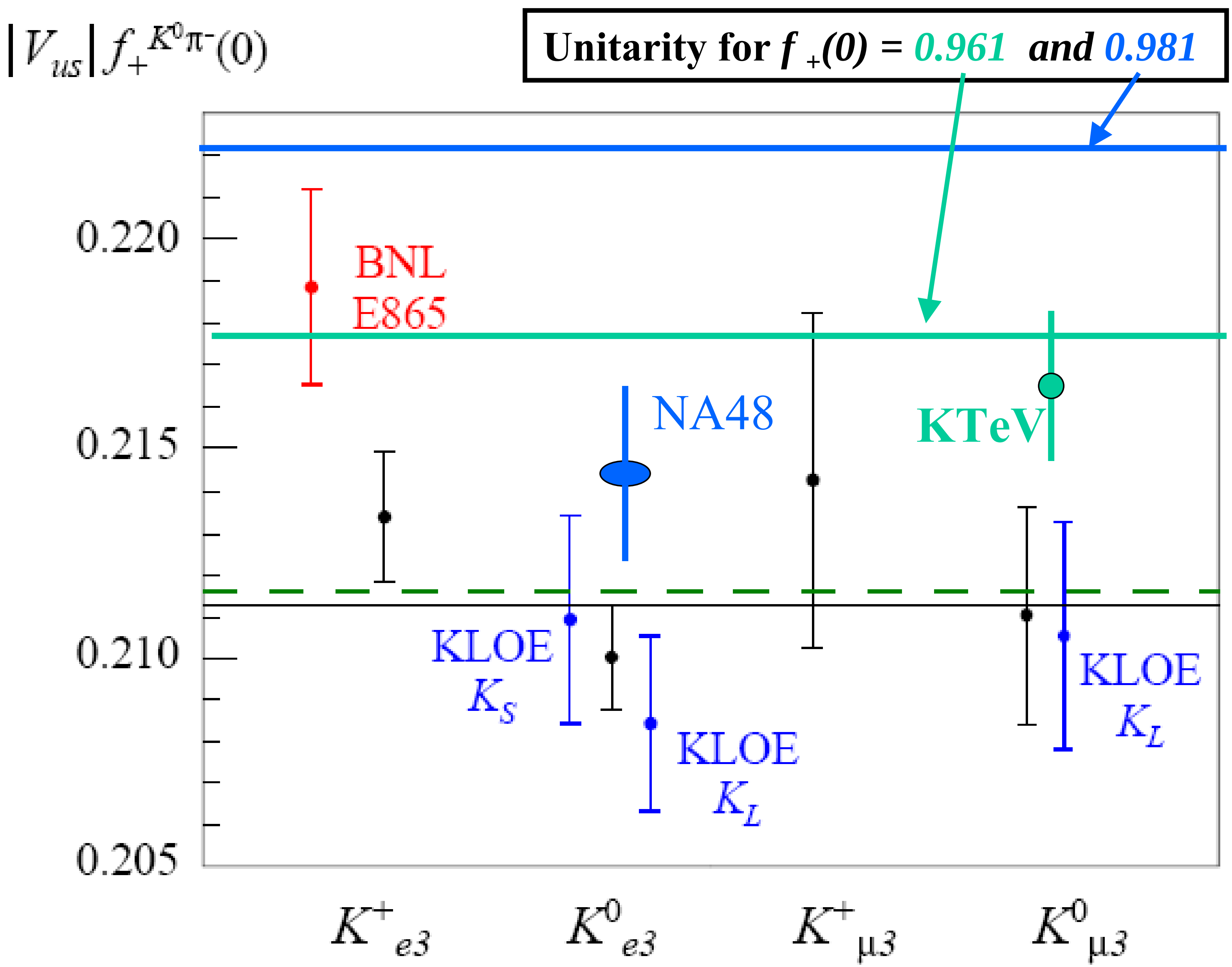
- **Obtained from semileptonic decay of neutral and charged kaons**

  - *four independent determinations* K^+_{e3}, $K^+_{\mu 3}$, K^o_{e3} *and* $K^o_{\mu 3}$
  - *need to measure the decay rate* $\Gamma(K \rightarrow \pi l \nu + n\gamma)$ *and the momentum dependence of two form factors* $f_+(t)$ *and* $f_o(t)$
  - *theoretical radiative and isospin-breaking corrections*
  - *present PDG value* $|V_{us}| = 0.2196\ (23)$

- **new experiments in progress E865, KLOE, NA48, KTeV, CMD2**

  - $K^+ \rightarrow \pi^o e^+ \nu_e\ (K^+_{3e})$ (*E865, Sher et al* PRL 91(2003)261802)

    results in $|V_{us}| = 0.2272\ (23_{rate})$
  - *removes unitarity problem but inconsistent with recent NA48 and KLOE data*



$|V_{us}|f_+^{K^0\pi^-}(0)$
Unitarity for $f_+(0)$ = 0.961 and 0.981
0.220
0.215
0.210
0.205
BNL
E865
NA48
KTeV
KLOE
K_S
KLOE
K_L
KLOE
K_L
K^+_{e3}
K^0_{e3}
$K^+_{\mu 3}$
$K^0_{\mu 3}$

Nuclear Physics Contribution to the CKM Matrix

- $V_{ud}^2 = \frac{G_V^2}{G_F^2}$ where G_F^2 is the Fermi coupling constant determined from muon decay and G_V^2 is related to the β decay between T=1, $J^\pi=0^+$ analogue states by:

$0^+ \rightarrow 0^+$ partial half life

constant

Phase space factor and takes into account interaction of nuclear coulomb field and β particle

$$ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{constant}$$

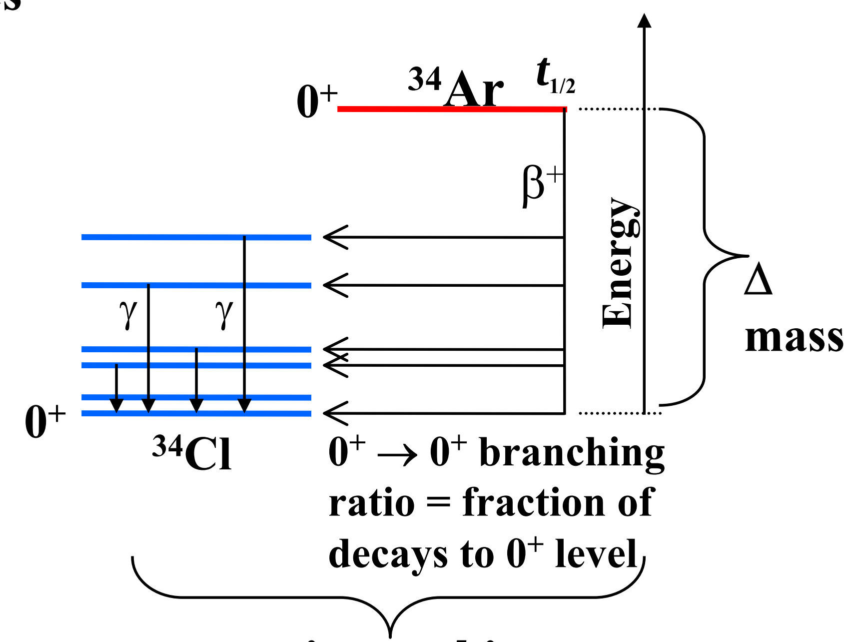
Calculated corrections dependent on nuclear structure

Radiative correction independent of nuclear structure

- Leading order terms in δ_R and Δ_R^V (radiative corrections) are on a firm footing (QED)
- δ_C represents isospin-symmetry-breaking correction
  - viewed as greatest contribution to overall uncertainty

Experimental quantities needed for CKM Matrix Unitarity tests

- **In order to extract G_V^2, the decay process must be limited to pure Fermi decay, achieved by considering only $0^+(A,Z) \rightarrow 0^+(A,Z-1)$ decays between isobaric analogue states**
- **The experimental contribution to $f\,t\,(1-\delta_c)(1+\delta_R)$**
  1) **decay Q value (or masses of initial and final state) to determine f**
  2) **Half life $t_{1/2}$**
  3) **$0^+ \rightarrow 0^+$ branching ratio**

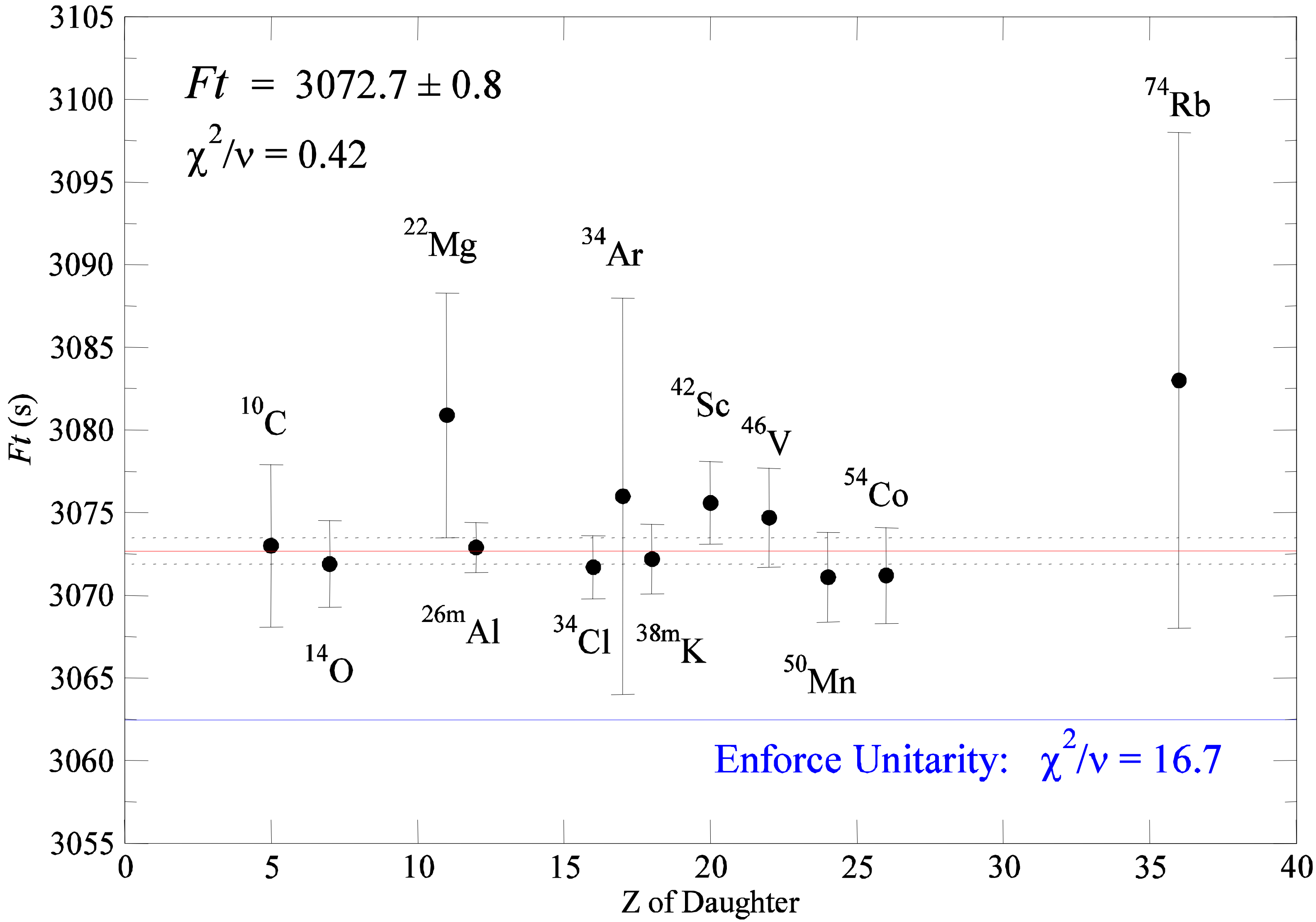


- **Experimentally, need $t_{1/2}$, branching ratio, and masses measured to better than ± 0.1%**

Experimental input to

$$f\,t\,(1-\delta_c)(1+\delta_R)$$

Current status of precision *Ft* values



J.C. Hardy and I.S. Towner, PRC **71**, 055501 (2005)

Future directions for superallowed β-decay studies

- **Present uncertainty in V_{ud} is dominated by theoretical corrections**

(Towner and Hardy, Phys. Rev C66(2002)035501)

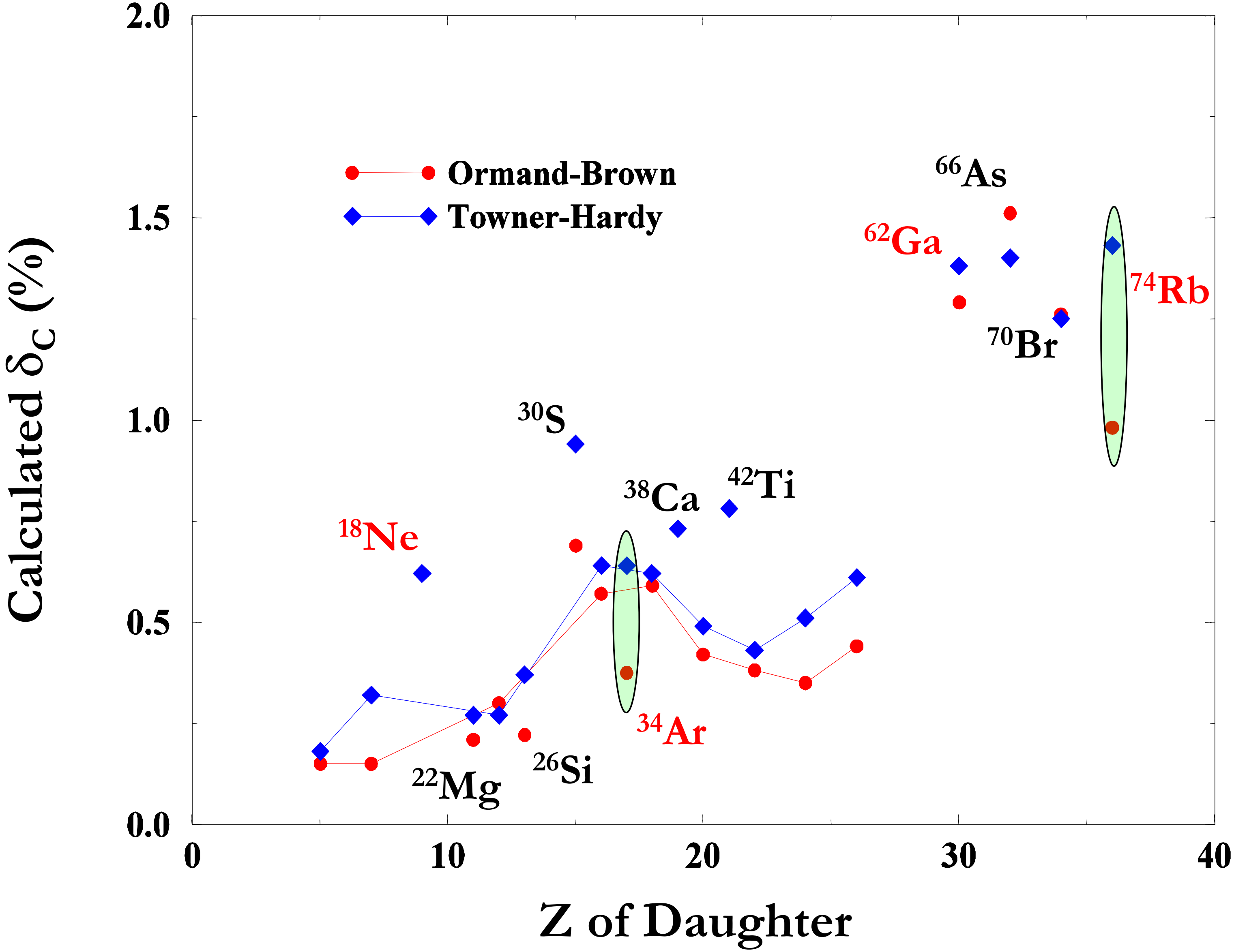
- *uncertainties in radiative corrections are small*
- *focus is on isospin symmetry-breaking corrections (δ_C)*

Experimental Measurements

- **Improved precision for nine well-known transitions**
- **Study of $T_Z = 0$, odd-odd nuclei with $A \geq 62$**
  - *all nuclei are near proton drip line resulting in large Q values (~10 MeV) and short half-lives (~ 50-100 ms)*
- **Study of $T_Z = 1$ nuclei with $18 \leq A \leq 38$**
  - *all nuclei have large (~ 5-50%) branches to excited 1^+ states*

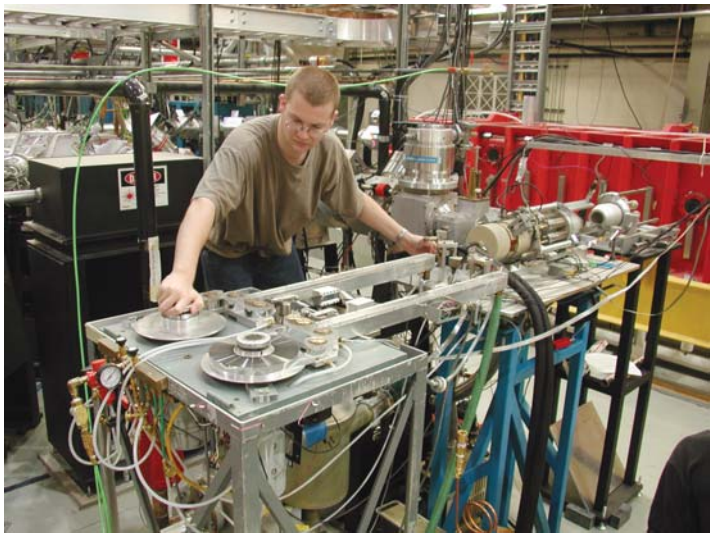
Improved theoretical calculation needed especially for $A \geq 62$

Isospin Symmetry Breaking Corrections

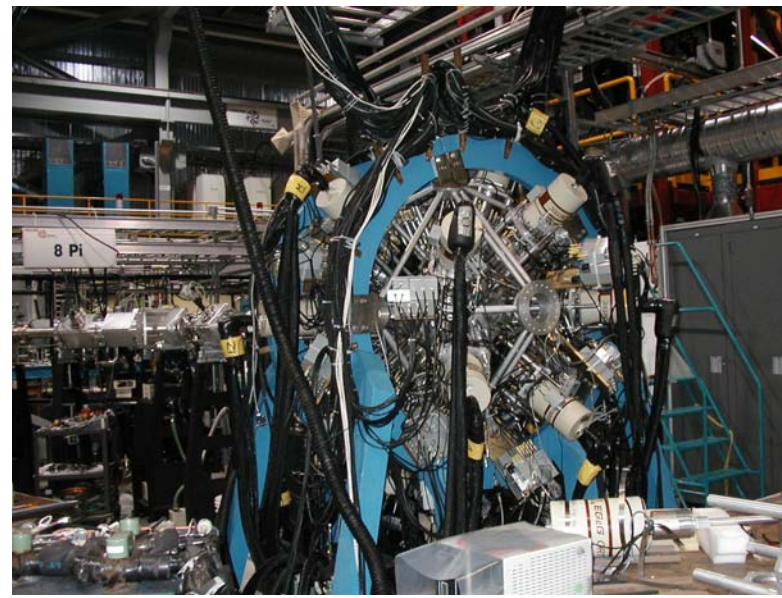


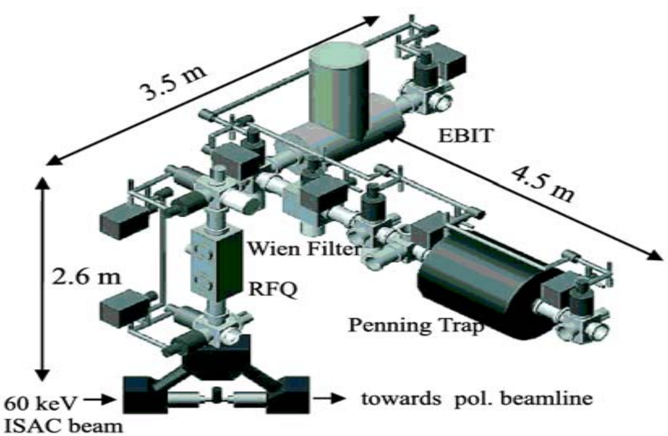
High-precision Superallowed β-decay studies at ISAC

High precision lifetime measurements at GPS

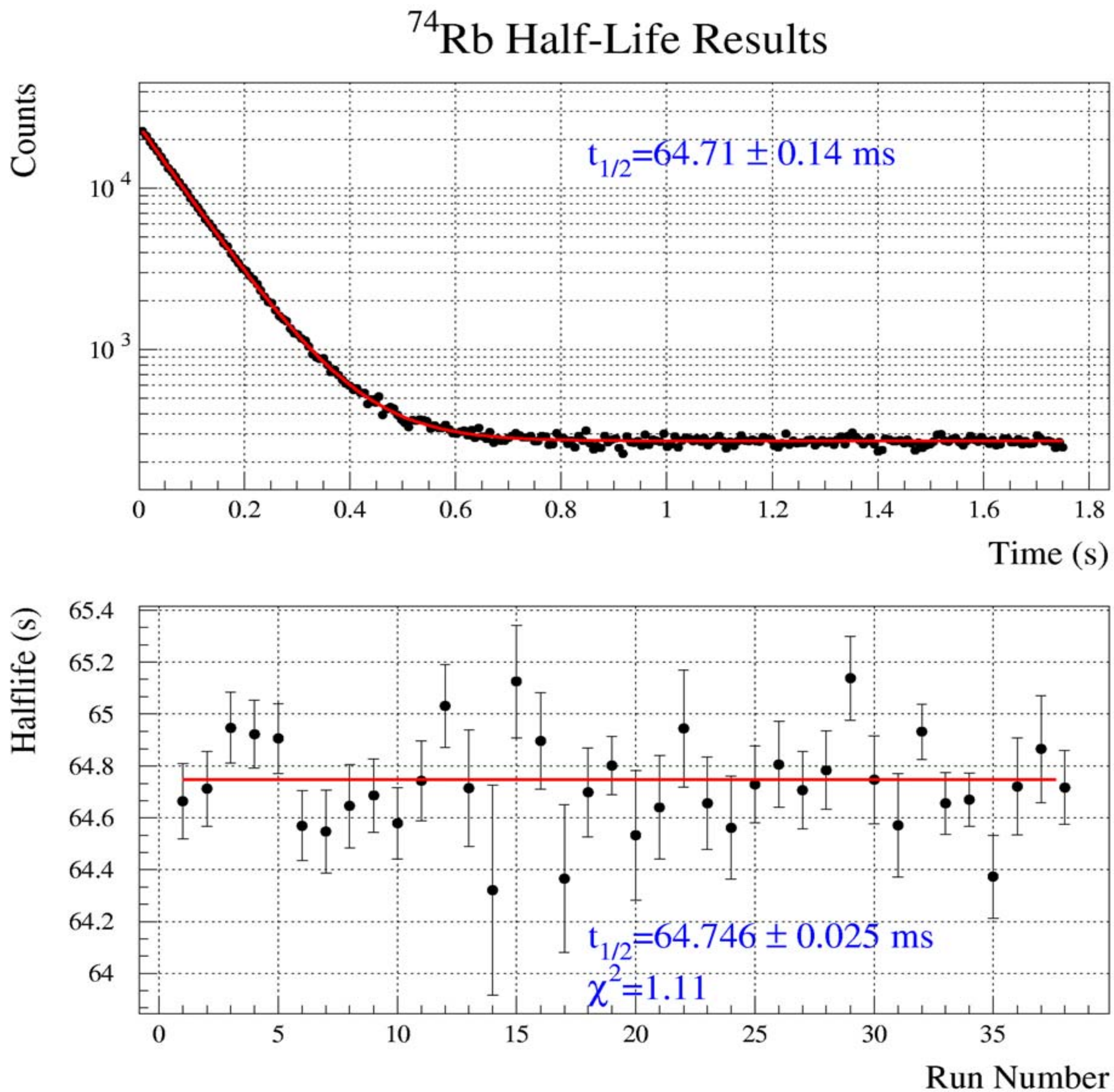


High-precision branching ratio and lifetime measurements with the 8π and SCEPTAR





High-precision mass measurements with TITAN



$^{74}_{37}\mathrm{Rb}_{37}$

Half-Life

previous:

64.9 ± 0.5 ms

ISAC:

- **~ 4000 ^{74}Rb ions s^{-1}**
- **isobaric contaminant ^{74}Ga (t ½ = 8.12 m)**
- **$t_{1/2}$ uncertainty 0.05%**

64.761 ± 0.031 ms

G.C. Ball *et al.,* Phys. Rev. Lett. 86, 1454 (2001)

Summary of high-precision lifetime measurements for ^{26m}Al

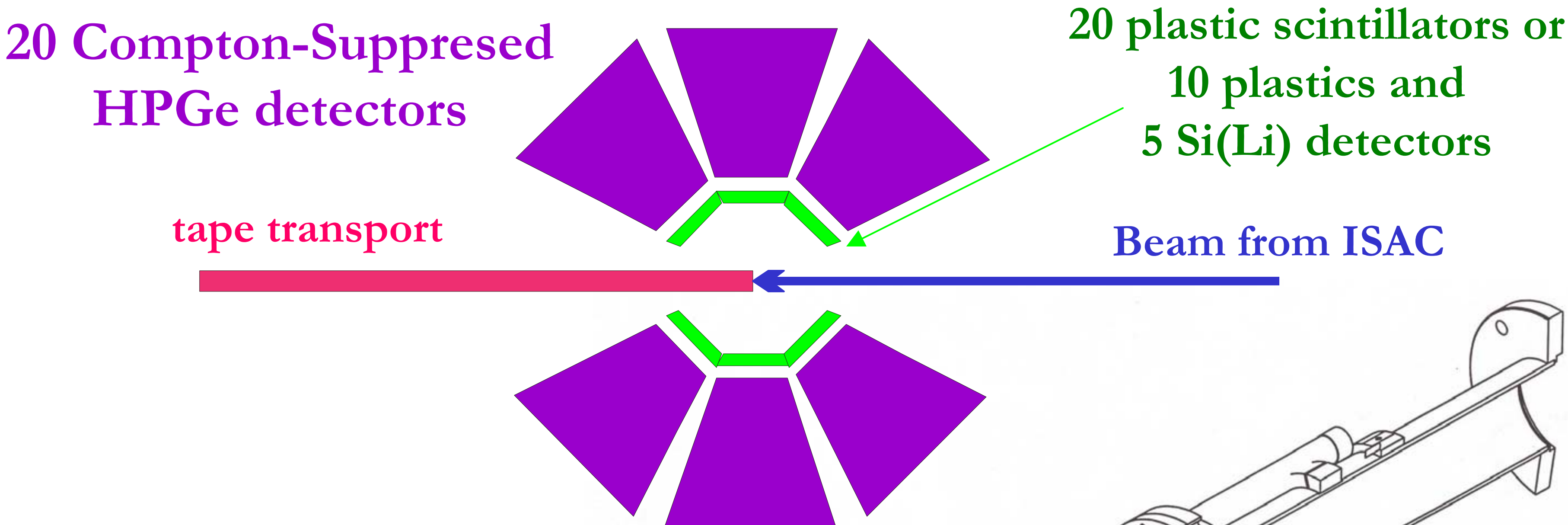
- 6346 ± 5 ms Freeman et al (1969)
- 6346 ± 5 ms Azuelos et al (1974)
- 6339.5 ± 4.5 ms Alburger el al (1977)
- 6346.2 ± 2.6 ms Koslowsky et al (1983)

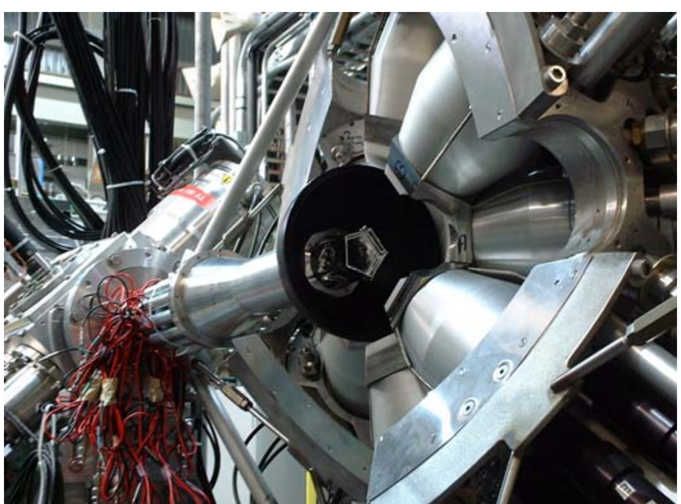
6344.9 ± 1.9 ms weighted average

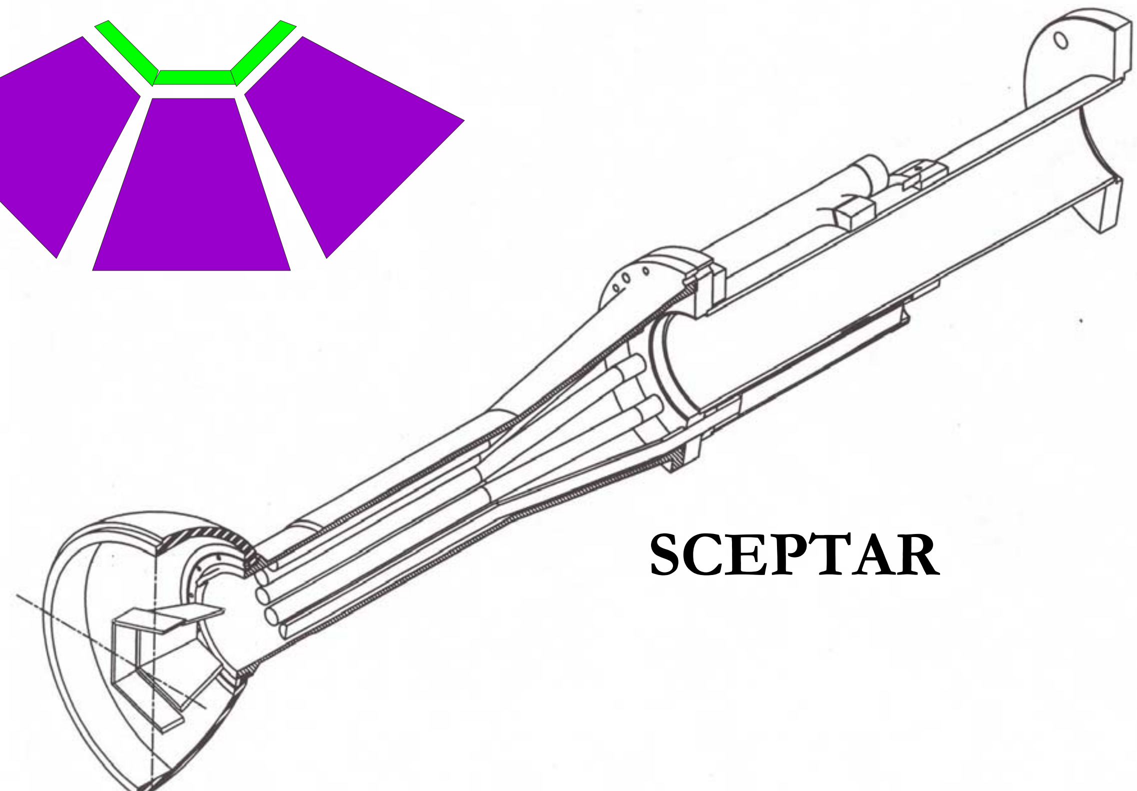
Present objectives:

- a new measurement with a precision of 1.5 – 2.0 ms
- requires a beam intensity of ~ 5 x 10^4 /s and a purity of >99.99%

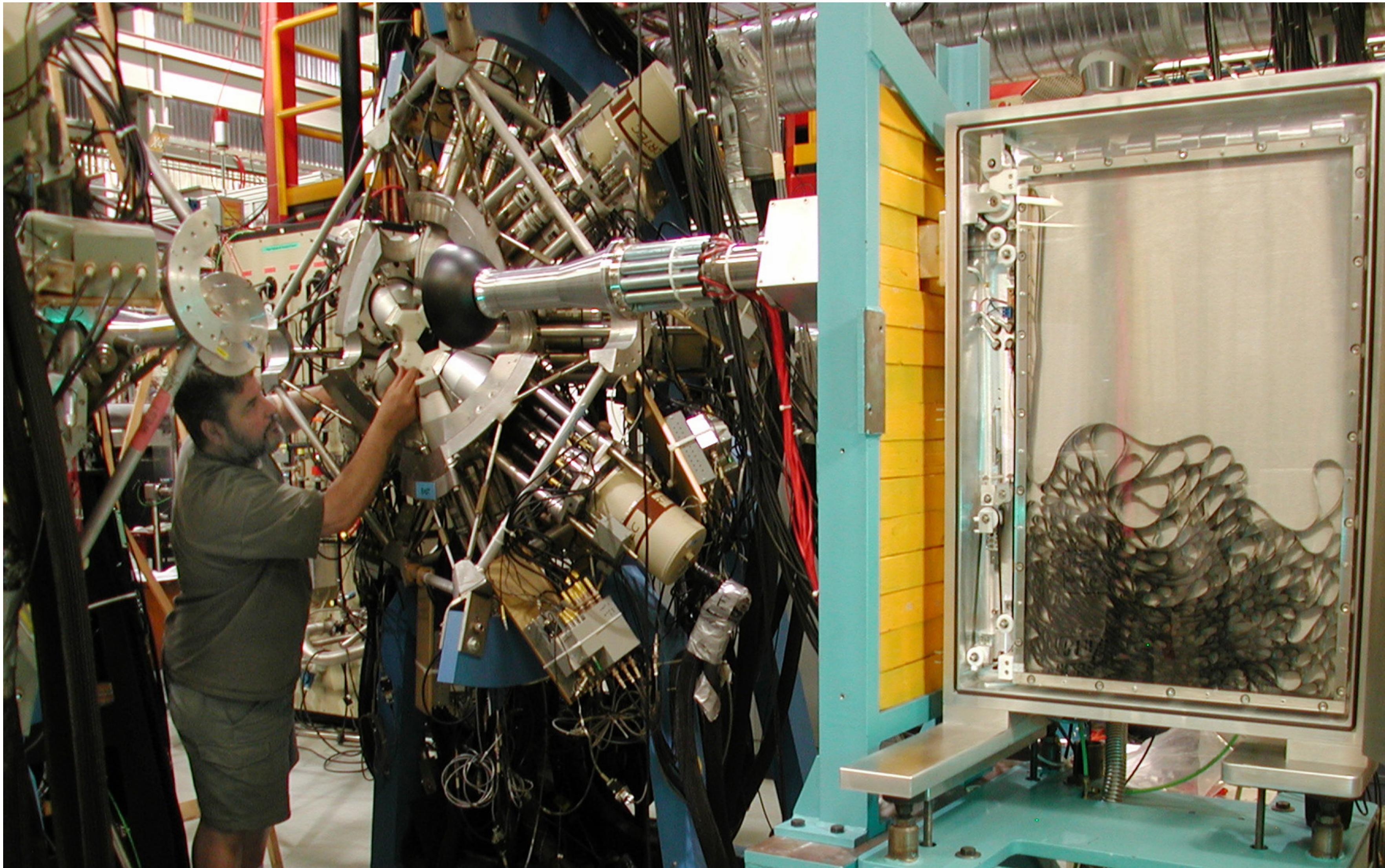
β-decay studies with the reconfigured 8π gamma-ray spectrometer and SCEPTAR at ISAC-I







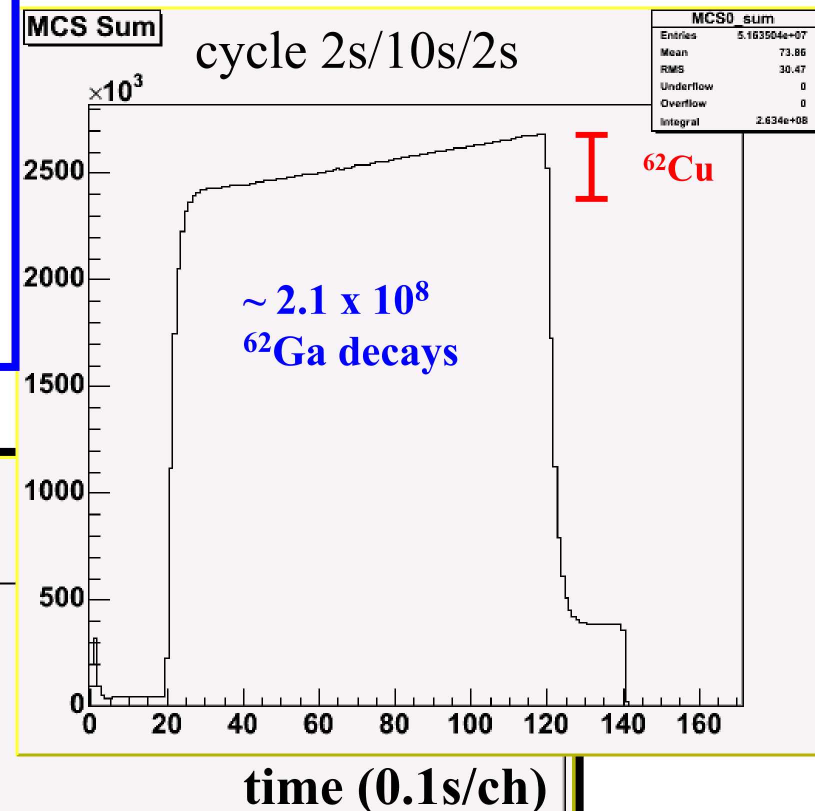
8π Spectrometer with SCEPTAR and moving tape system

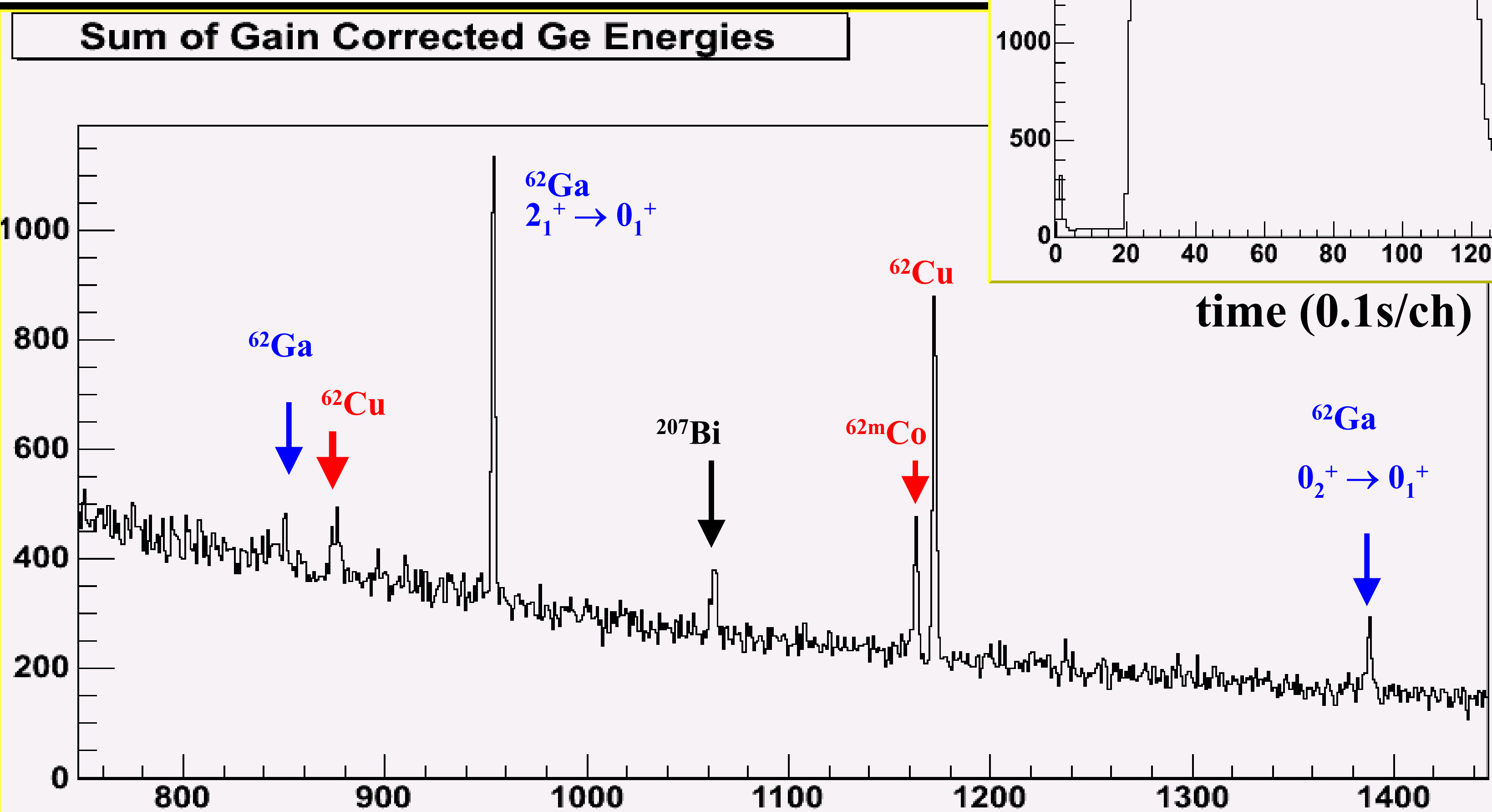


Online ^{62}Ga β-γ Coincidence Spectra

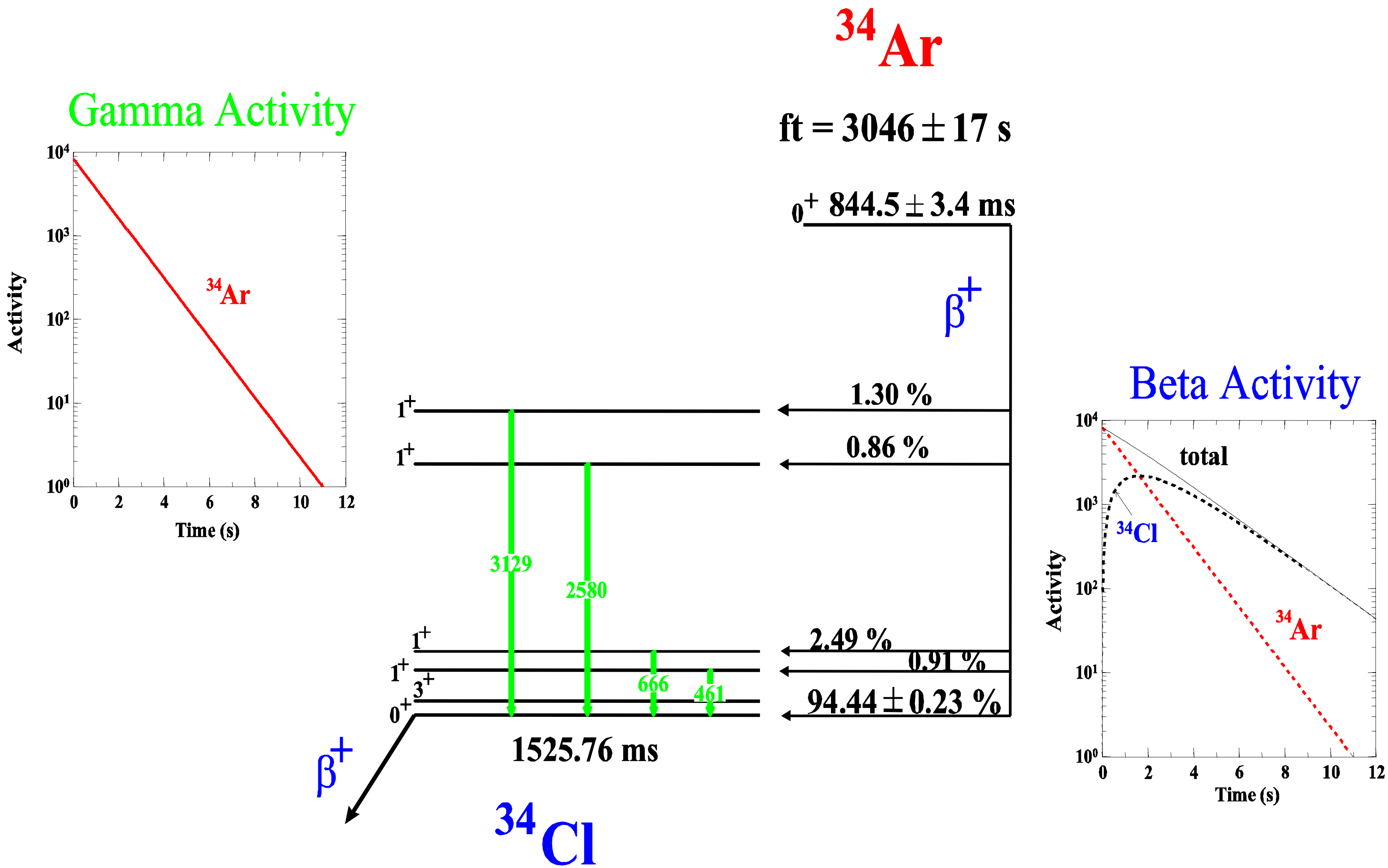
- ~ 1600 ^{62}Ga/s for 3 days
- ~ 80% laser ionized
- ^{62}Cu bkg reduced by a factor of ~20

MCS betas from SCEPTAR

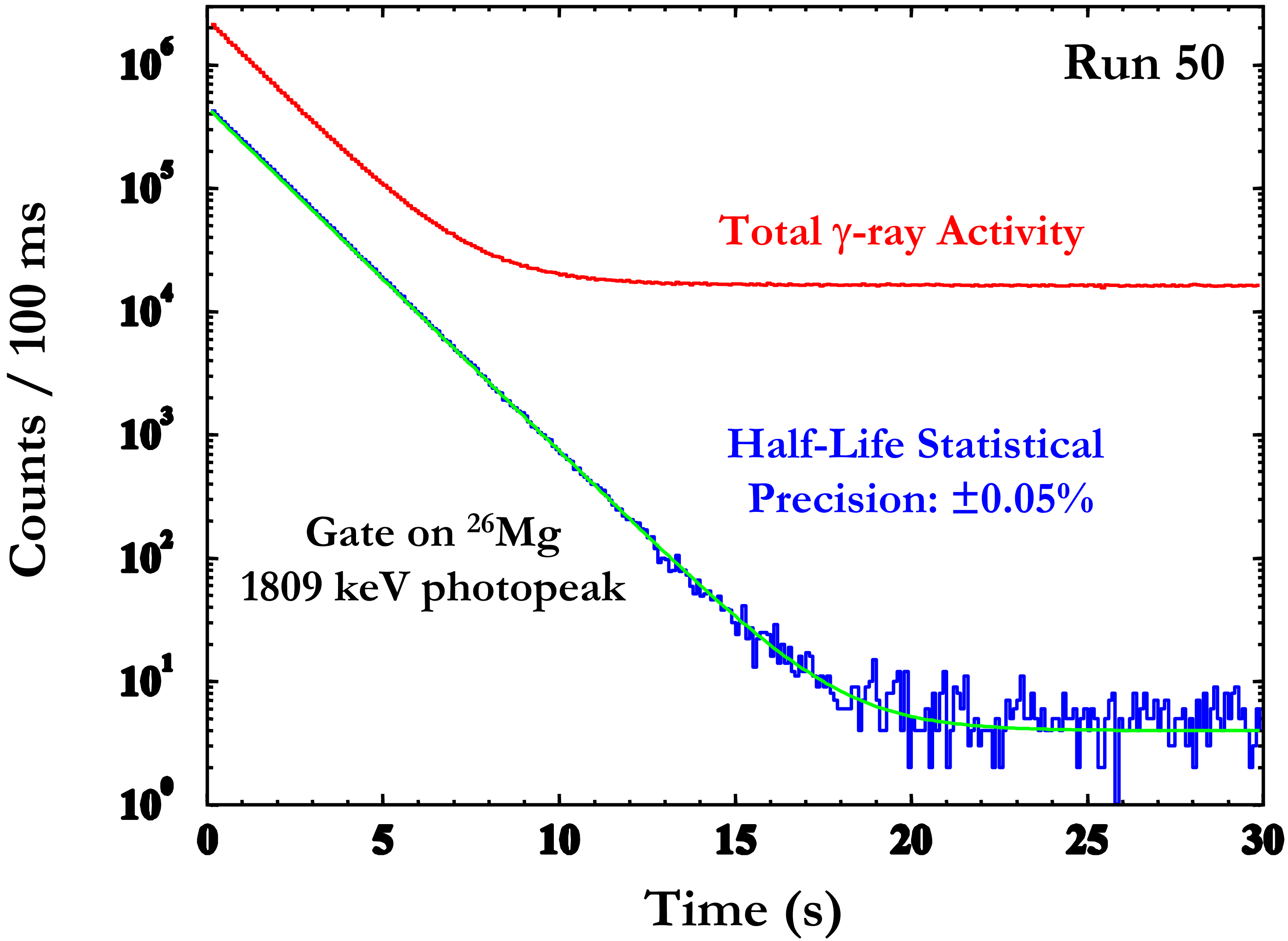




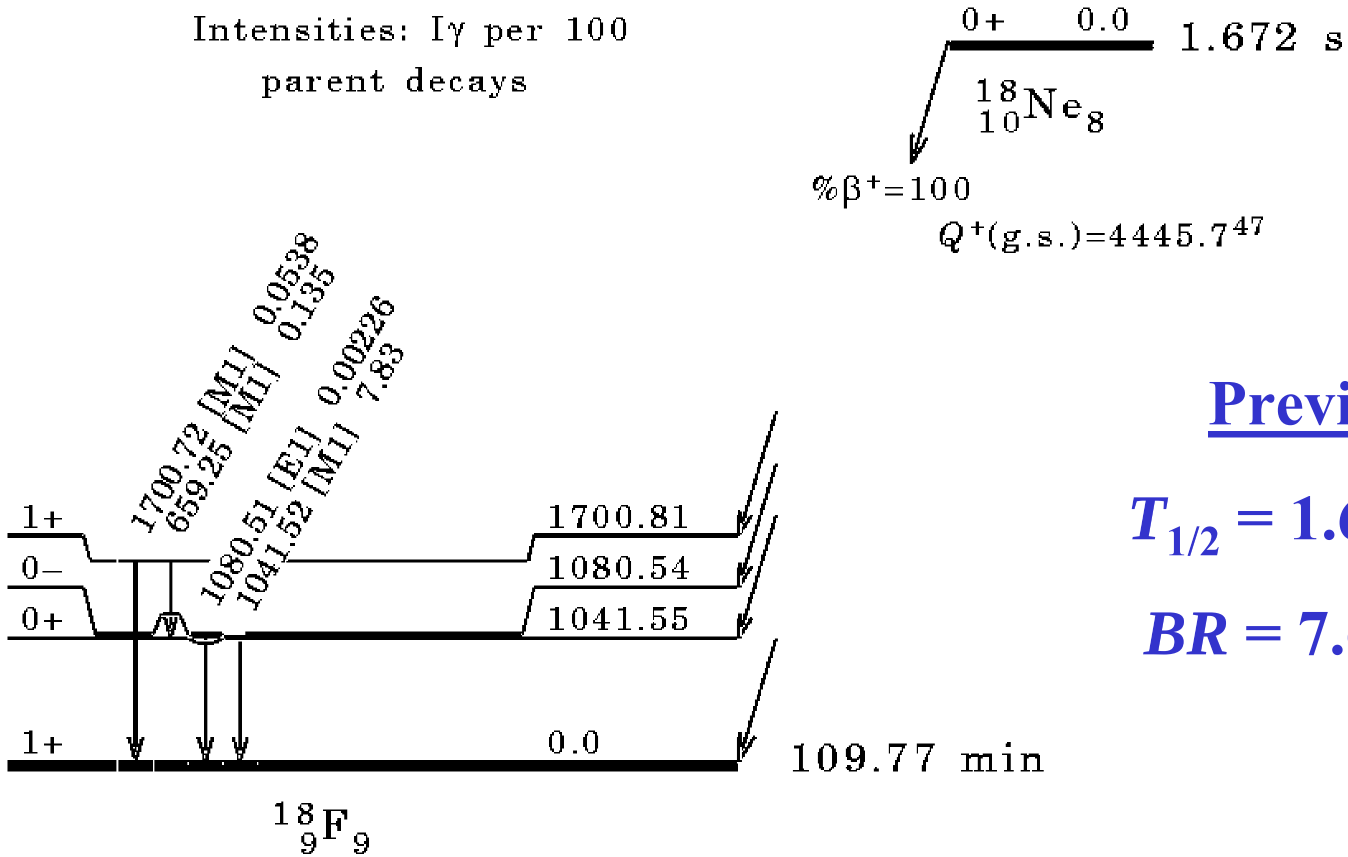
^{34}Ar Superallowed Beta Decay



Test of Gamma-Ray Lifetime Method with Radioactive ^{26}Na Beam to 8π – August 2002



E985: Half-life and Branching-ratio Measurement of ^{18}Ne Superallowed Fermi β decay (Spokesperson: M.B. Smith)



Previous work

$T_{1/2}$ = 1.672 ± 0.004 s

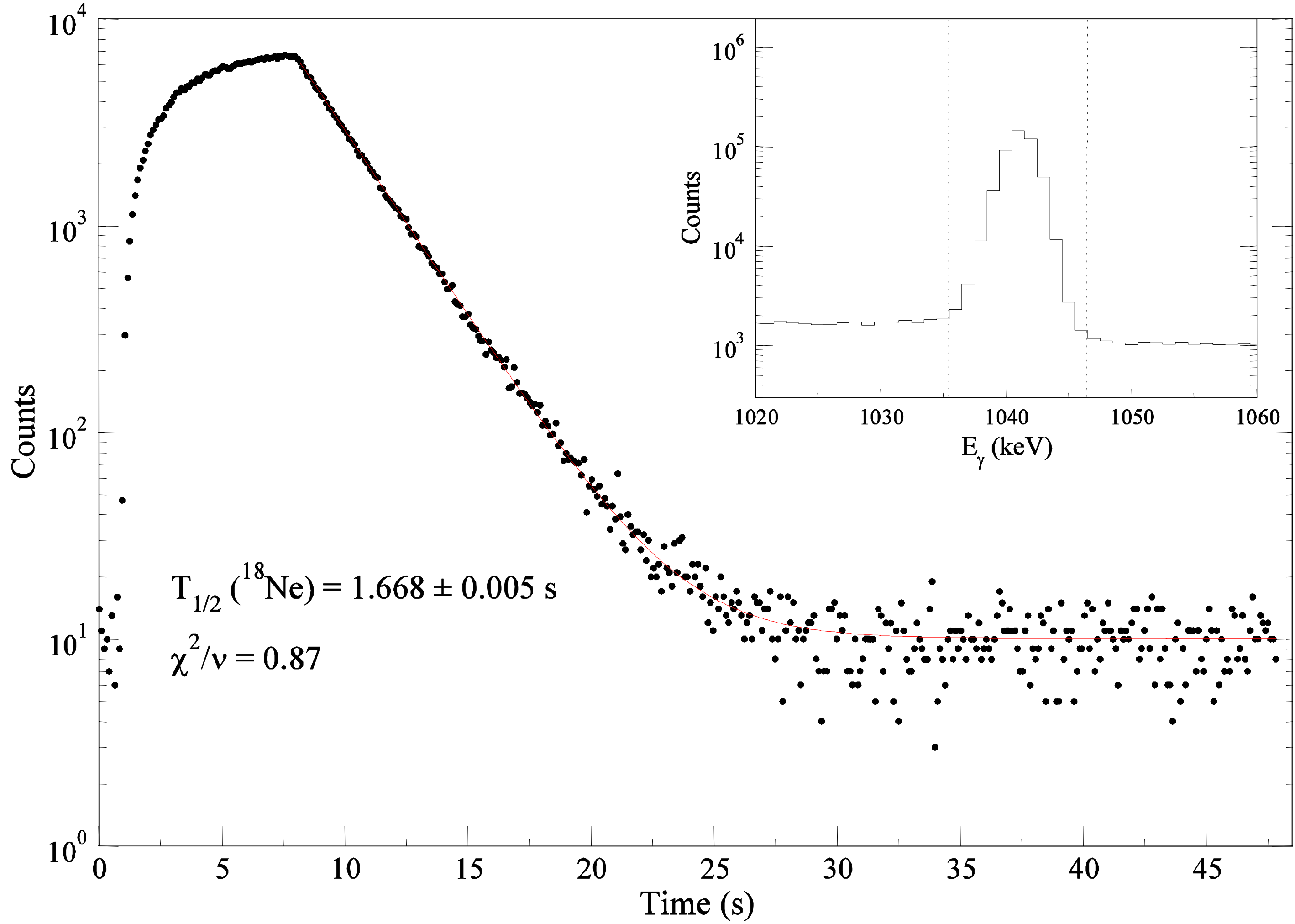
BR = 7.69 ± 0.21 %

Mass excess (Q_{EC}) known to ± 1.5 keV (^{18}Ne) and ± 0.6 keV (^{18}F)
Excitation energy of 0^+ state known to ± 0.08 keV

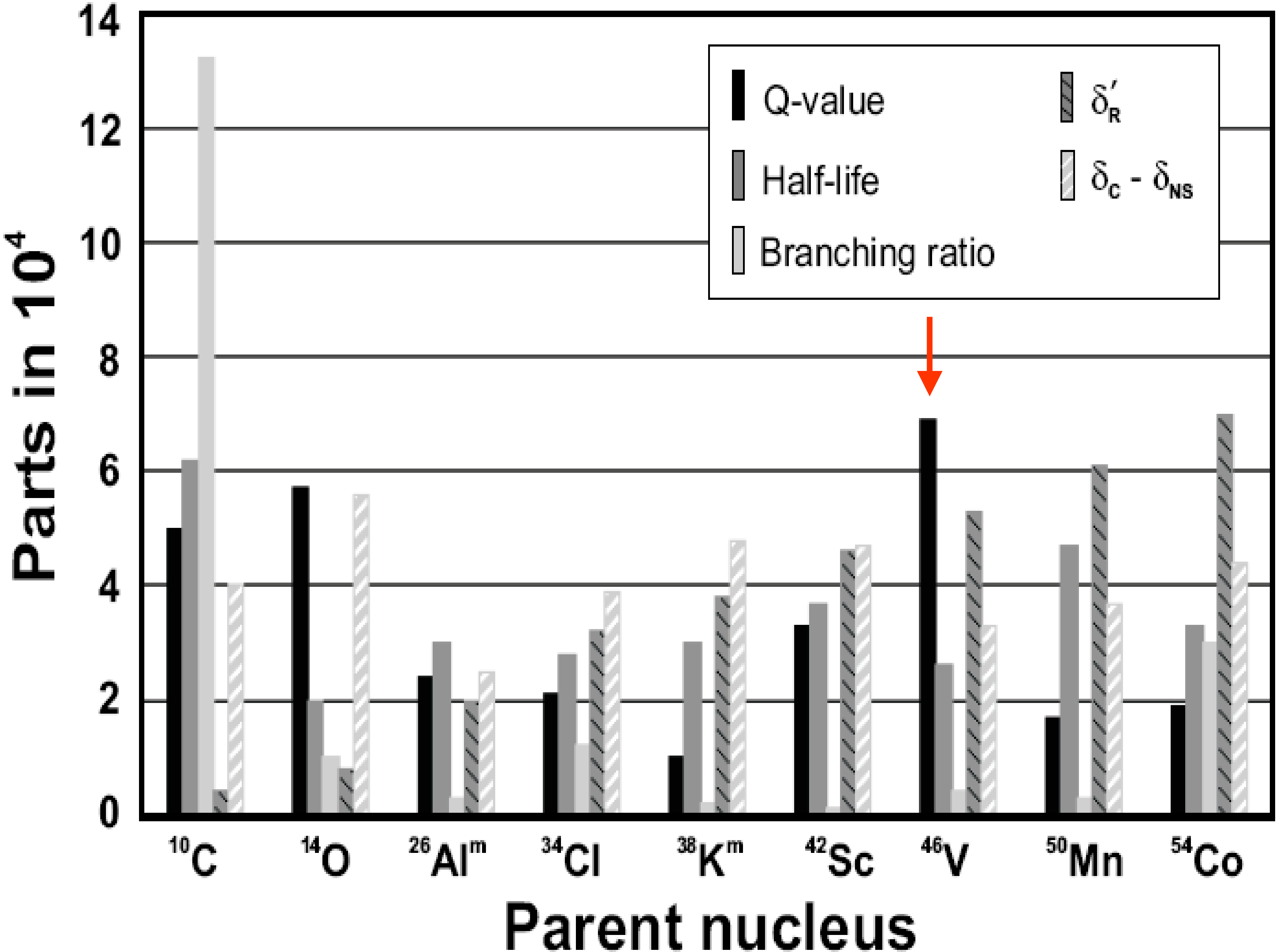
Half-life measurement with the 8π spectrometer

- **90 hours of beam at 10,000 – 30,000 ^{18}Ne ions/s**
- **$t_{1/2}$ ~ 0.1 % precision**
- **first Fermi β decay half-life measured with the 8π at ISAC**

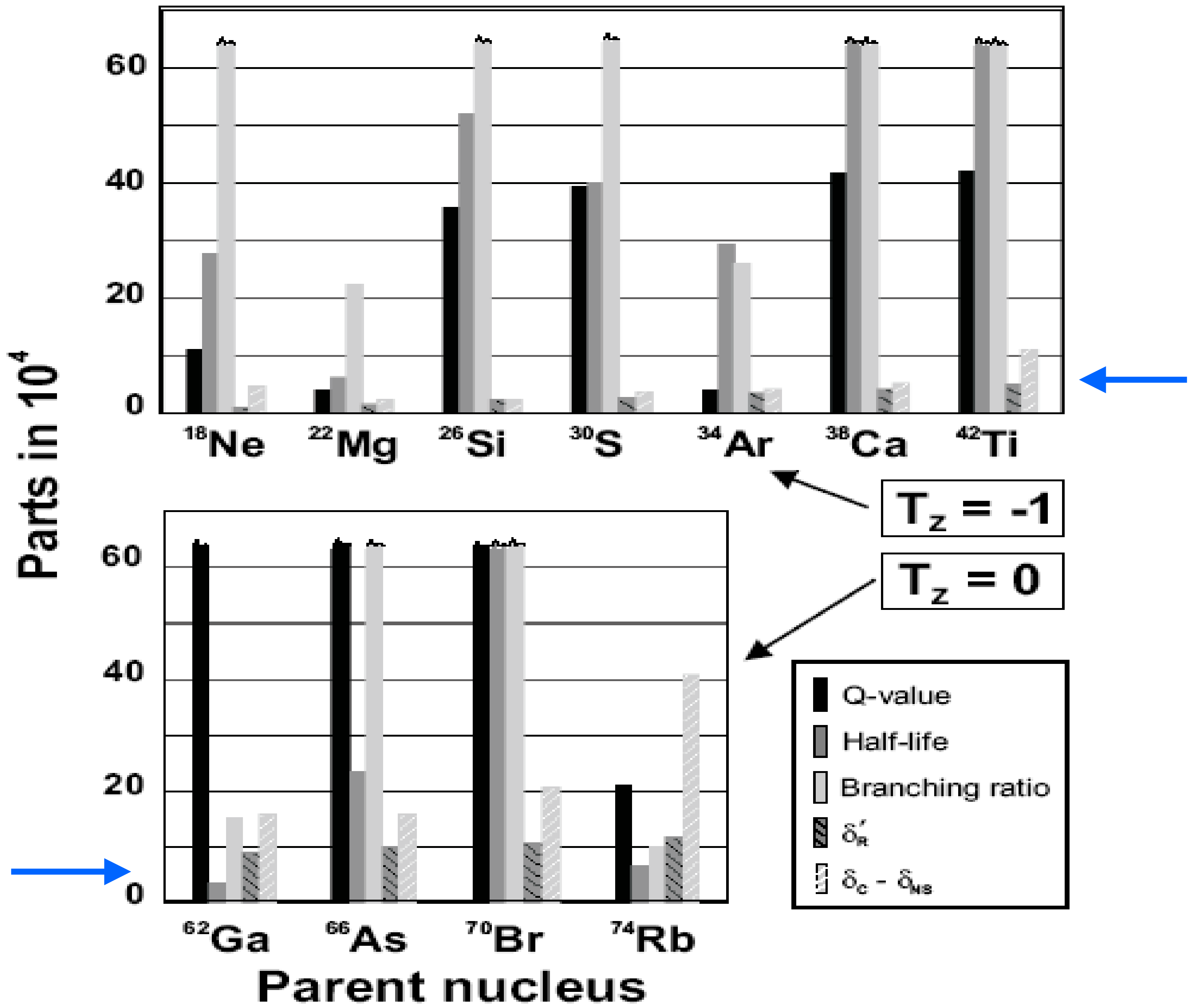
7s beam implantation followed by 40 s decay



M.B. Smith, G.F. Grinyer *et al.*, to be published



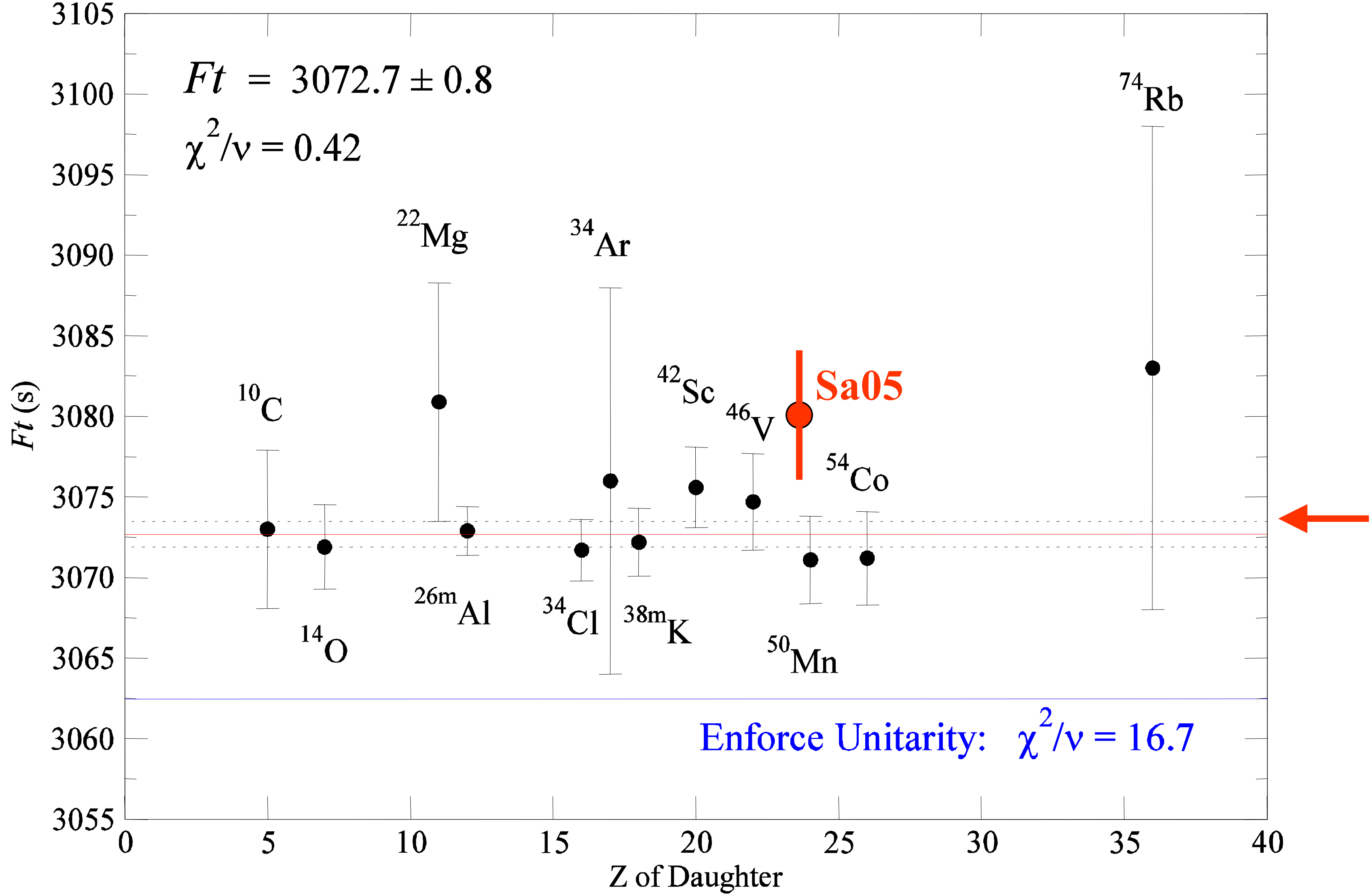
Q-value
Half-life
Branching ratio
δ′R
δC - δNS
Parts in 10^4
0
2
4
6
8
10
12
14
10C
14O
26Alm
34Cl
38Km
42Sc
46V
50Mn
54Co
Parent nucleus



60
40
20
0
Parts in 10^4
^{18}Ne
^{22}Mg
^{26}Si
^{30}S
^{34}Ar
^{38}Ca
^{42}Ti
T_z = -1
T_z = 0
^{62}Ga
^{66}As
^{70}Br
^{74}Rb
Parent nucleus
Q-value
Half-life
Branching ratio
δ_R'
$\delta_C - \delta_{NS}$

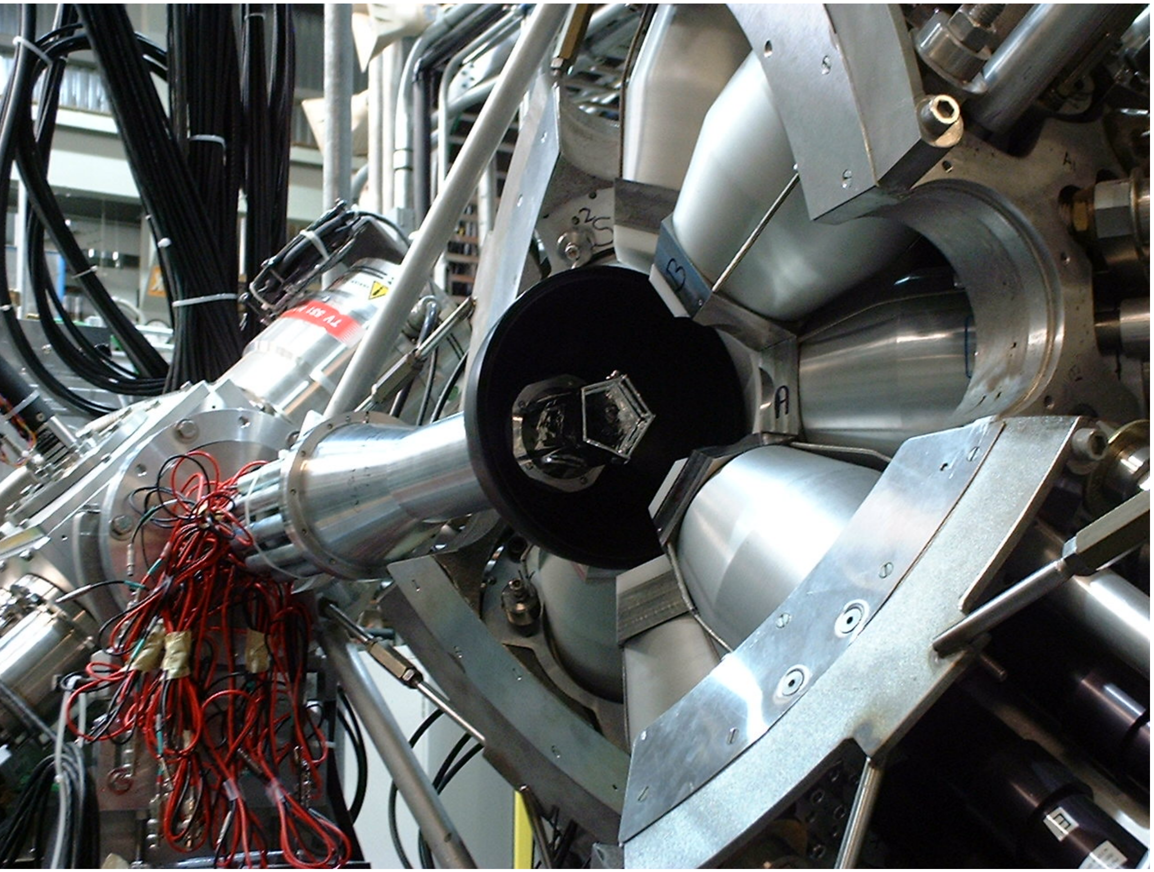
Parent/daughter nuclei		property[1]	Measured energy, Q_{EC} (keV)			Average value	
			1	2	3	Energy (keV)	Scale
$^{38}K^m$	^{38}Ar	$Q_{EC}(gs)$	5914.76 ± 0.60 [Ja78]			5914.76 ± 0.60	
		$E_x(p0^+)$	130.4 ± 0.3 [En98]			130.4 ± 0.3	
		$Q_{EC}(sa)$	6044.6 ± 1.5 [Bu79]	6044.38 ± 0.12 [Ha98]		6044.40 ± 0.11	1.0
^{42}Sc	^{42}Ca	$Q_{EC}(sa)$	6423.71 ± 0.40 [Vo77]	6425.84 ± 0.17[8]		6425.63 ± 0.38[3]	3.2
^{46}V	^{46}Ti	$Q_{EC}(sa)$	7053.3 ± 1.8 [Sq76]	7050.41 ± 0.60 [Vo77]		7050.71 ± 0.89	1.6
^{50}Mn	^{50}Cr	$Q_{EC}(sa)$	7632.8 ± 2.8 [Ha74d]	7631.91 ± 0.40 [Vo77]		7632.43 ± 0.23[3]	1.0
^{54}Co	^{54}Fe	$Q_{EC}(sa)$	8241.2 ± 1.8 [Ho74]	8245.6 ± 3.0 [Ha74d]	8241.61 ± 0.60 [Vo77]	8242.60 ± 0.29[3]	1.5
^{74}Rb	^{74}Kr	$ME(p)$	−51915.2 ± 4.0 [Ke04]			−51915.2 ± 4.0	
		$ME(d)$	−62332.0 ± 2.1 [Ke04]			−62332.0 ± 2.1	
		$Q_{EC}(sa)$				10416.8 ± 4.5	

Current status of precision *Ft* values



J.C. Hardy and I.S. Towner, PRC **71**, 055501 (2005)

Future High Precision measurements for Superallowed β-Decay Studies at ISAC



- ^{34}Ar : $t_{1/2}$, BR
- ^{74}Rb BR, mass
- ^{62}Ga $t_{1/2}$, BR, mass
- ^{66}As $t_{1/2}$, BR, mass
- ^{70}Br $t_{1/2}$, BR, mass
- ^{38m}K BR, 0_2^+
- ^{18}Ne $t_{1/2}$, BR, mass
- ^{26m}Al $t_{1/2}$, BR. mass

Summary

- **New techniques are improving the precision of superallowed β-decay studies and providing for the extension to other cases such as the short lived heavier nuclei**
- **Higher precision mass measurements are needed not only to determine the Q_{EC} values for $A \geq 62$, $T_Z = 0$ nuclei but also to improve and/or verify previous data for the nine "*well known*" cases**
- **Improved theoretical corrections for δ_C are needed especially for heavier nuclei.**
- **The theoretical uncertainty in Δ_R common to neutron, pion and beta decay needs to be addressed.**
- **Several new high statistics measurements of V_{us} are in progress but uncertainties of the vector form factor remain**
- **What will be the outcome, trivial or not ?**

8π Collaborators 2002 - 2004

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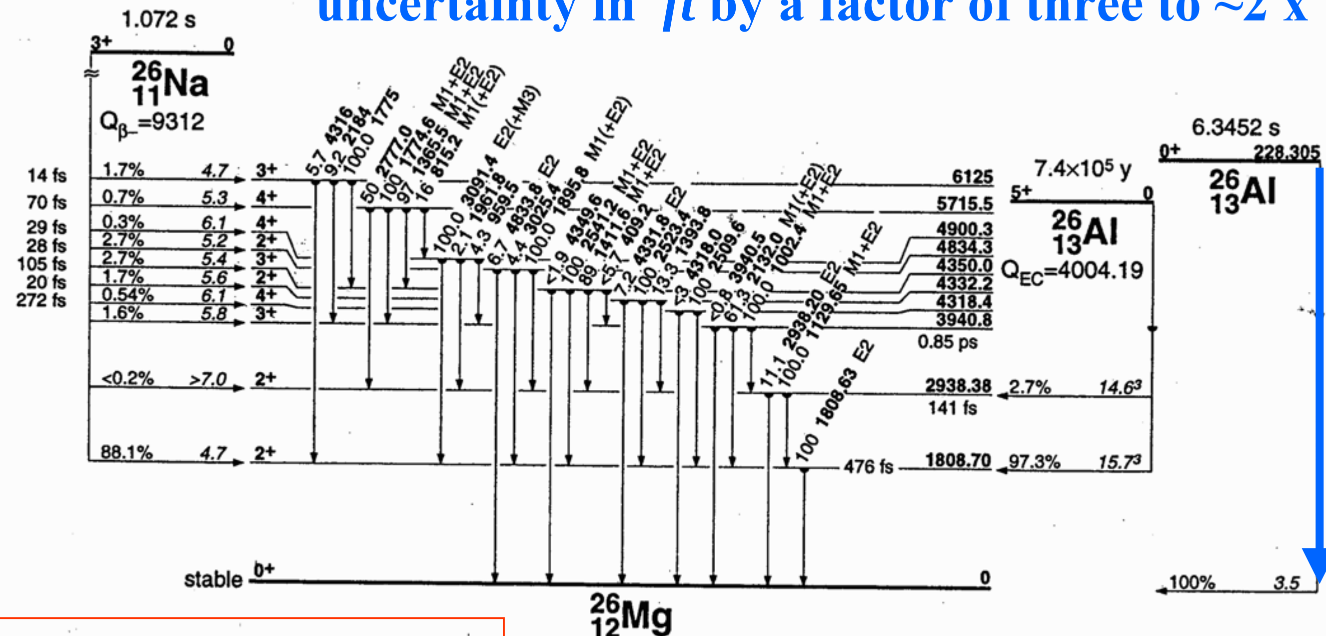
The superallowed β-emitter ^{26m}Al

The objective is to reduce the experimental uncertainty in *ft* by a factor of three to ~2 x 10^{-4}



Present status

$t_{1/2} = 6.3449 \pm 0.0019$ s

BR $\geq 99.97\%$

$Q_{EC} = 4232.42 \pm 0.35$ keV

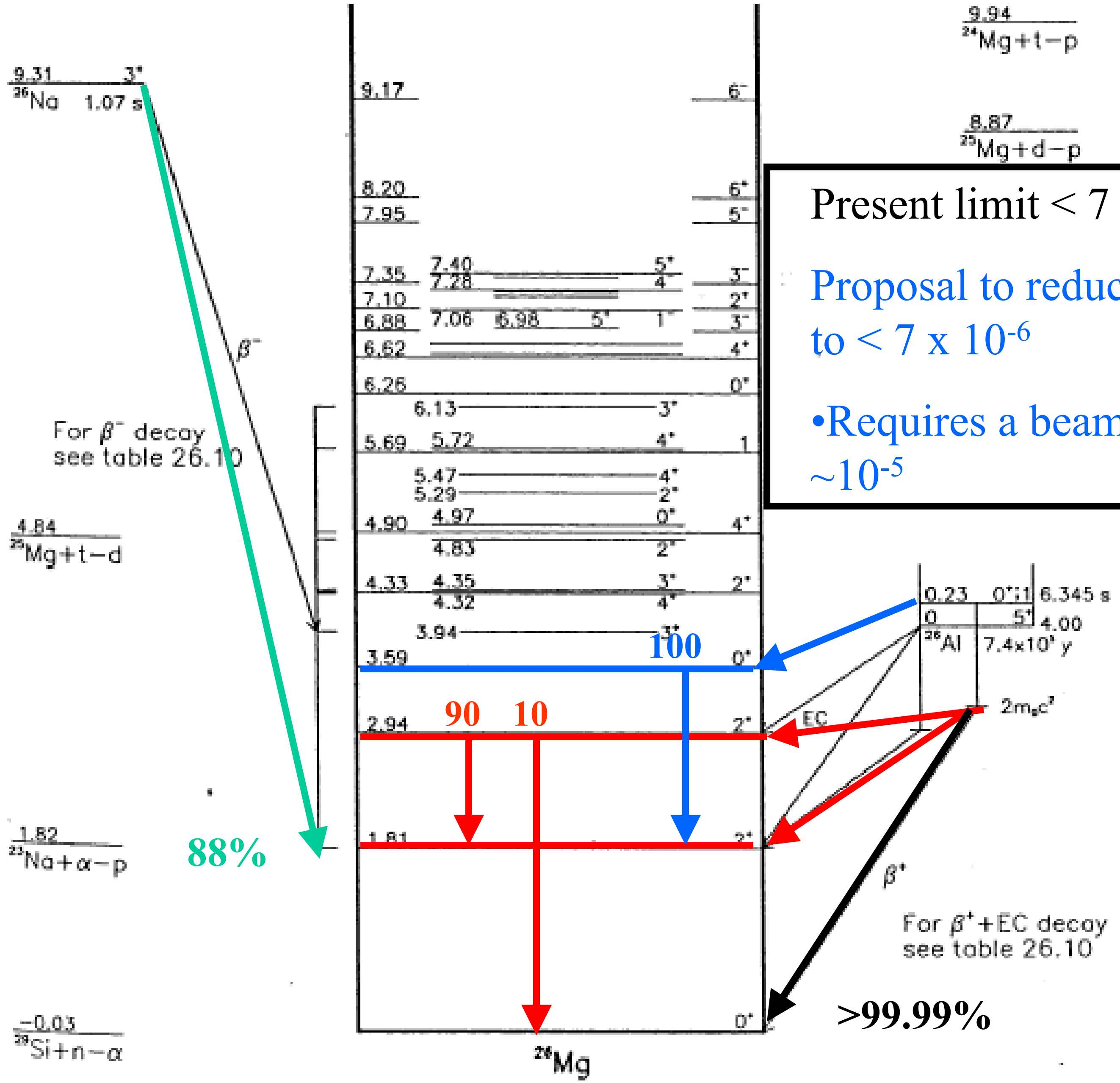
ft = 3035.8(17)

Theoretical corrections

$\delta_C - \delta_{NS} = 0.261(24)\%$

$\delta^1_R = 1.46(2)\ \%$

High-precision branching ratio measurement for ^{26m}Al



Present limit < 7 x 10^{-5}

Proposal to reduce the limit to < 7 x 10^{-6}

- Requires a beam purity of ~10^{-5}

Theoretical corrections in superallowed Fermi β decay

•it is convenient to separate the radiative corrections into two terms

$$\delta_R = \delta^1_R + \delta_{NS}$$

• combining the radiative and Coulomb nuclear structure dependent corrections we obtain:

$$Ft = ft\,(1 + \delta^1_R)(1 + \delta_{NS} - \delta_C)$$

Parent	$\delta_{NS}(\%)$	$\delta_{C1}(\%)$	$\delta_{C2}(\%)$	$\delta_C - \delta_{NS}(\%)$
$T_z = -1$				
^{10}C	−0.360(35)	0.010(10)	0.170(15)	0.540(39)
^{14}O	−0.250(50)	0.050(20)	0.270(15)	0.570(56)
^{18}Ne	−0.290(35)	0.230(30)	0.390(10)	0.910(47)
^{22}Mg	−0.240(20)	0.010(10)	0.255(10)	0.505(24)
^{26}Si	−0.230(20)	0.040(10)	0.330(10)	0.600(24)
^{30}S	−0.190(15)	0.195(30)	0.740(20)	1.125(39)
^{34}Ar	−0.185(15)	0.030(10)	0.610(40)	0.825(44)
^{38}Ca	−0.180(15)	0.020(10)	0.710(50)	0.910(53)
^{42}Ti	−0.240(20)	0.220(100)	0.555(40)	1.015(110)
$T_z = 0$				
^{26m}Al	0.009(20)	0.040(10)	0.230(10)	0.261(24) ←
^{34}Cl	−0.085(15)	0.105(20)	0.530(30)	0.720(39)
^{38m}K	−0.100(15)	0.100(20)	0.520(40)	0.720(47)
^{42}Sc	0.030(20)	0.060(30)	0.430(30)	0.460(47)
^{46}V	−0.040(7)	0.095(20)	0.330(25)	0.465(33)
^{50}Mn	−0.042(7)	0.055(20)	0.450(30)	0.547(37)
^{54}Co	−0.029(7)	0.040(15)	0.570(40)	0.639(43)
^{62}Ga	−0.040(20)	0.330(40)	1.05(15)	1.42(16)
^{66}As	−0.050(20)	0.250(40)	1.15(15)	1.45(16)
^{70}Br	−0.060(20)	0.350(40)	1.00(20)	1.41(21)
^{74}Rb	−0.065(20)	0.130(60)	1.30(40)	1.50(41)