V_{ud} from superallowed nuclear β^+ decays: new high-precision experimental results

V.E. Iacob

Cyclotron Institute, Texas A&M University, College Station, TX 77843

**11th International Workshop on the CKM Unitarity Triangle,
(CKM2021)
Nov 22-26, 2021**

22:18

Presentation based on following papers

- J. C. Hardy and I. S. Towner, Phys. Rev. C **102**, 045501, (2020)
- B. Blank *et al.*, Eur. Phys. J. A **56**:156, (2020)
- A. D. MacLean *et al.*, Phys. Rev. C **102**, 054325 (2020)
- M. Bencomo *et al.,* Phys.Rev. C **100**, 015503 (2019)
- V. E. Iacob *et al.,* Phys.Rev. C **101**, 045501 (2020)
- V. E. Iacob *et al.,* Phys.Rev. C **101**, 015504 (2020)
- H. I. Park *et al.,* Phys.Rev. C **102**, 045502 (2020)

CKM Matrix and Unitarity, 2020

Cabibbo-Kobayashi-Maskawa Quark-Mixing-Matrix

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

weak eigenstates — mass eigenstates

Three-Generation Unitarity

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

$|V_{ud}| = G_V/G_\mu$
nuclear (&neutron) decays
muon decay
0.97373±0.00031

$|V_{us}|$
$K^+ \rightarrow \pi^0 e^+ \nu_e$
$K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$
0.21652±0.00041

$|V_{ub}|$
B decays
0.00394±0.00036

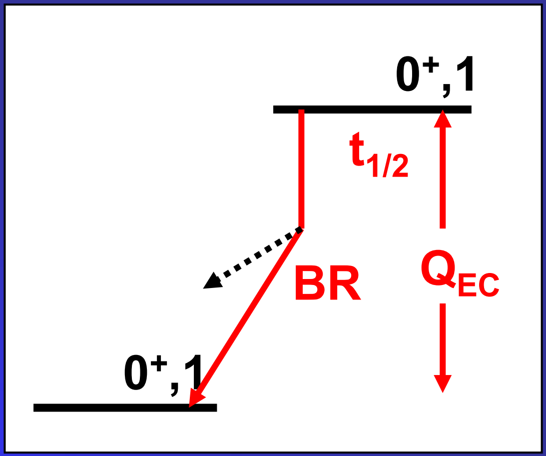
World Data, 2020
J. C. Hardy and I. S. Towner,
DOI: 10.1103/PhysRevC.102.045501

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9985 \pm 0.0006$$

V.E. Iacob

22:18

Superallowed $0^+ \rightarrow 0^+$ β decay



Experiment **precision: 0.1%**

Weak Decay Equation

$$ft = \frac{K}{G_V^2 \langle \tau \rangle^2}$$

$$f = \text{f}(Z, Q_{EC})$$

$$t = \text{f}(t_{1/2}, BR)$$

$$G_V = \text{coupling constant}$$

$$\langle \tau \rangle = \text{matrix element}$$

$$\delta_R^{'} = \text{f}(Z, Q_{EC})$$

$$\delta_{NS} = \text{f}(\text{nuclear structure})$$

$$\delta_C = \text{f}(\text{nuclear structure})$$

$$\Delta_R^V = \text{f}(\text{interaction})$$

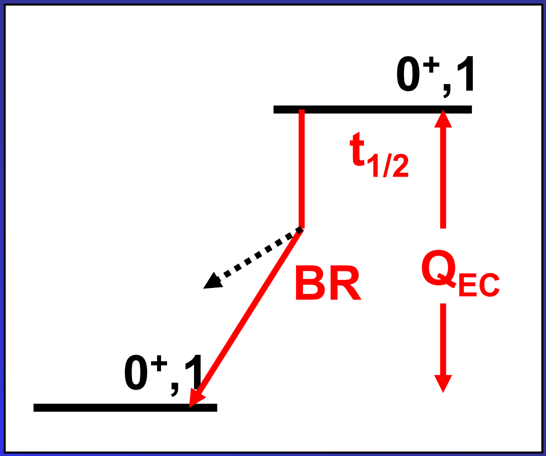
CVC

$$\mathcal{F}t = ft(1 + \delta_R^{'})(1 + \delta_{NS} - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R^V)} \quad \text{constant}$$

V.E. Iacob

22:18

Superallowed $0^+ \rightarrow 0^+$ β decay



Experiment precision: 0.1%

Weak Decay Equation

$$ft = \frac{K}{G_V^2 \langle \tau \rangle^2}$$

$f = \mathrm{f}(Z, Q_{EC})$

$t = \mathrm{f}(t_{1/2}, BR)$

G_V = coupling constant

$\langle \tau \rangle$ = matrix element

$\delta_R' = \mathrm{f}(Z, Q_{EC})$

$\delta_{NS} = \mathrm{f}(\text{nuclear structure})$

$\delta_C = \mathrm{f}(\text{nuclear structure})$

$\Delta_R^V = \mathrm{f}(\text{interaction})$

Test CKM Matrix Unitarity

CVC

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} \quad \text{constant}$$

World data for superallowed $0^+ \rightarrow 0^+$ β decay (2020)

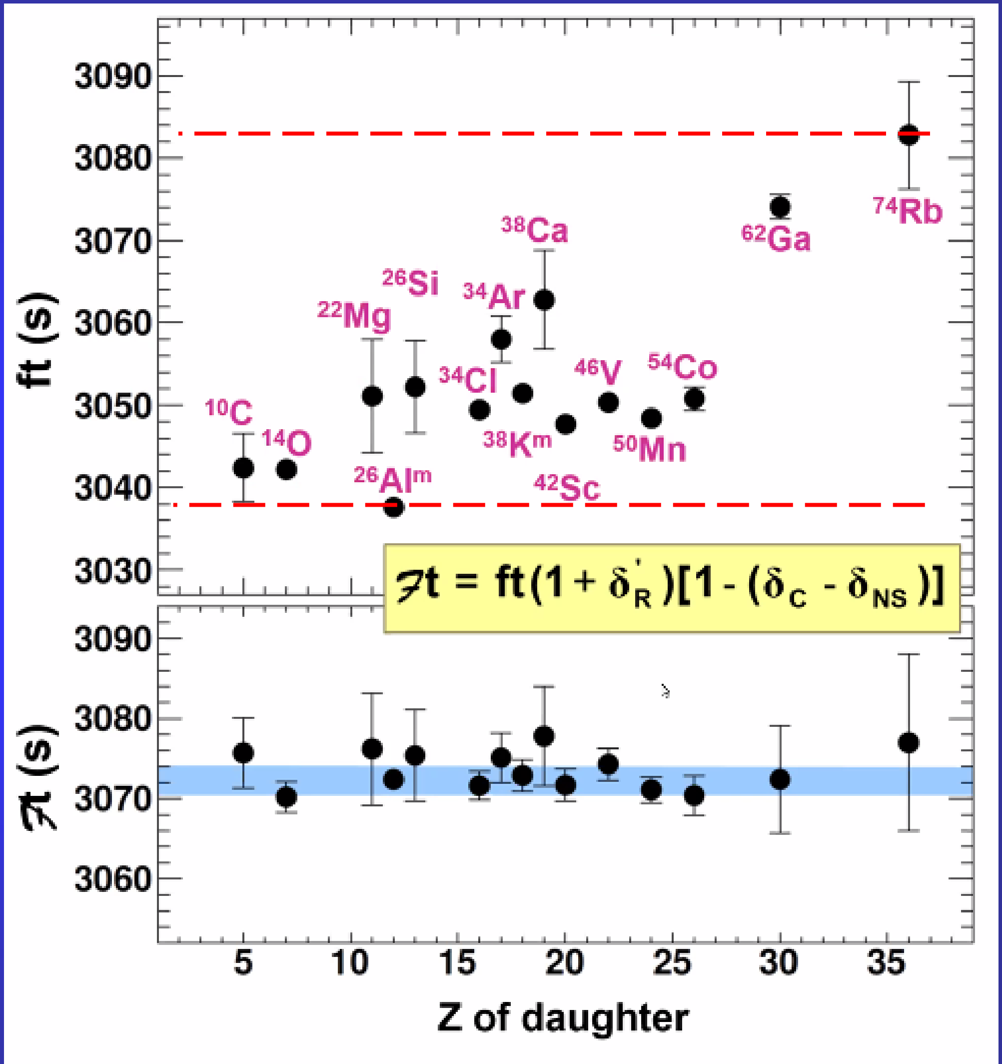
ft **values for the 15 best known transitions**

Over 220 individual precise measurements

- **9 cases accurate to <0.05%**
- **6 more cases accurate 0.05-0.23%**

$$\overline{\mathcal{F}t} = 3072.24 \pm 1.85\, s$$

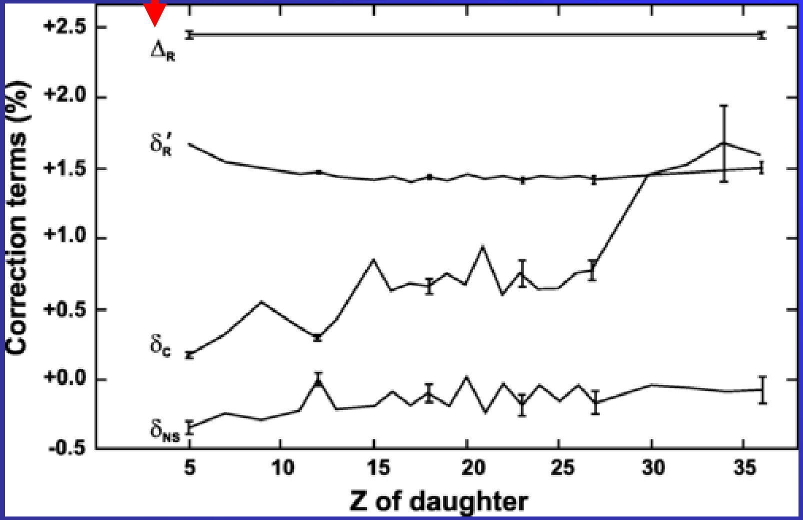
J. C. Hardy and I. S. Towner,
Phys Rev C **102**, 045501 (2020)

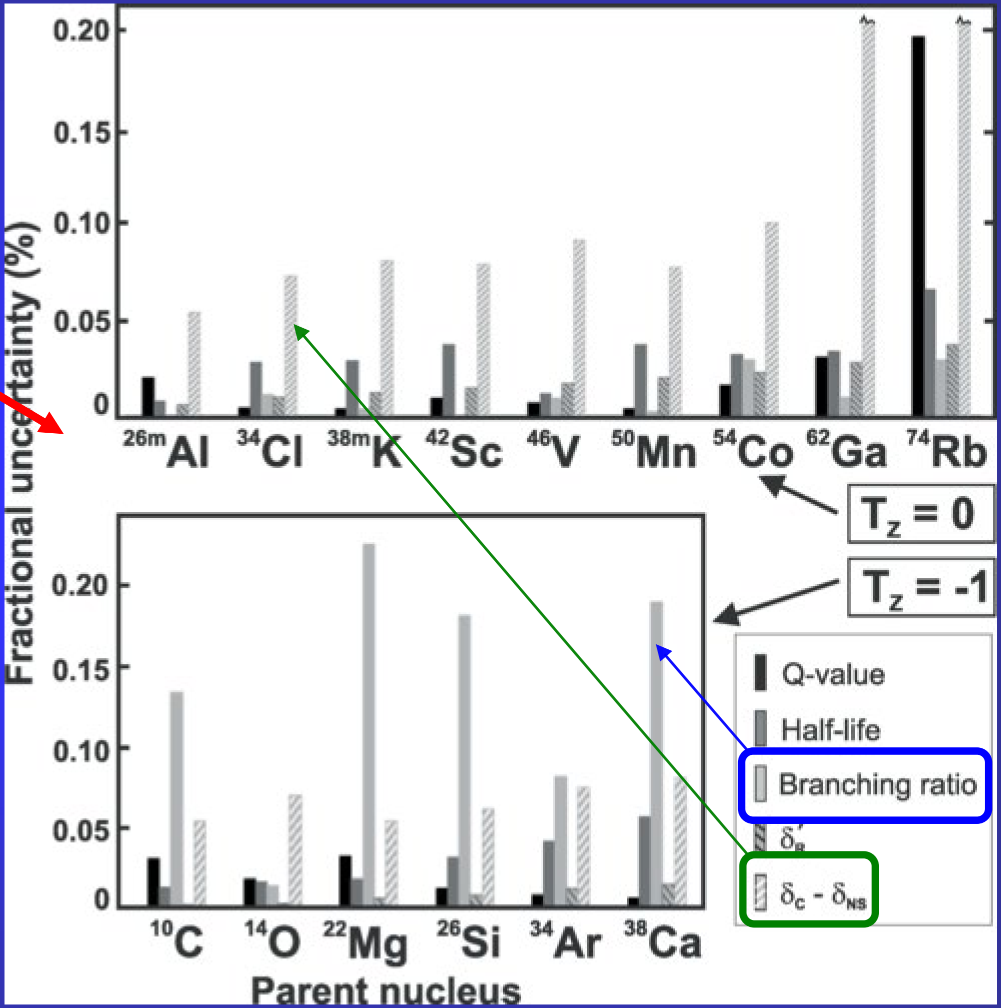


World data for superallowed $0^+ \rightarrow 0^+$ β decay (2020)

Correction terms

- Relative contribution to the corrected $\mathcal{F}t$
- Magnitude



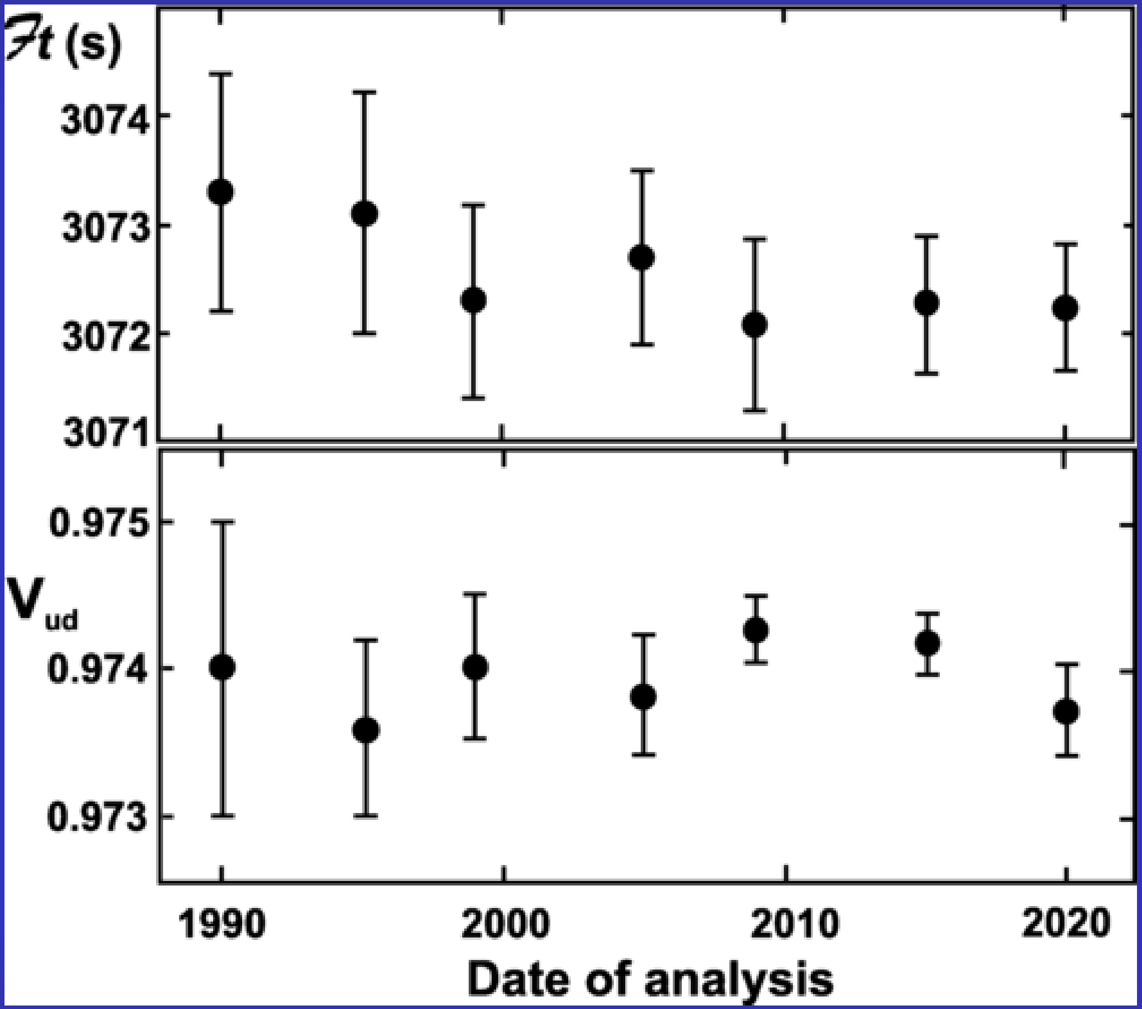


J. C. Hardy and I. S. Towner, Phys Rev C **102**, 045501 (2020)

V.E. Iacob

22:18

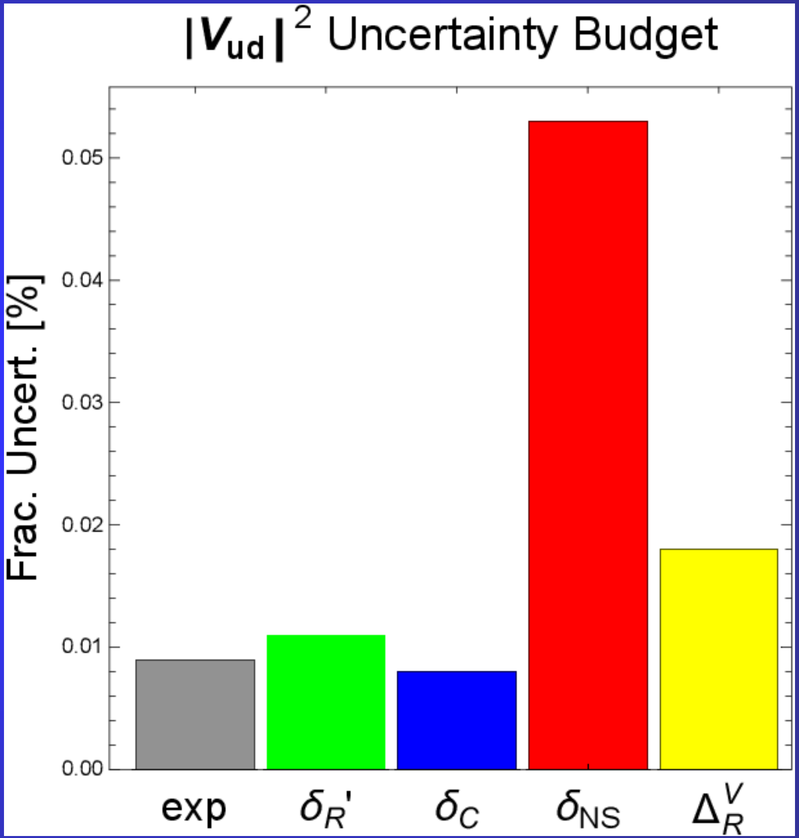
World data for superallowed $0^+ \rightarrow 0^+$ β decay (2020)



J. C. Hardy and I. S. Towner,
Phys Rev C **102**, 045501 (2020)

Value of V_{ud}, using world data 2020

$$\left|V_{ud}\right|^2 = 0.94815 \pm 0.00060$$

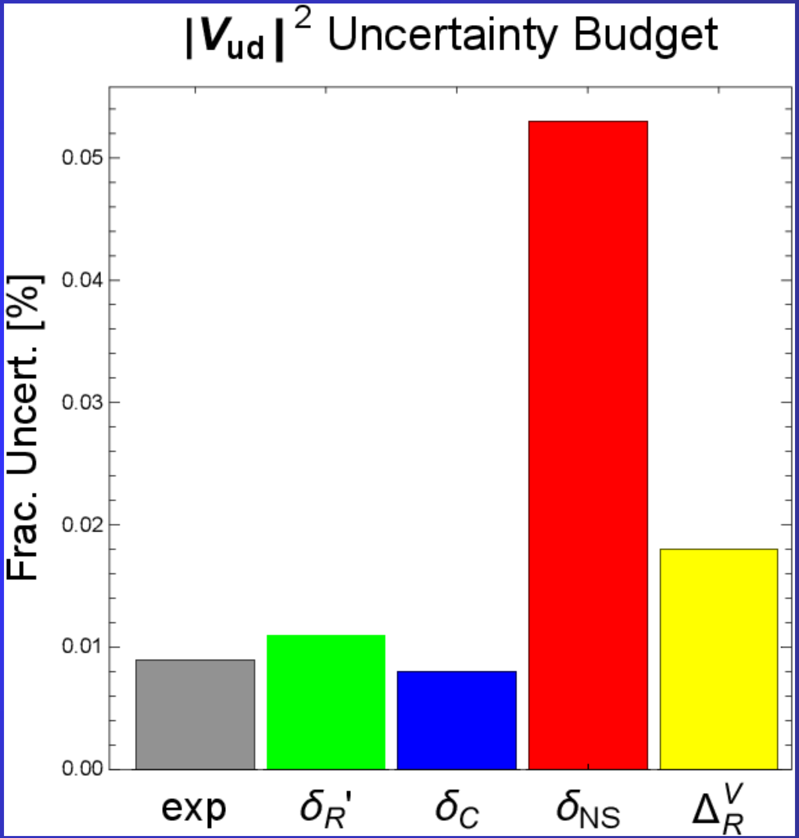


World Data, 2020
J. C. Hardy and I. S. Towner,
DOI: 10.1103/PhysRevC.102.045501

Value of V_{ud}, using world data 2020

$$|V_{ud}|^2 = 0.94815 \pm 0.00060$$

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$



World Data, 2020
J. C. Hardy and I. S. Towner,
DOI: 10.1103/PhysRevC.102.045501

V.E. Iacob

22:18

New precise experiments in T=1 superallowed $0^+ \rightarrow 0^+$ β decay (since 2018)

^{10}C B.Blank *et al.*, Eur. Phys. J. A (2020) **56**:156

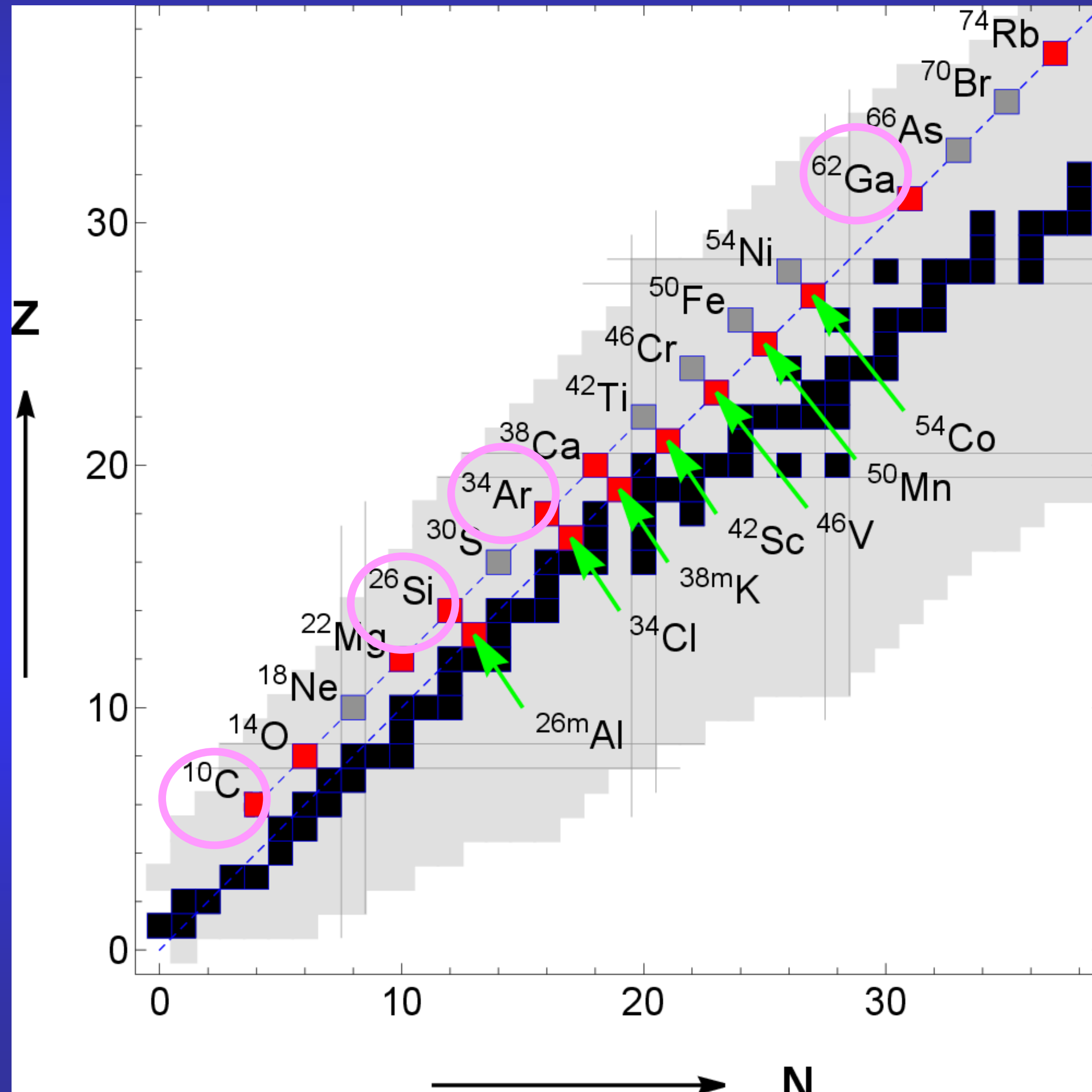
^{26}Si M.Bencomo *et al.*, Phys.Rev. C **100**, 015503 (2019)

^{34}Ar V. E. Iacob *et al.*, Phys.Rev. **C 101**, 045501 (2020)
V. E. Iacob *et al.*, Phys.Rev. **C 101**, 015504 (2020)
H. I. Park *et al.*, Phys.Rev. **C 102**, 045502 (2020)

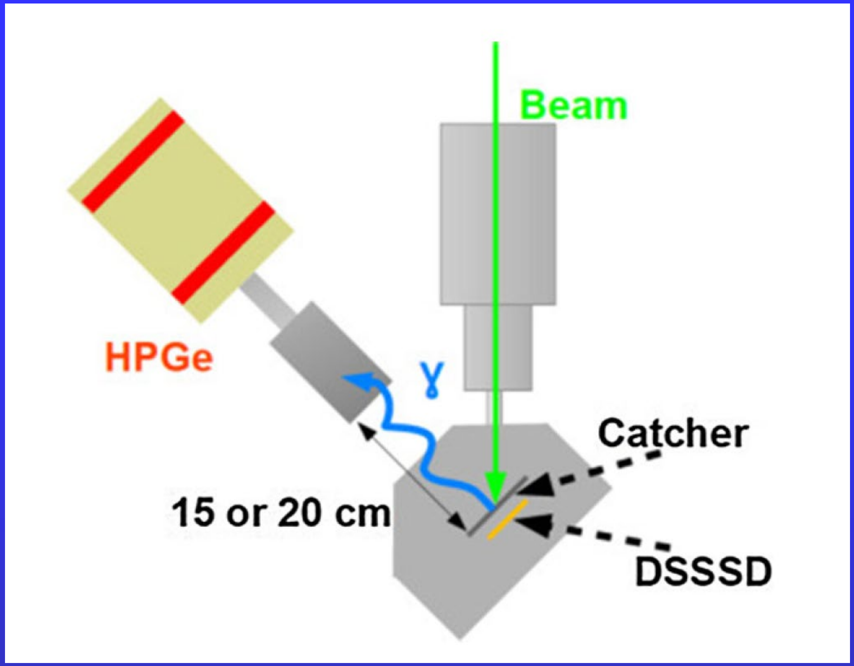
^{62}Ga A.D.MacLean *et al.*, Phys.Rev. C **102**, 054325 (2020)

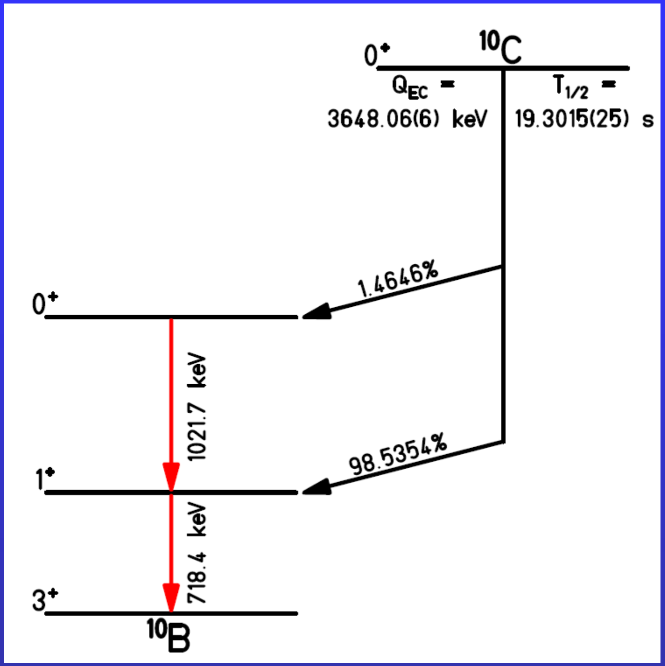
New precise experiments in T=1 superallowed $0^+ \rightarrow 0^+$ β decay (since 2018)

- ^{10}C branching ratio
- ^{26}Si branching ratio
- ^{34}Ar branching ratio & half life
- ^{62}Ga branching ratio



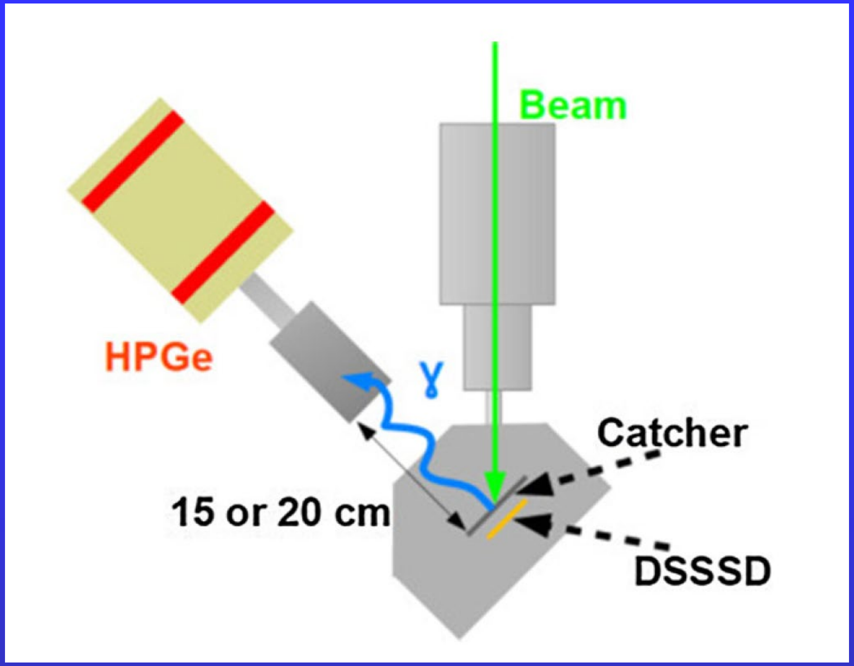
^{10}C branching ratio

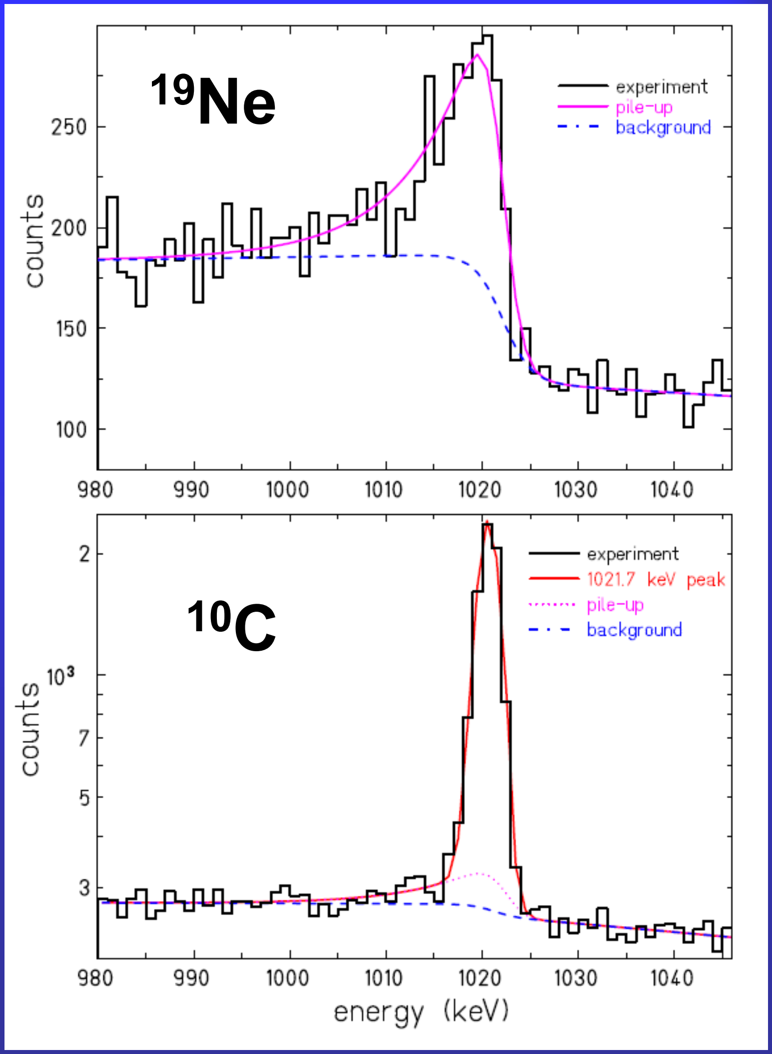




B.Blank *et al.*, Eur. Phys. J. A (2020) **56**:156

^{10}C branching ratio



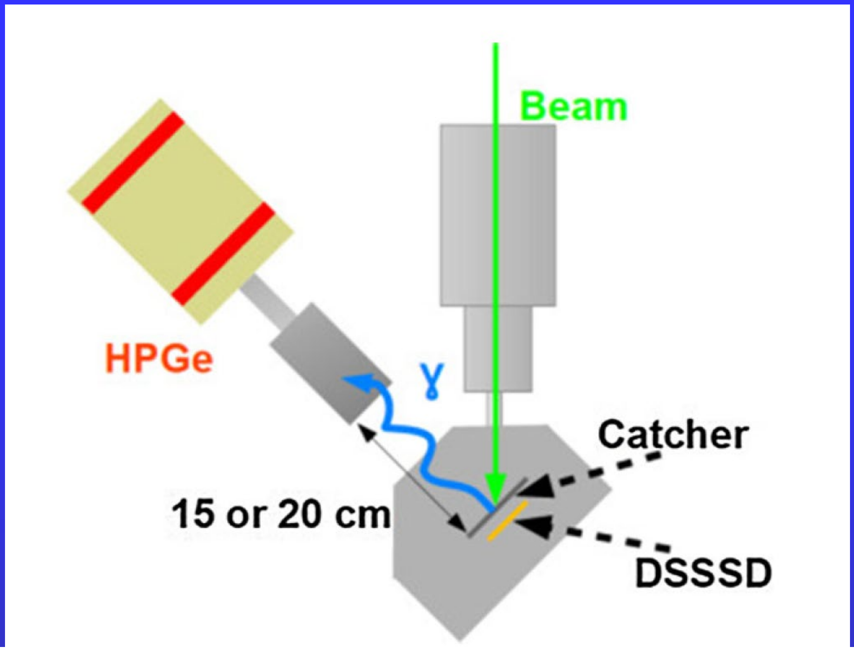


B.Blank *et al.*, Eur. Phys. J. A (2020) **56**:156

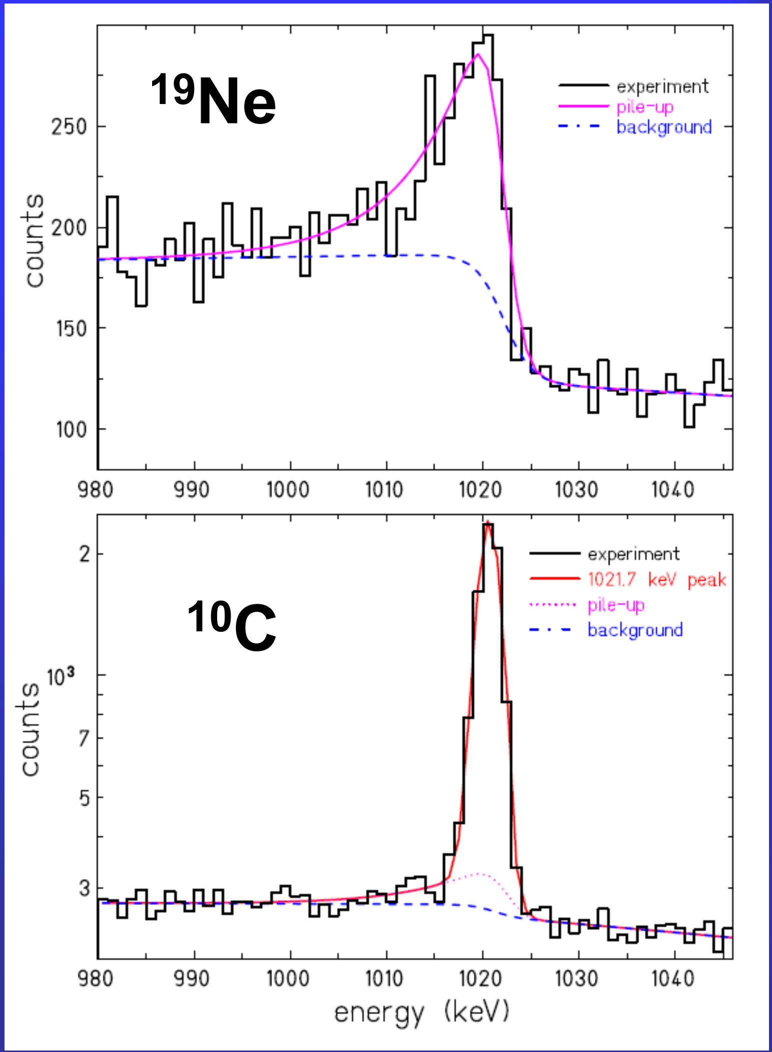
V.E. Iacob

22:18

^{10}C branching ratio



Our result of BR = 1.4638(50)% is a factor of 1.5–2 less precise than the most precise literature values. Nevertheless the present result demonstrates that the problems with the pile-up of two 511 keV γ rays can be overcome. In a future experiment, a higher precision can be reached with a longer beam time and a better beam purification scheme. However, it will be very challenging to reach the same precision for the branching ratio as for the half-life and the Q value of ^{10}C.

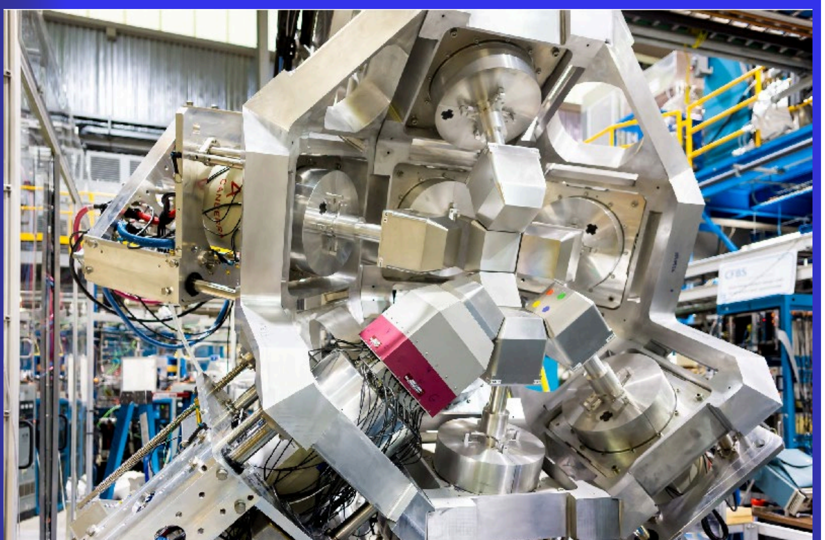


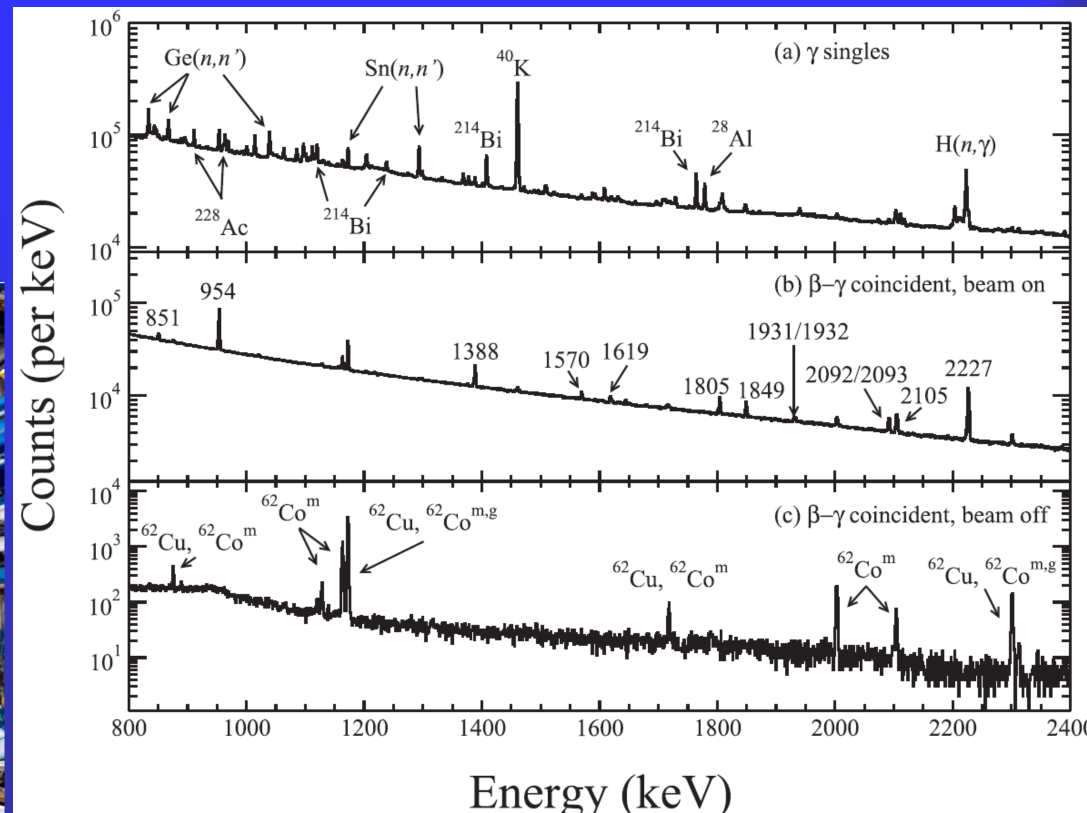
B.Blank *et al.*, Eur. Phys. J. A (2020) **56**:156

V.E. Iacob

^{62}Ga branching ratio

- **Q = 9181keV**
- **Weak β branches difficult to observe (Pandemonium effect)**



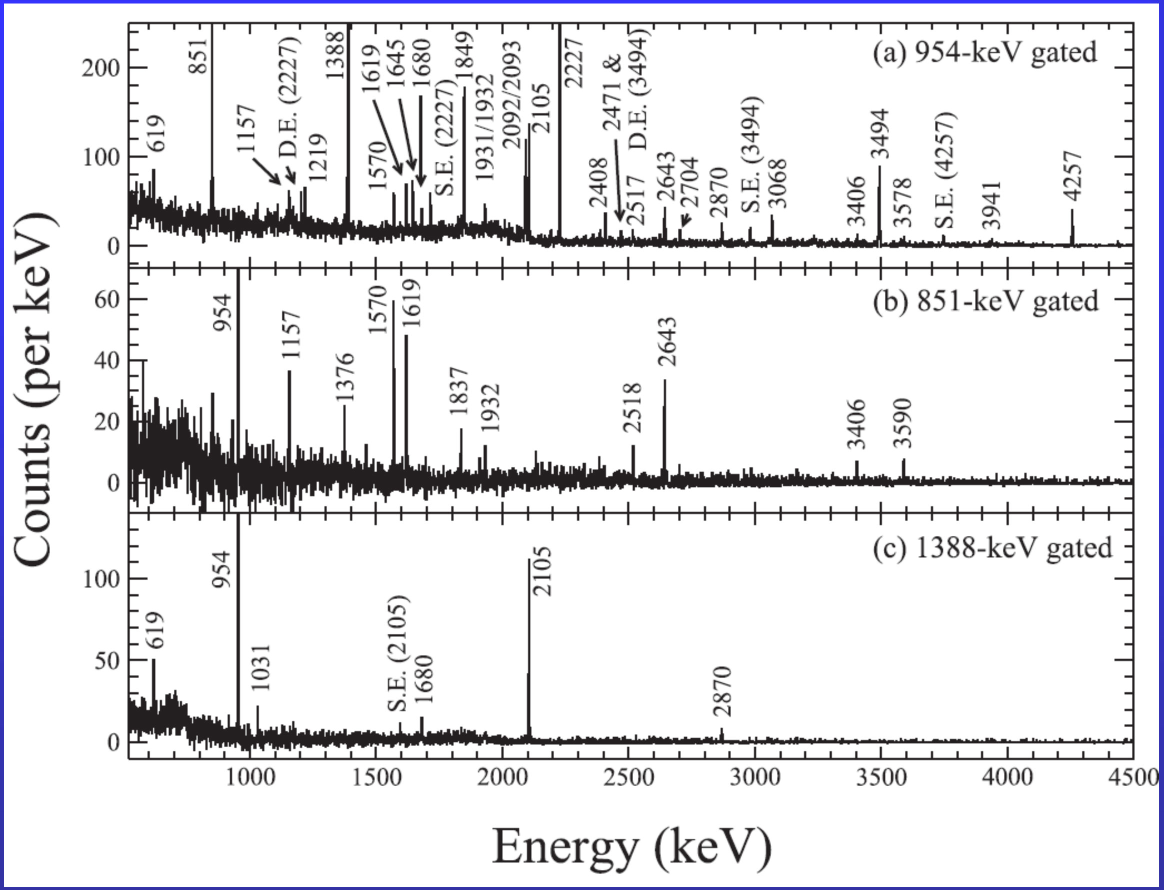


A.D.MacLean *et al.*, Phys.Rev. C **102**, 054325 (2020)

V.E. Iacob

^{62}Ga branching ratio

- 63 γ-rays identified
- 24 excited states

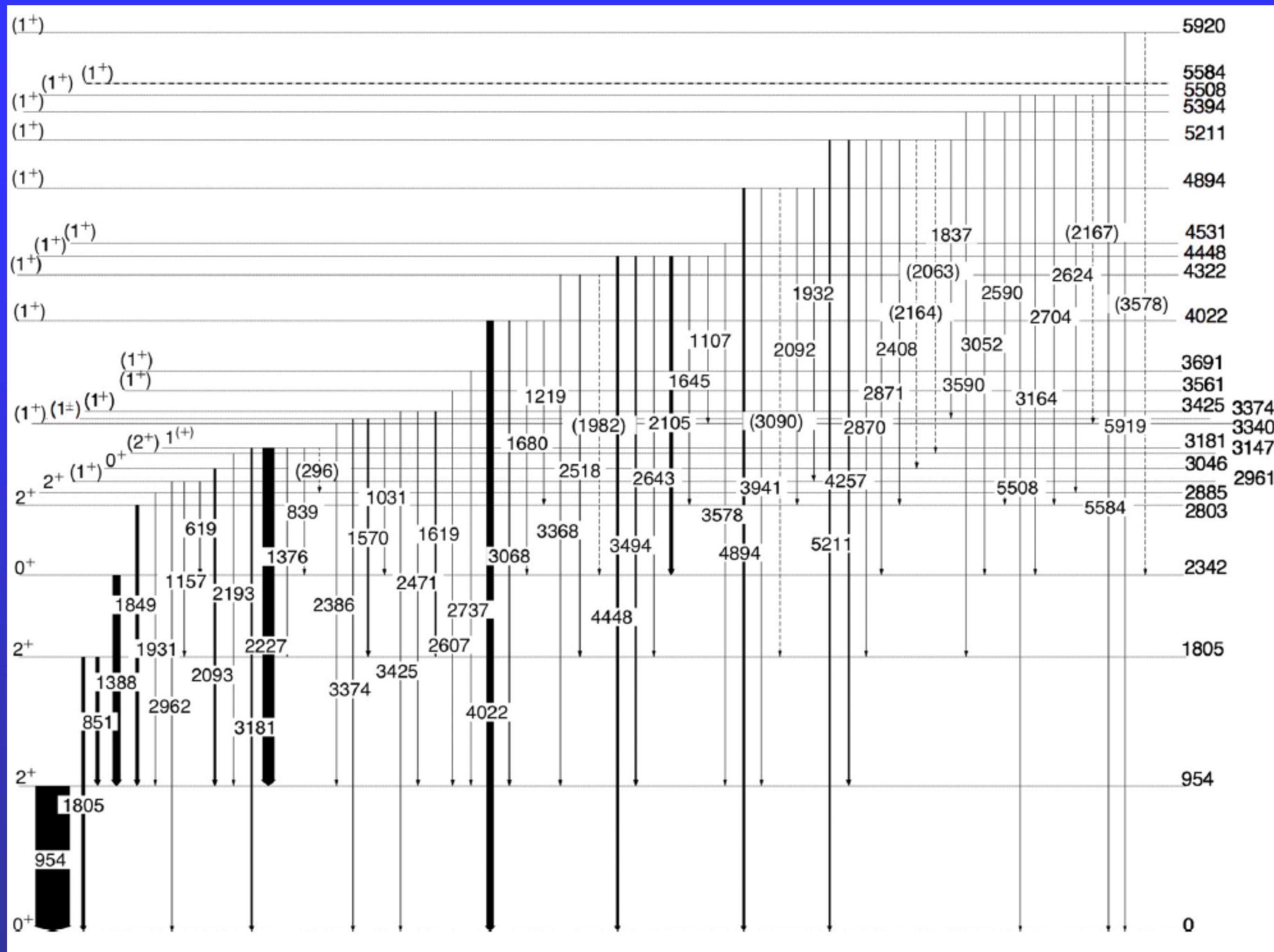


A.D.MacLean *et al.*, Phys.Rev. C **102**, 054325 (2020)

V.E. Iacob

22:18

^{62}Ga branching ratio



. Level scheme of ^{62}Zn populated in the β^+ decay of ^{62}Ga. The widths of the arrows indicate the relative intensities of the tr

A.D.MacLean *et al.*, Phys.Rev. C **102**, 054325 (2020)

V.E. Iacob

22:18

^{62}Ga branching ratio

A high-precision measurement of the superallowed Fermi β branching ratio in the decay of ^{62}Ga was performed with the GRIFFIN γ-ray spectrometer at the TRIUMF-ISAC facility. The result, $B_0 = 99.8577^{+0.0023}_{-0.0029}\%$, is consistent with, but a factor of 4 more precise than the previously adopted world-average for this quantity. The significant gain in precision was achieved through a careful control of the so-called Pandemonium effect via high-efficiency, high-resolution γ-ray spectroscopy. The high γ-γ coincidence efficiency also

A.D.MacLean *et al.*, Phys.Rev. C **102**, 054325 (2020)

V.E. Iacob

^{26}Si & ^{34}Ar experiments: TEST $\delta_C - \delta_{NS}$

Strategy: compare *ft*-values from pairs of mirror superallowed decays

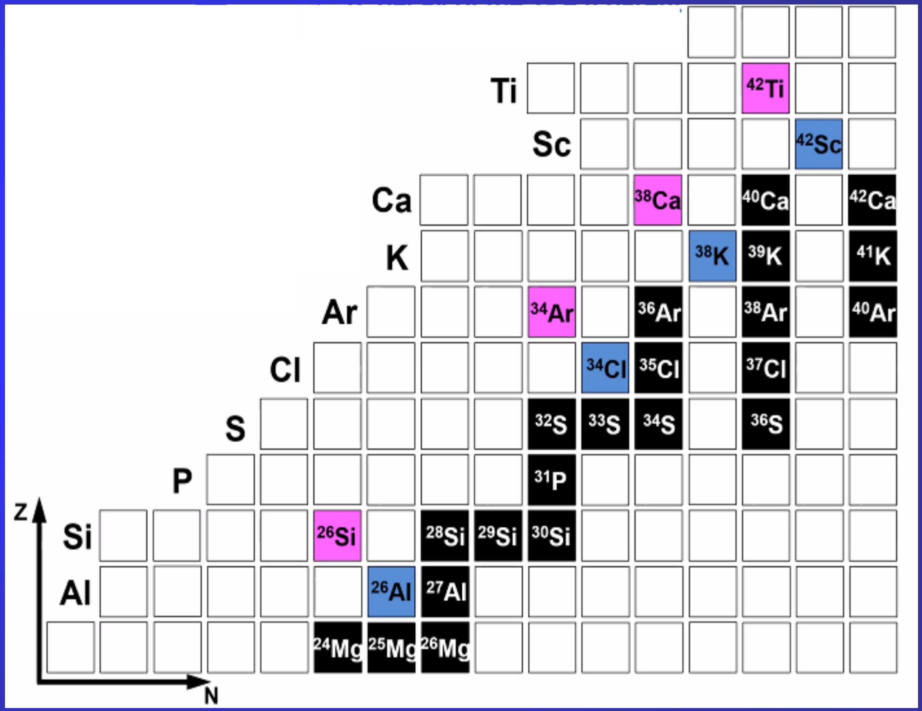
Accepting **CVC** $\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \text{constant}$

The ratio of *ft* values for a pair of mirror superallowed decays is

$$\frac{ft^a}{ft^b} = 1 + (\delta_R'^b - \delta_R'^a) + (\delta_{NS}^b - \delta_{NS}^a) - (\delta_C^b - \delta_C^a)$$

a. Decay of the $T_Z=-1$ parent (need to be measured)

b. Decay of the $T_Z=0$ parent (known to better than 0.1%)



V.E. Iacob

22:18

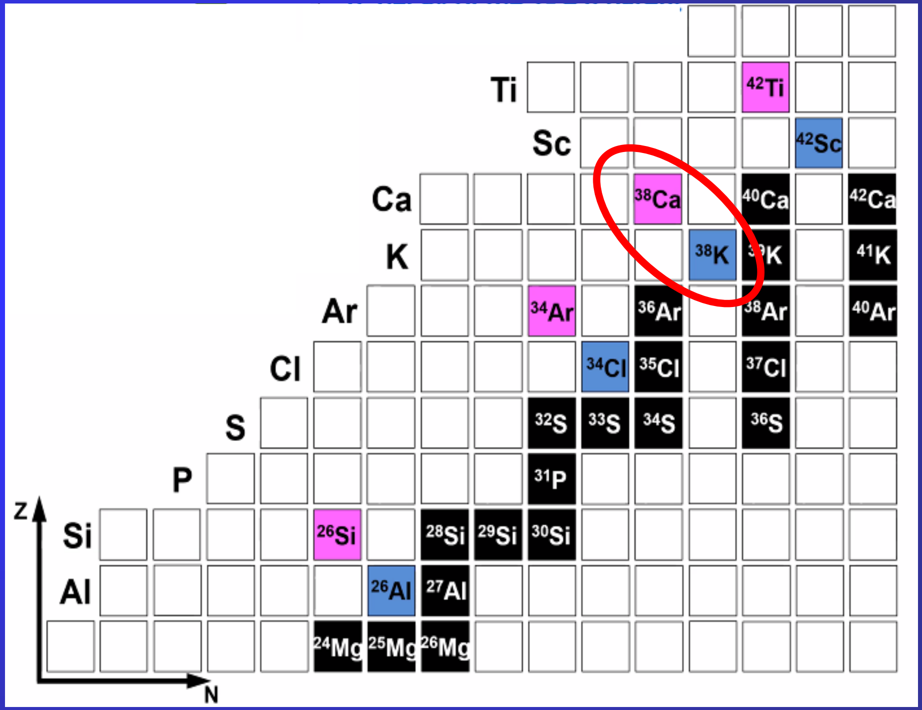
^{26}Si & ^{34} Ar experiments: TEST $\delta_C - \delta_{NS}$

Strategy: compare *ft*-values from pairs of mirror superallowed decays

Accepting **CVC** $\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \text{constant}$

The ratio of *ft* values for a pair of mirror superallowed decays is

$$\frac{ft^a}{ft^b} = 1 + (\delta_R'^b - \delta_R'^a) + (\delta_{NS}^b - \delta_{NS}^a) - (\delta_C^b - \delta_C^a)$$



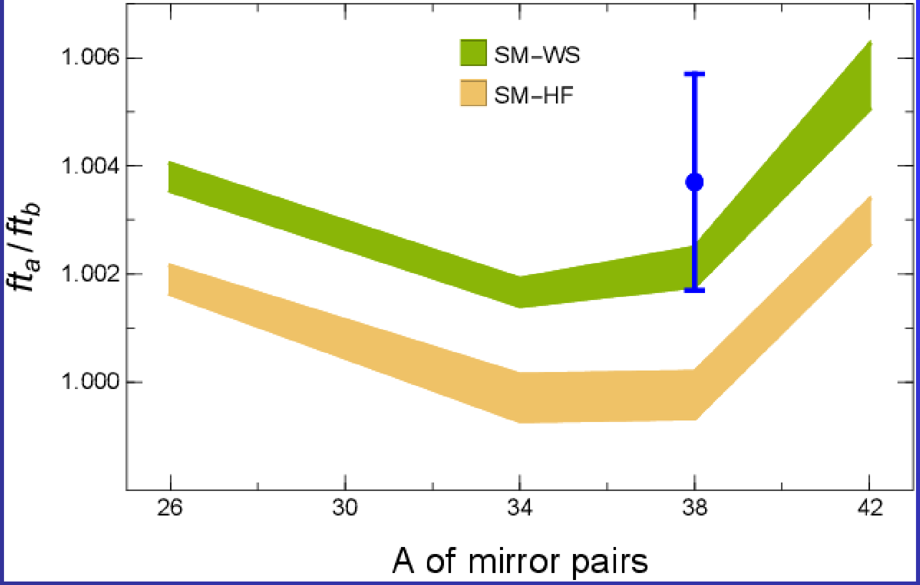
a. Decay of the T_Z=-1 parent (need to be measured)
b. Decay of the T_Z=0 parent (known to better than 0.1%)

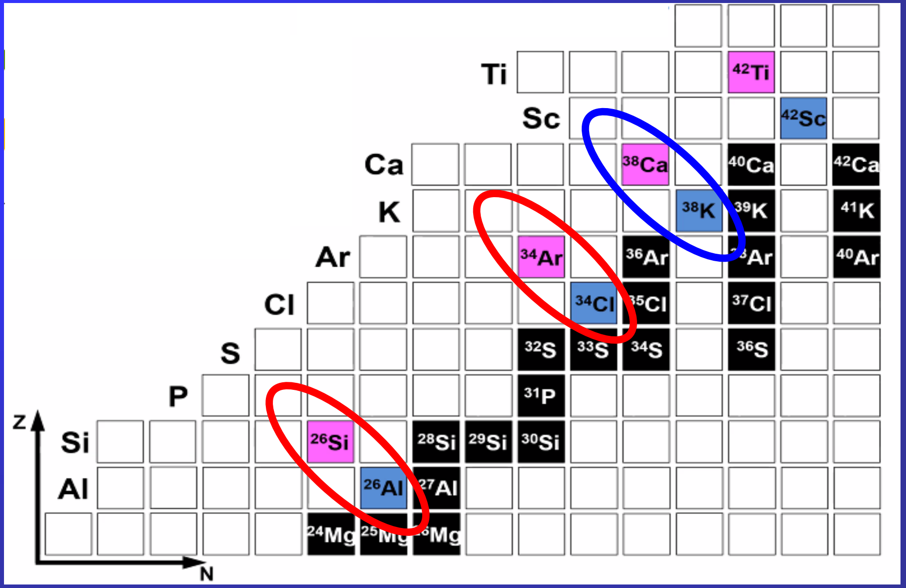
A=38: H.I.Park *et al.*, Phys.Rev.Lett. **112**, 102502 (2014)

^{26}Si & ^{34} Ar experiments: TEST $\delta_C - \delta_{NS}$

- crucial: the theoretical uncertainty on differences in corrections (evaluated for adjacent nuclei) is significantly smaller than the uncertainty of the individual correction terms themselves
- the difference in correction terms removes entirely systematic errors

$$\frac{ft^a}{ft^b} = 1 + (\delta_R'^b - \delta_R'^a) + (\delta_{NS}^b - \delta_{NS}^a) - (\delta_C^b - \delta_C^a)$$





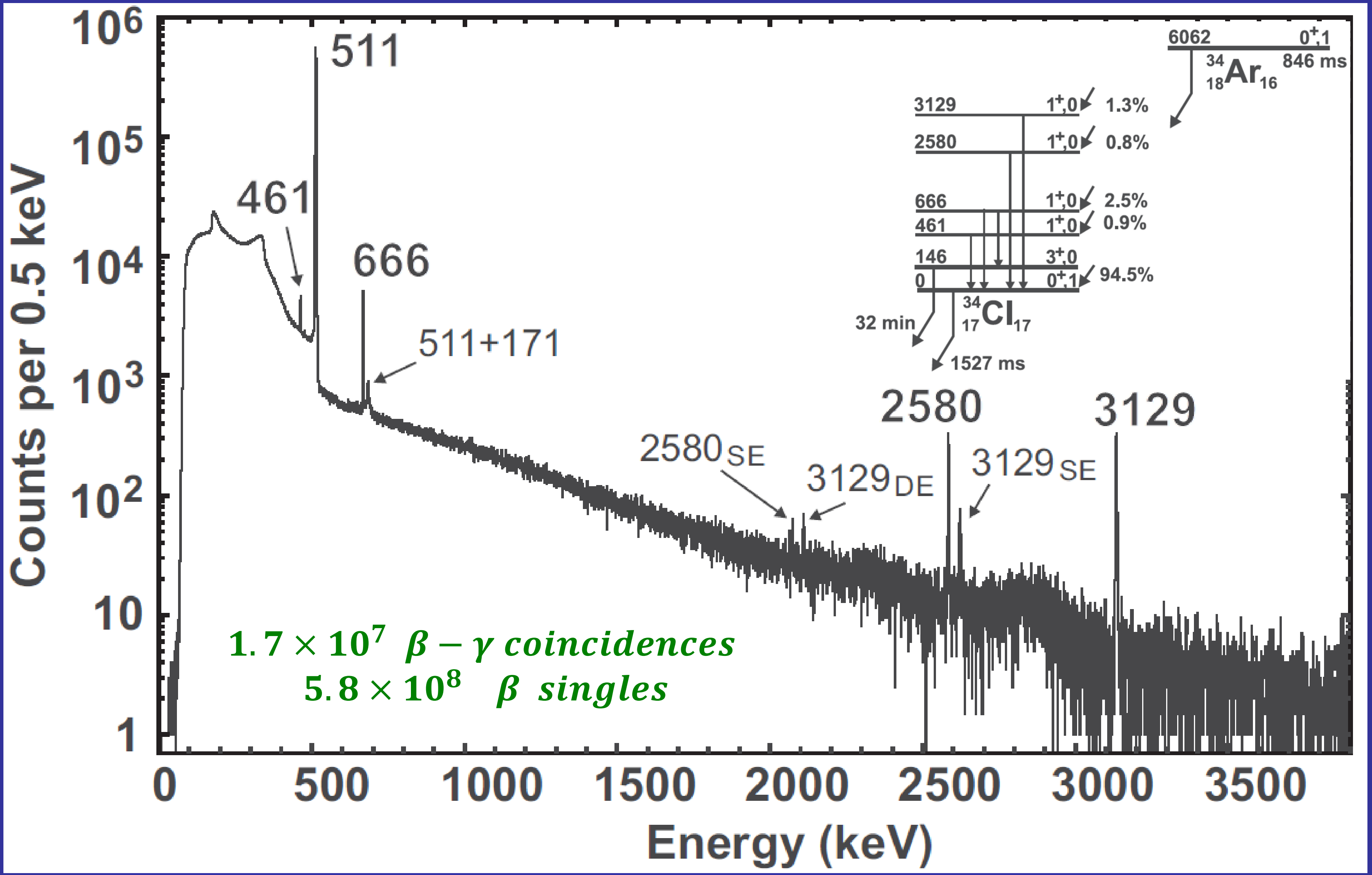
M. Bencomo *et al.*, Phys.Rev. **C 100**, 015503 (2019)

V. E. Iacob *et al.*, Phys.Rev. **C 101**, 045501 (2020)

V.E. Iacob

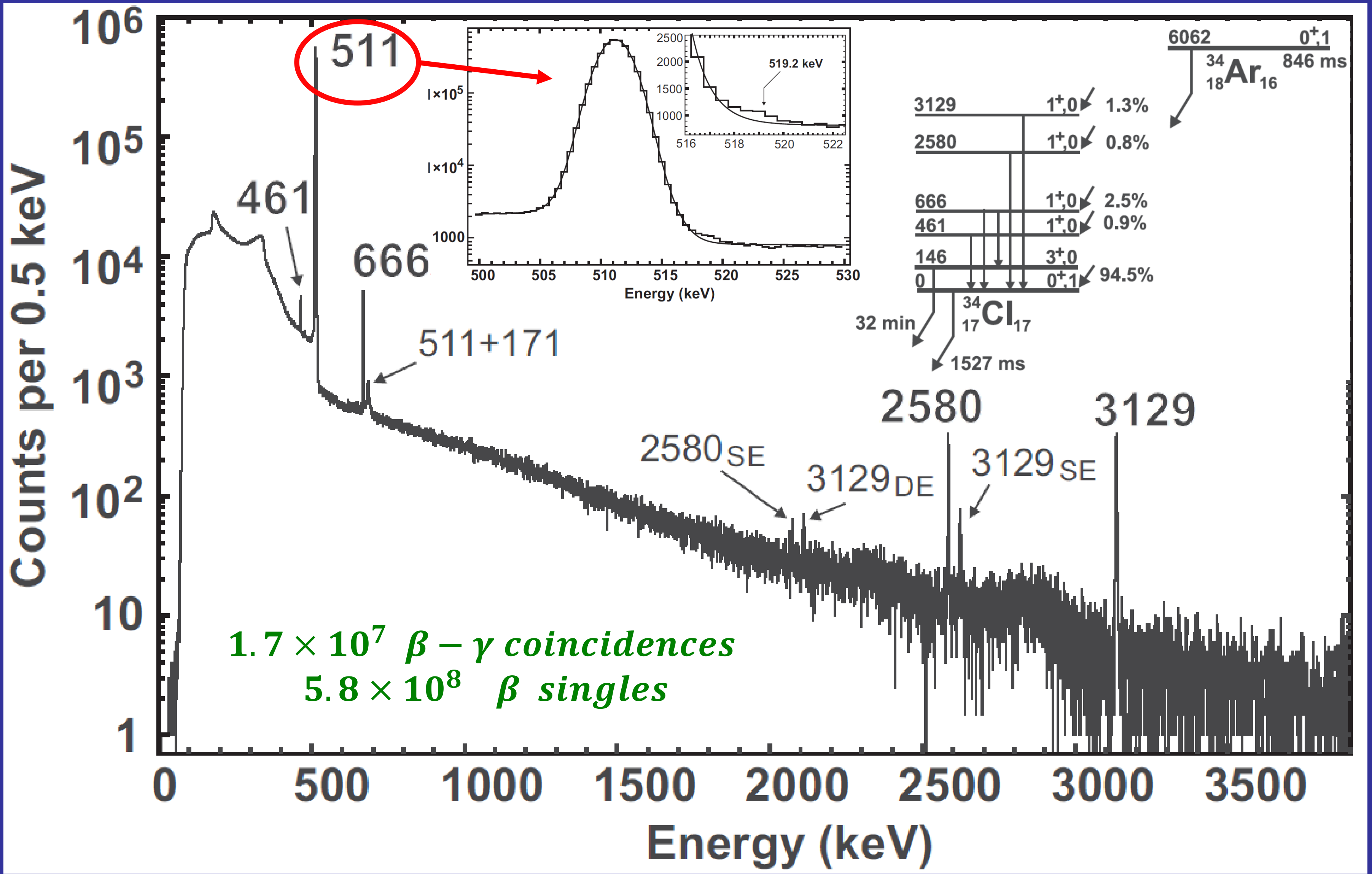
22:18

β-delayed γ-s in coincidence with positrons



V. E. Iacob *et al.*, Phys.Rev. **C 101**, 045501 (2020)

β-delayed γ-s in coincidence with positrons

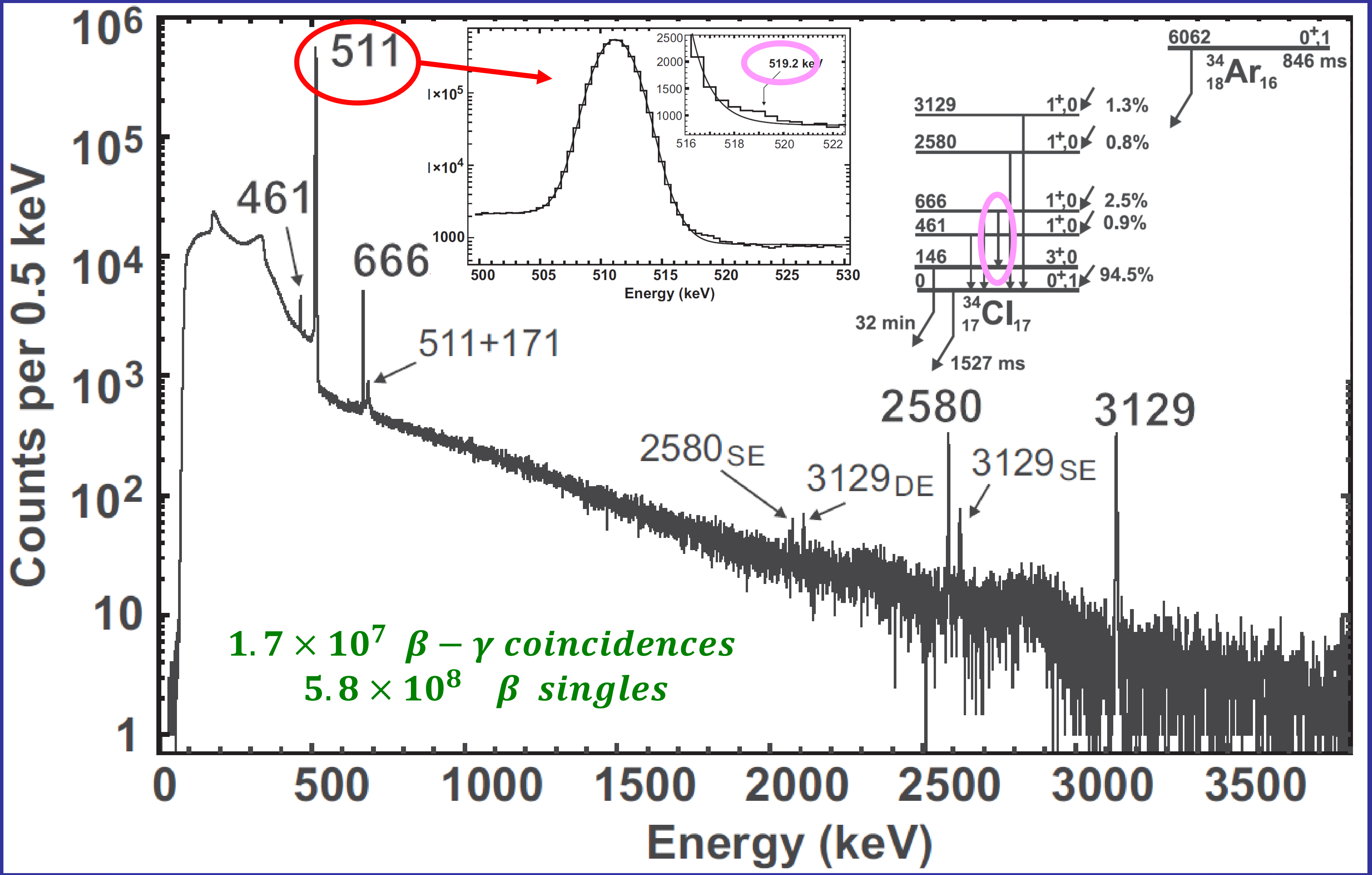


V. E. Iacob *et al.*, Phys.Rev. **C 101**, 045501 (2020)

V.E. Iacob

22:18

β-delayed γ-s in coincidence with positrons

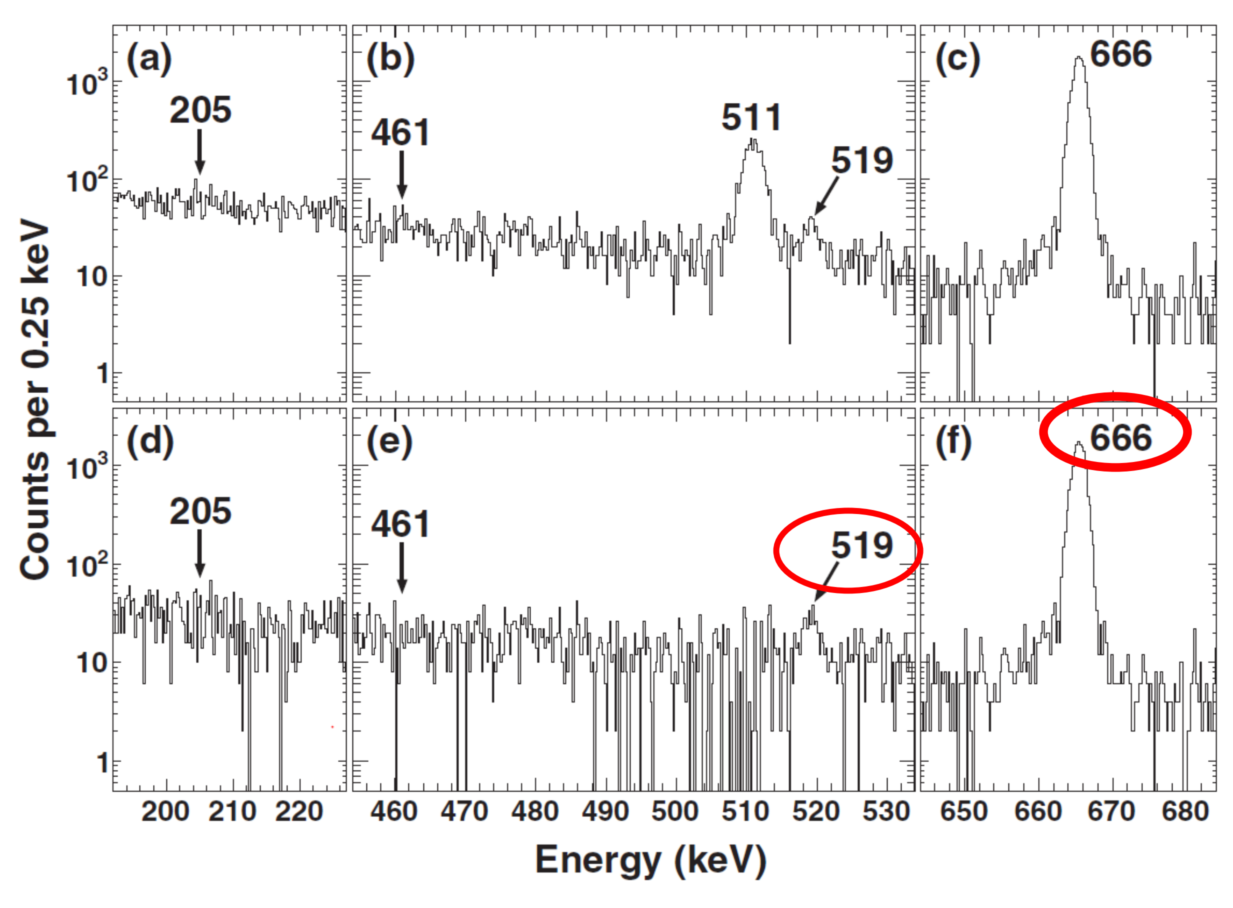


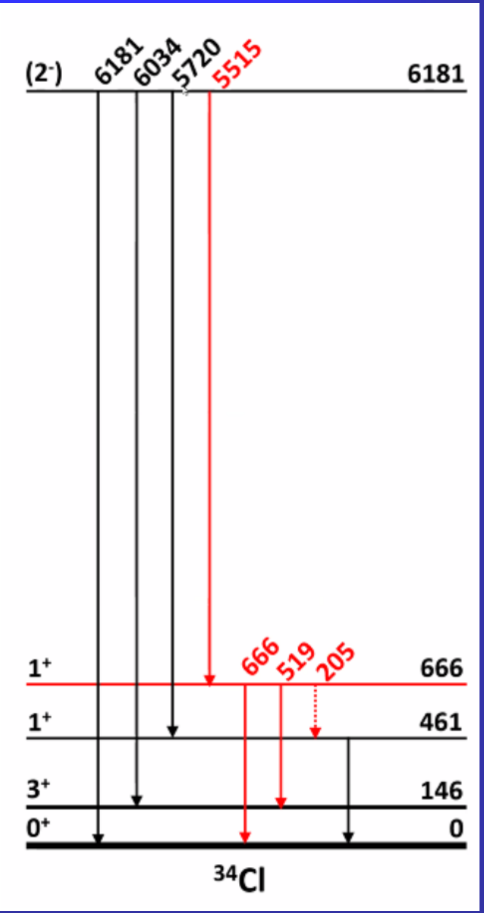
V. E. Iacob *et al.*, Phys.Rev. **C 101**, 045501 (2020)

V.E. Iacob

22:18

Improve intensity ratio 519keV/666keV
(resonant proton capture on $^{33}S \rightarrow E^*=6181$-keV)





H. I. Park *et al.*, Phys.Rev. **C 102**, 045502 (2020)
(experiment using Georgina setup at Notre Dame)

V.E. Iacob

22:18

Improved BR for the superallowed branch in ^{34}Ar

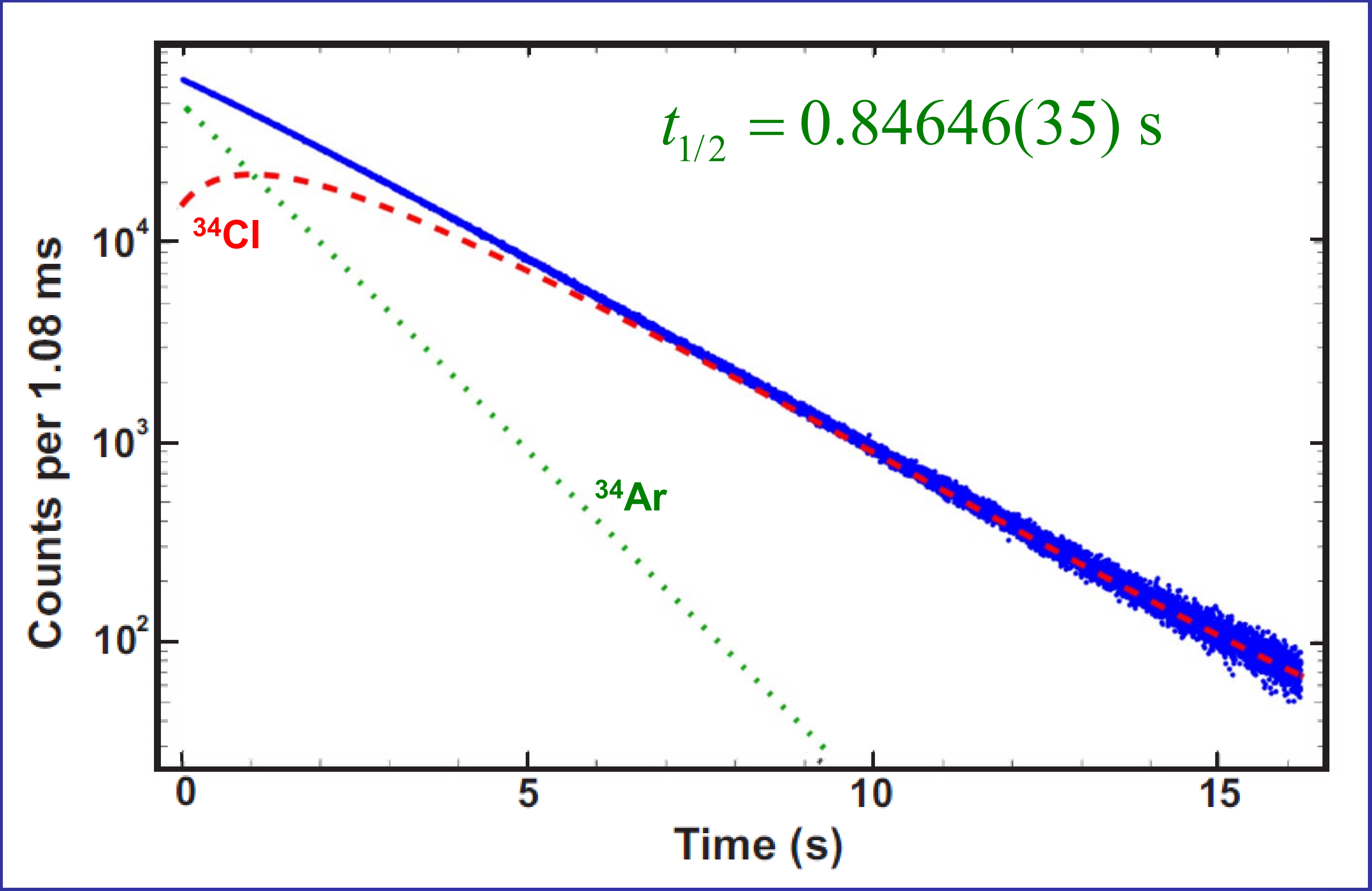
BR=94.48(8)%

Not only is the superallowed branching-ratio measurement valuable, but also there is good agreement between our results and shell-model calculations for the Gamow-Teller decay branches to 1^+ states in ^{34}Cl. This is an important result since the same effective interactions were used in the shell-model contributions to the calculation of both δ_C and δ_{NS}. Our results

V.E. Iacob

22:18

Improved $t_{1/2}$ for ^{34}Ar (1.7×10^8 decays)



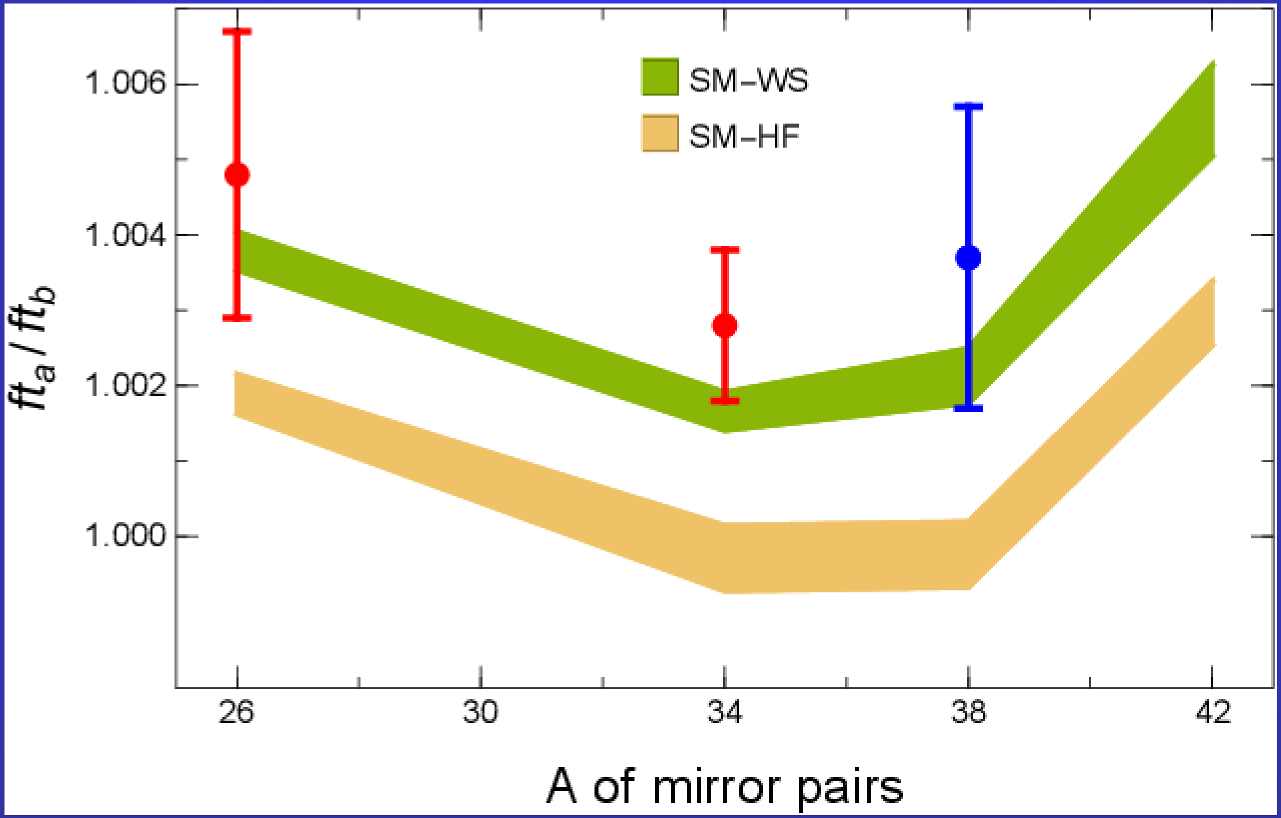
V. E. Iacob *et al.*, Phys.Rev. **C 101**, 015504 (2020)

Results

The *ft*-ratio for the new pairs of mirror superallowed decays

- ($^{26}Si \rightarrow ^{26m}Al$ and $^{26m}Al \rightarrow ^{26}Mg$), and
- ($^{34}Ar \rightarrow ^{34}Cl$ and $^{34}Cl \rightarrow ^{34}S$)

favor the phenomenological WS shell model



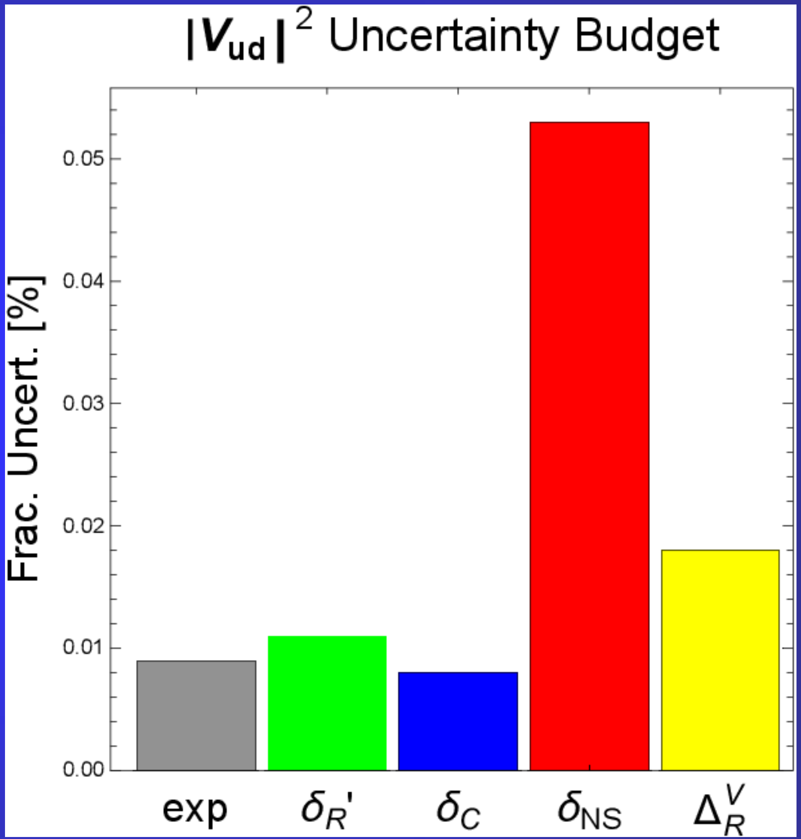
V.E. Iacob

22:18

Summary and Outlook

In fact, it has to be admitted that the motivation for a new generation of experiments to improve the ft values still further will be very weak until the theoretical uncertainties associated with δ_{NS} have been reduced substantially. Currently the δ_{NS} uncertainty exceeds the overall experimental one by nearly a factor of six. It is clear where future priorities must lie!

from being Δ_R^V to being δ_{NS}. For years we have called for improvements to the calculation of Δ_R^V, and it is gratifying that two new calculations have resulted in its uncertainty being reduced to the point where it is now only a factor of two greater than the uncertainty on the collected experimental results. Unfortunately though, the uncertainty on δ_{NS} has grown more than Δ_R^V's has shrunk. This is because the two new small effects that have been added to δ_{NS} were only quantified with relatively crude nuclear models, which necessarily brought with them rather large uncertainties. We urge that these models be refined in future so that the uncertainty on δ_{NS} can be brought more in line with the other four contributors to the $|V_{ud}|^2$ uncertainty.



J. C. Hardy and I. S. Towner,
Phys Rev C **102**, 045501 (2020)

Summary and Outlook

- Theory
  - Currently, the dominant contributor to the uncertainty in V_{ud} is δ_{NS}, asking for refinements in its calculation
    - Updates: Mikhail Gorchtein, WG1, 11/23/21, 10:50PM, contribution ID: 118

- Experiment
  - Precisely measured pairs of mirror superallowed decays allow to discriminate between different theoretical models *via* predicted correction differences $\delta_C - \delta_{NS}$; ^{42}Ti, ^{46}Cr, ^{50}Fe, and ^{54}Ni are good new challenging candidates
  - New precise measurements in low-Z parents (^{10}C) could further improve the current limit on the Fierz interference term ($|b_F| \leq 0.0033$)

Thank you!