Nuclear ground state properties for studies of fundamental symmetries
(and other ongoing work at ISOLDE)

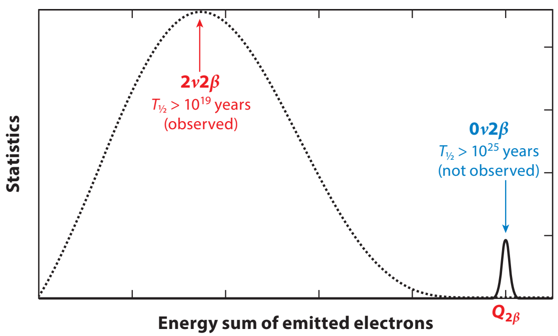
Stephan Malbrunot-Ettenauer
CERN Research Physicist

nuclear ground state properties and BSM physics

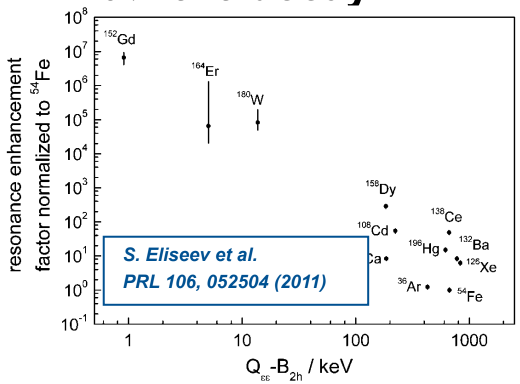
transition energies: Q-values ⟺ mass differences

J. Dilling et al, Annu. Rev. Nucl. Part. Sci. (2018).68:45
K. Blaum et al., Phys. Scr. T152, 014017 (2013)

0νββ-decay



0νEcEc-decay

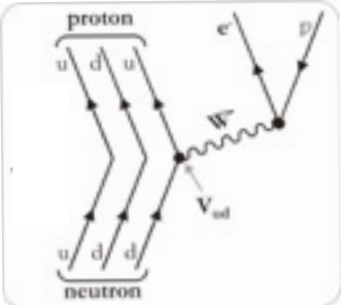


ν− mass

- tritium β^- decay (e.g. KATRIN)
- EC in ^{163}Ho
- goal: eV uncertainty in Q-value

β decays

- V_{ud} of CKM matrix
- CKM unitarity test
- limits on scalar & tensor currents
- …



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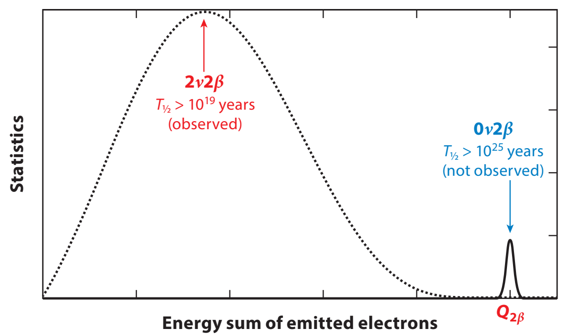

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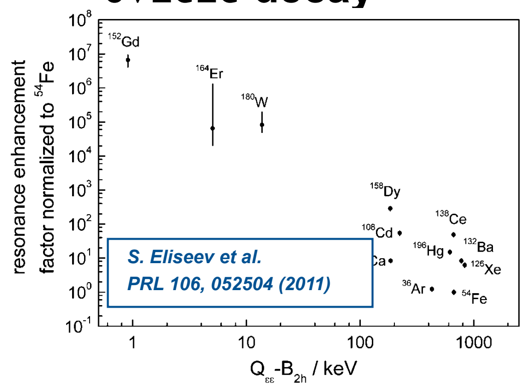

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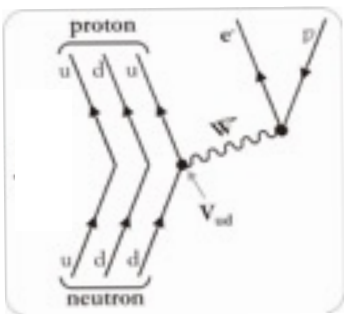
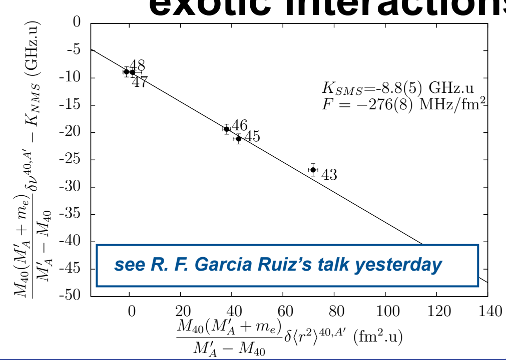


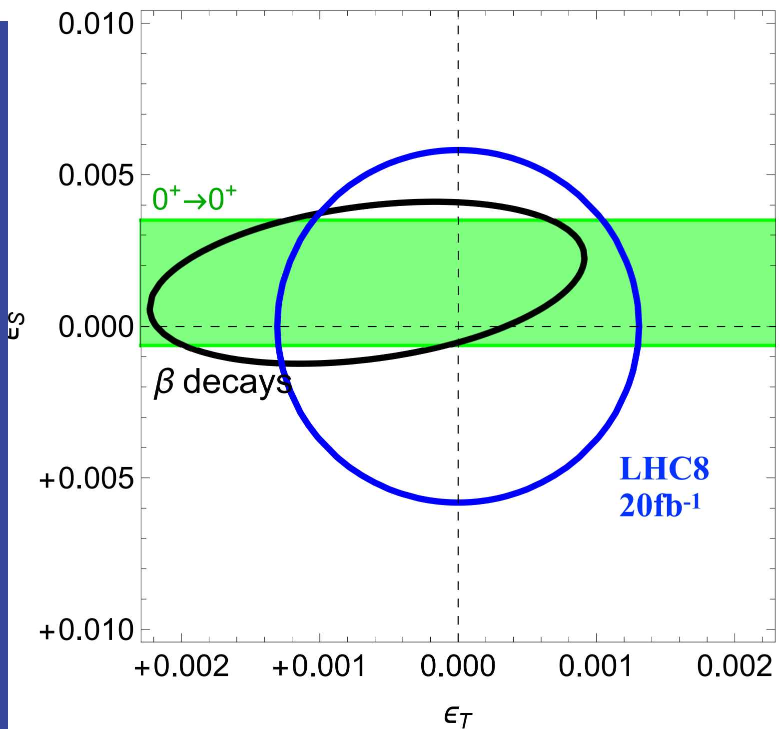
nuclear charge radii

theoretical corrections in β decays

King plots & exotic interactions



β decays and BSM physics



EFT approach

- linking β decays and collider searches
- truly complementary and competitive

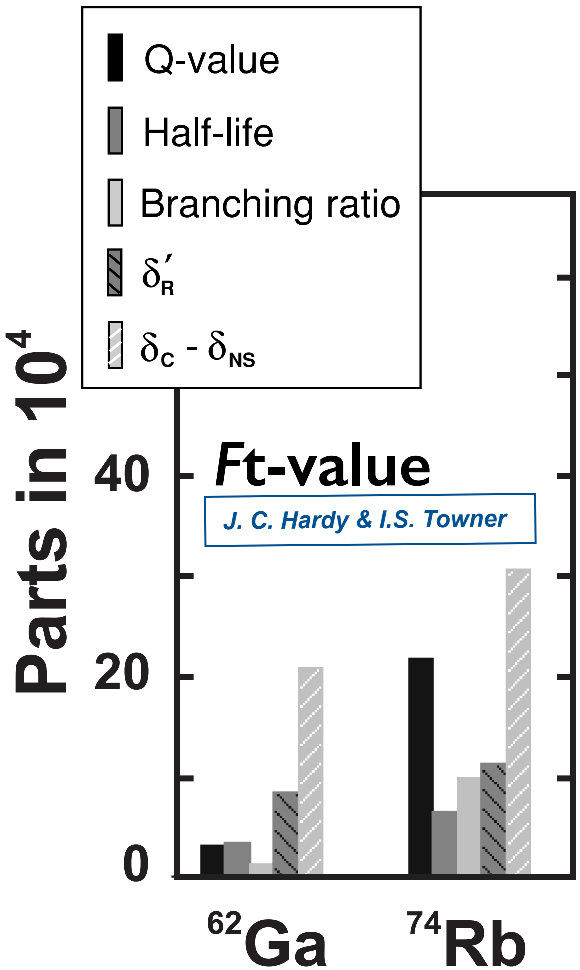
M. González-Alonso et al., Prog. Part. Nucl. Phys., 104, 165 (2019)

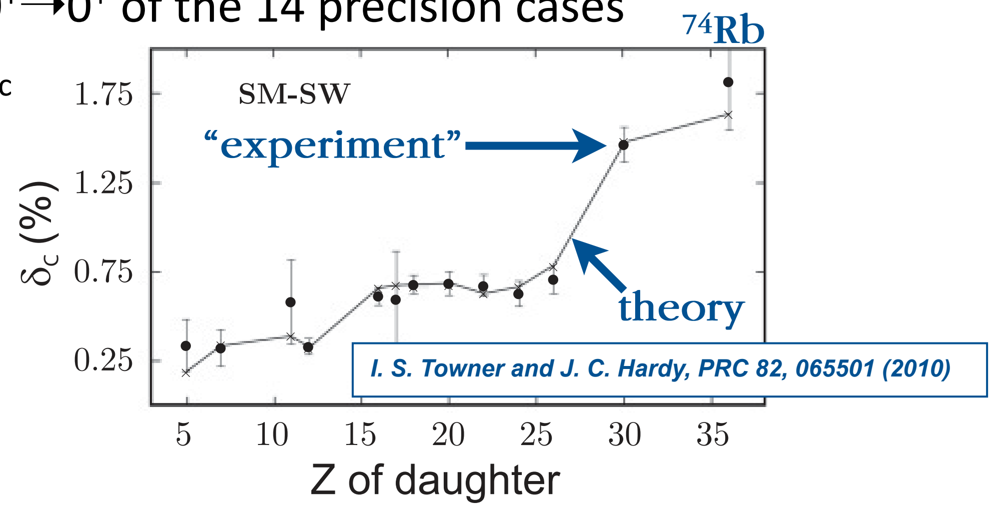
Outlook of this talk

- example(s) for high-precision mass measurements
- experimental nuclear charge radii and their impact in theoretical corrections
- applications of the developed experimental techniques
- other BSM work at ISOLDE

The case of ^{74}Rb

- heaviest superallowed $0^+ \rightarrow 0^+$ of the 14 precision cases
- largest ISB corrections $\boldsymbol{\delta}_C$





- interesting for upcoming *ab initio* based $\boldsymbol{\delta}_C$

Kyle G. Leach, Jason D. Holt, arXiv:1809.10793

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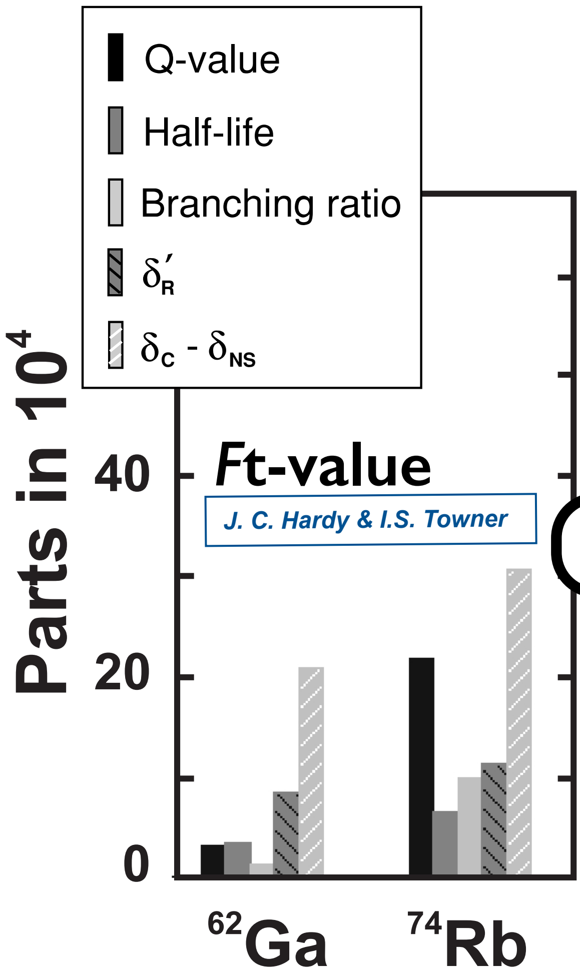

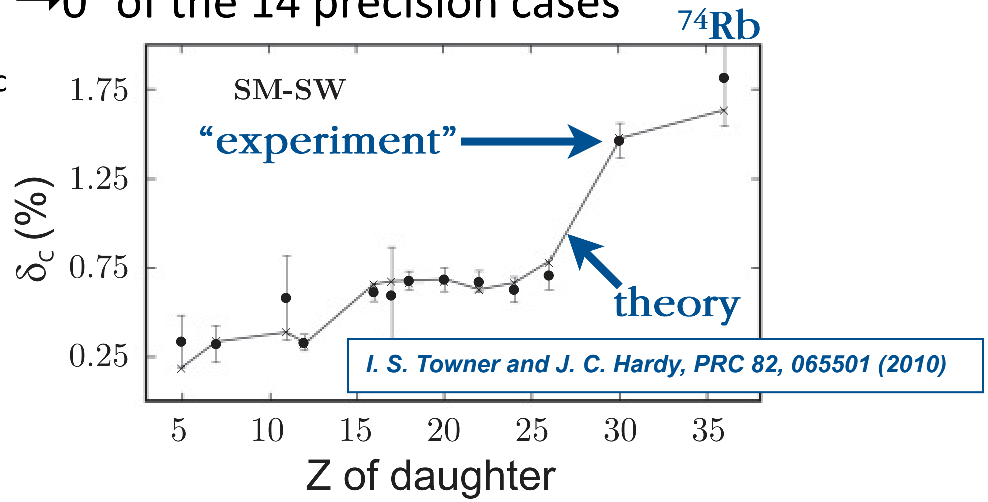

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to which extend/precision is CVC a result of QCD?

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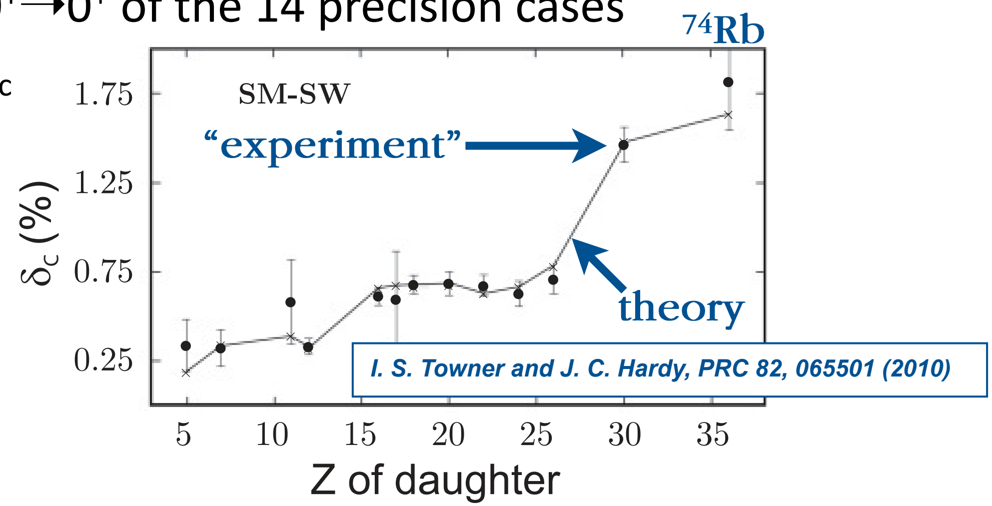

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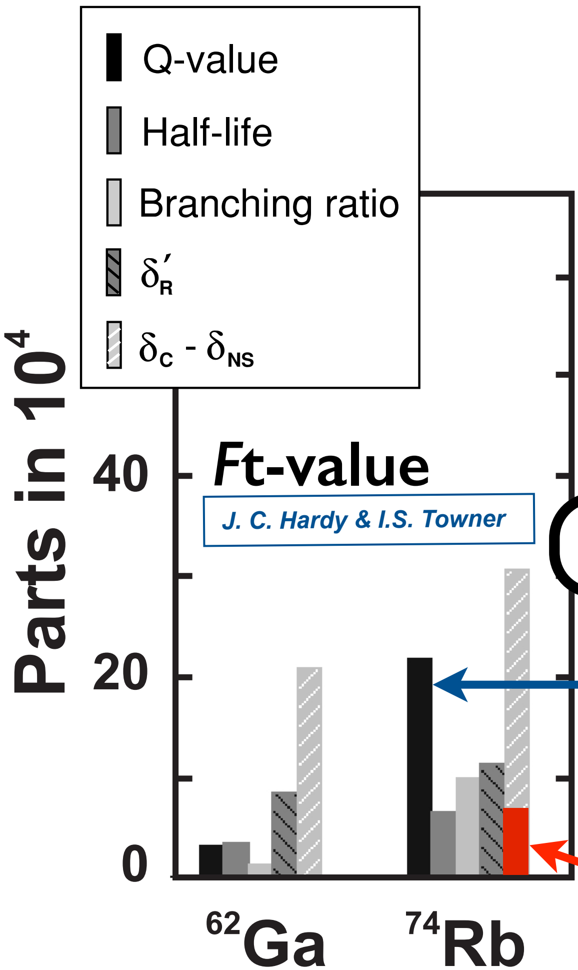


?

to which extend/precision is CVC a result of QCD?

Q-value

⇒precision Penning-trap mass measurement

≈20 % due to charge radius

⇒ accessible through laser spectroscopy

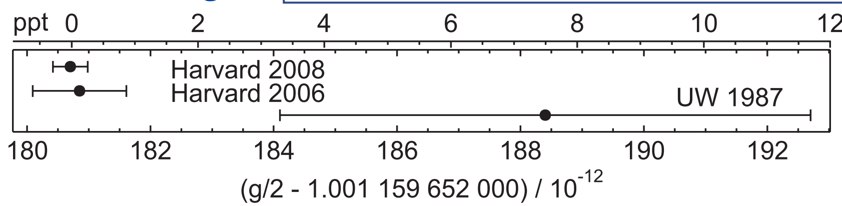
E. Mané et al., PRL 107, 212502 (2011)

Hans G. Dehmelt
Nobel Prize 1989

Penning traps

electron g-2

D. Hanneke et al., Phys. Rev. Lett. 100, 120801 (2008)



antimatter (antiproton q/m, μ_p)

Gabrielse, G. et al. Phys. Rev. Lett. 82, 3198 (1999)
S. Ulmer et al., Nature 524, 196–199 (2015)

A. Mooser et al. Nature 509, 596 (2014)
G. Schneider et al., 358, 1081, Science (2017)

masses (and test of $E=mc^2$)

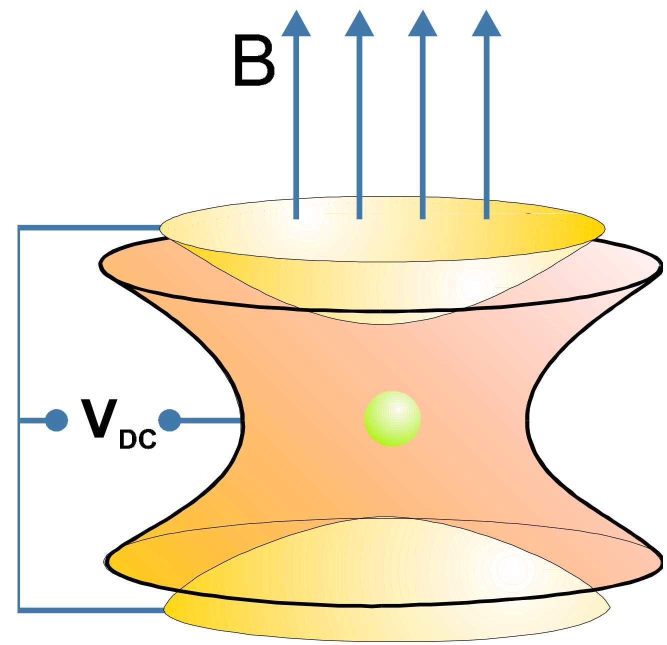
S. Rainville et al., Science 303, 334 (2004)
Nature 438, 1096 (2005)

improved mass of electron

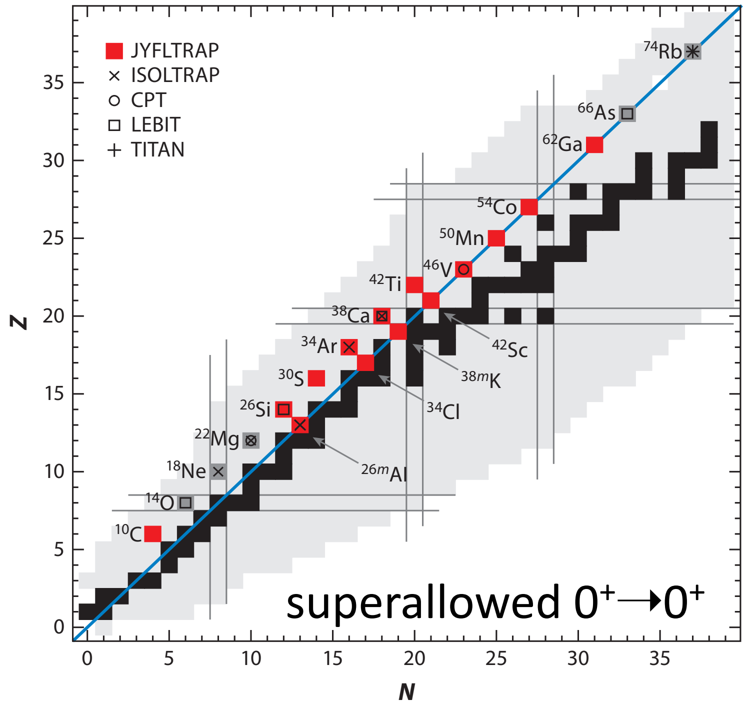
S. Sturm et al., Nature 506, 467-470 (2014)

improved mass of proton

F. Heiße et al., Phys. Rev. Lett. 119, 033001 (2017)



Penning traps and radionuclides for BSM

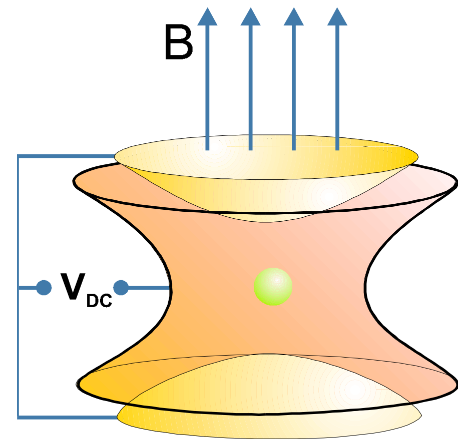


required precision

$\delta m/m \sim 1\cdot 10^{-9/-8}$

accurate,
but not precise

precise,
but not accurate



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

Accuracy

- exact theoretical description

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
M. König et al., Int. J. Mass Spect. 142, 95 (1995)
M. Kretzschmarr, Int. J. Mass Spect. 246, 122 (2007)

- even for non-ideal traps

G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)

- off-line tests with stables

Precision

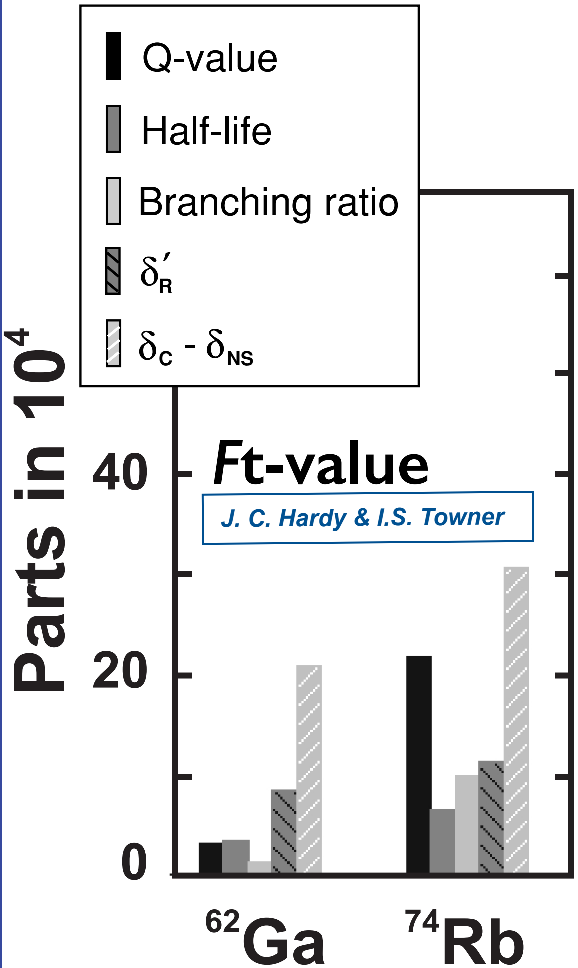
line-width (FWHM):

$$\Delta\nu \approx 1/T_{rf}$$

⇒ resolution:

$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta\nu_c} \approx \nu_c T_{rf} \approx \frac{qBT_{rf}}{2\pi m}$$

Q-value of ^{74}Rb



- ISOLTRAP @ ISOLDE/CERN

A. Kellerbauer et al., PRL 93, 072502 (2004), PRC 76, 045504 (2007)

Nuclide	D_{exp} (keV)			
	2000	2002	2003	mean
^{64}Zn		−65 998.6(7.8)		−65 998.6(7.8)
^{71}Ga		−70 137.5(1.2)		−70 137.5(1.2)
^{74}Ga	−68 047(21)		−68 019(32)	−68 041(18)[a]
^{74}Rb	−51 905(18)[b]	−51 917.3(4.8)[c]	−51 910.7(7.0)[c]	−51 914.7(3.9)

- limitation due to $T_{1/2}$ = 65 ms

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$

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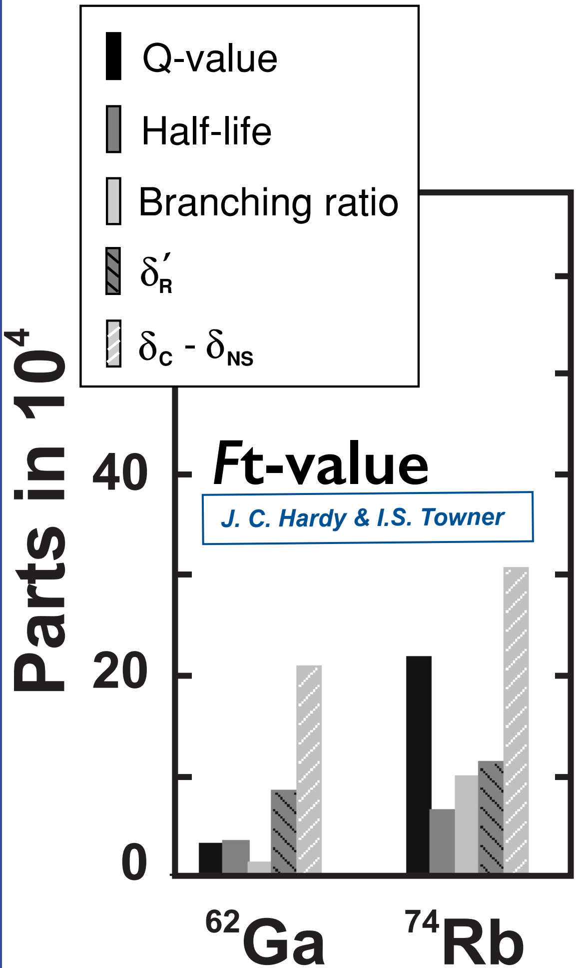

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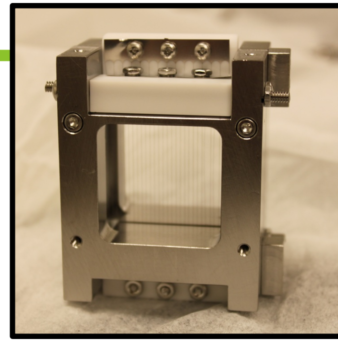
$$\frac{\delta m}{m} \propto \frac{m}{q} \frac{1}{B T N^{1/2}}$$

to improve precision further: new approach needed ⇒ HCI

TITAN @ISAC



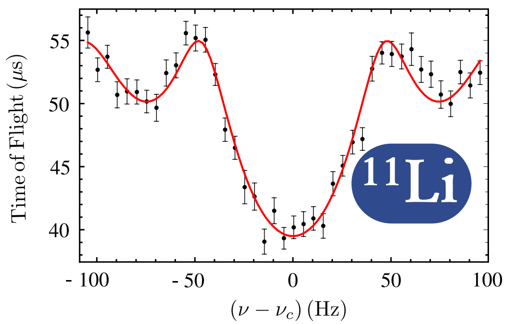
Penning traps:

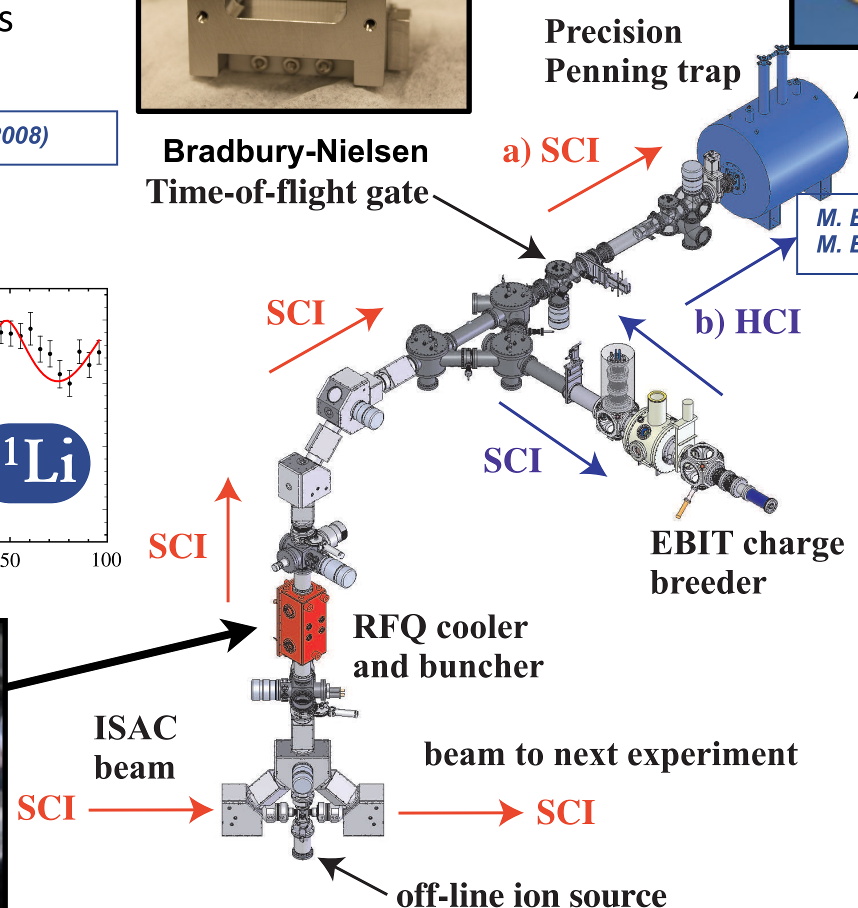
- highest precision
- down to $T_{1/2}$ < 10 ms

(^{11}Li $T_{1/2}$ = 8.8 ms @ TITAN)

M. Smith et al., PRL 101, 202501 (2008)

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

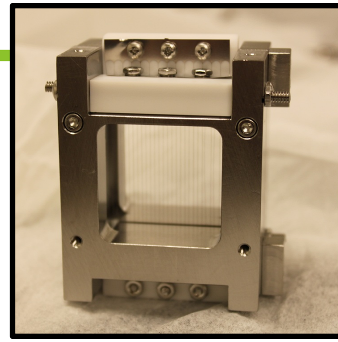




systematics < 5 ppb

M. Brodeur et al, PRC 80, 044318 (2009)
M. Brodeur et al., IJMS 310, 20 (2012)

TITAN @ISAC



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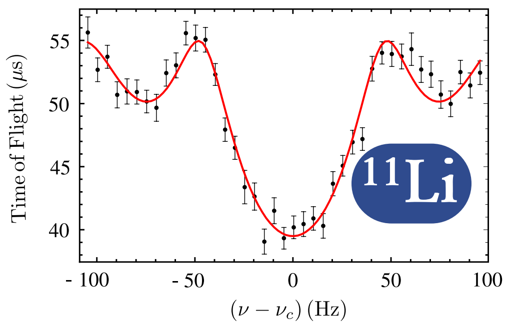

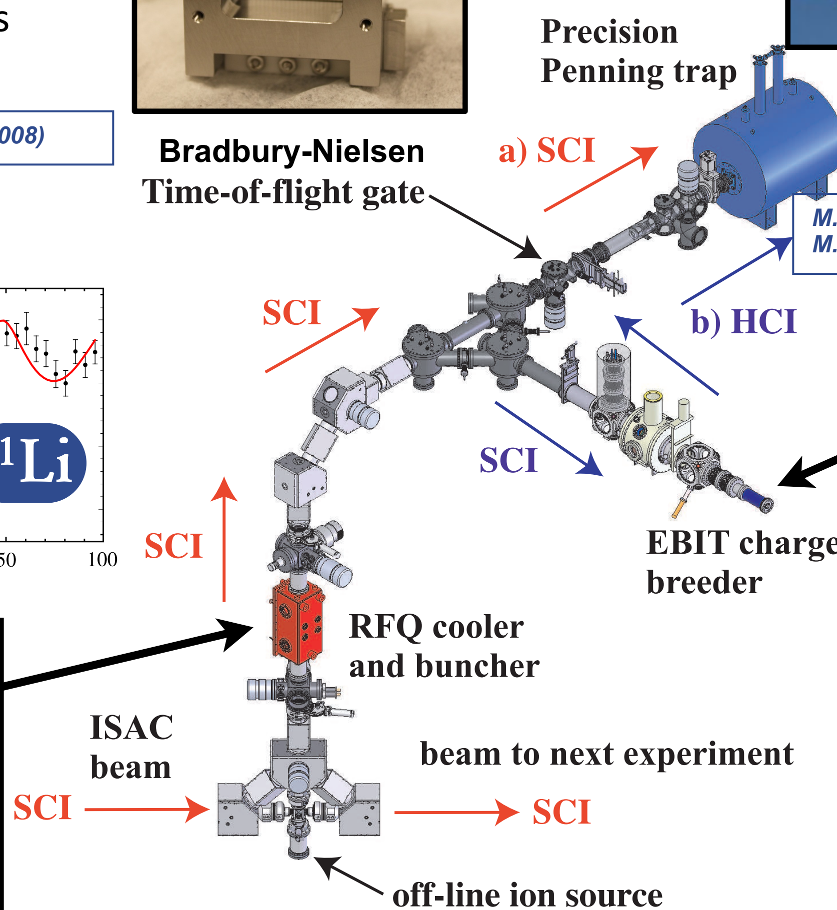

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M. Brodeur et al, PRC 80, 044318 (2009)
M. Brodeur et al., IJMS 310, 20 (2012)

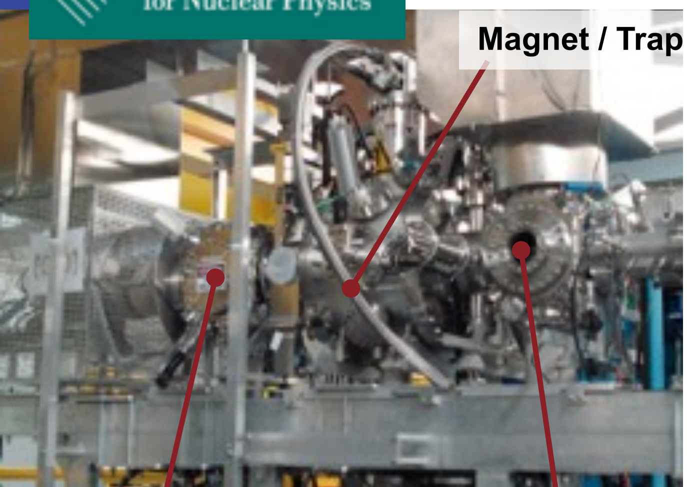
highly charged ions:

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$

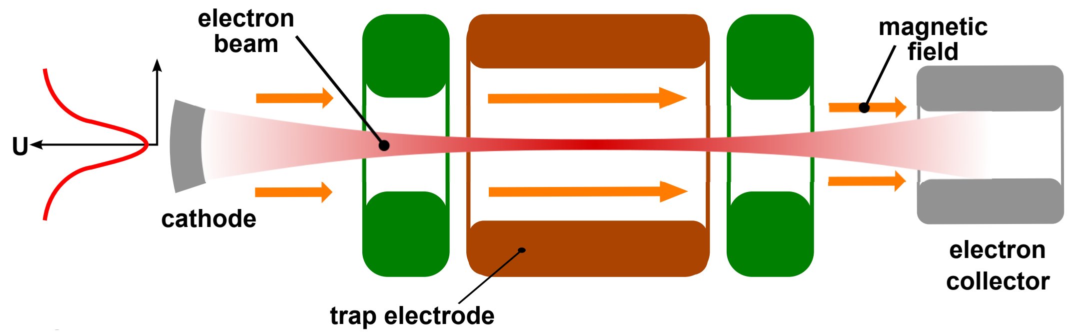
S. Malbrunot-Ettenauer et al.,
Phys. Rev. Lett. 107, 272501 (2011)
PRC 91, 045504 (2015)

Electron Beam Ion Trap

Max Planck Institute for Nuclear Physics

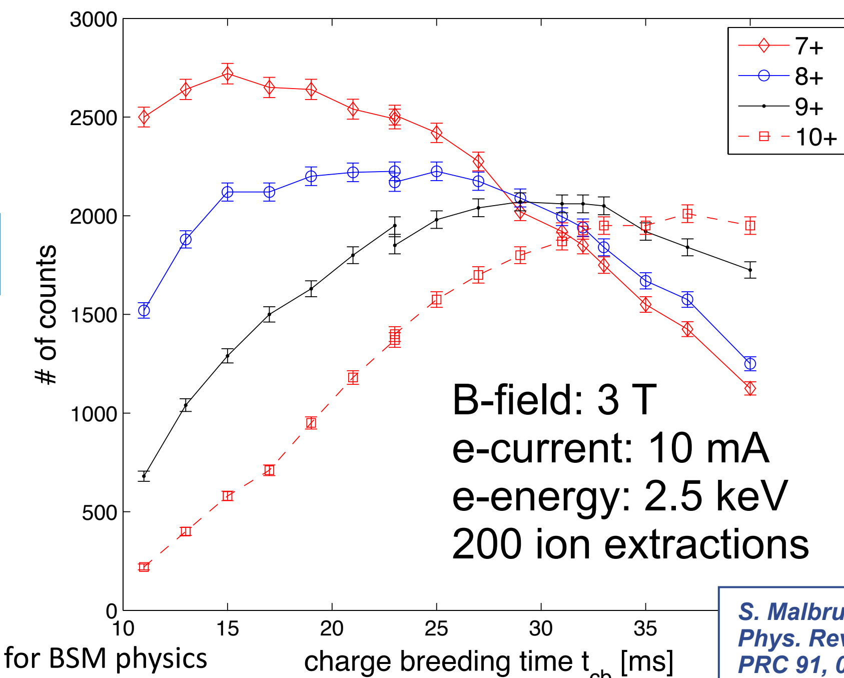


M. Froese et al., Hyperfine Interactions 173, 85 (2006)
A.Lapierre et al.,Nucl. Instr. andMeth. A 624, 54 (2010)



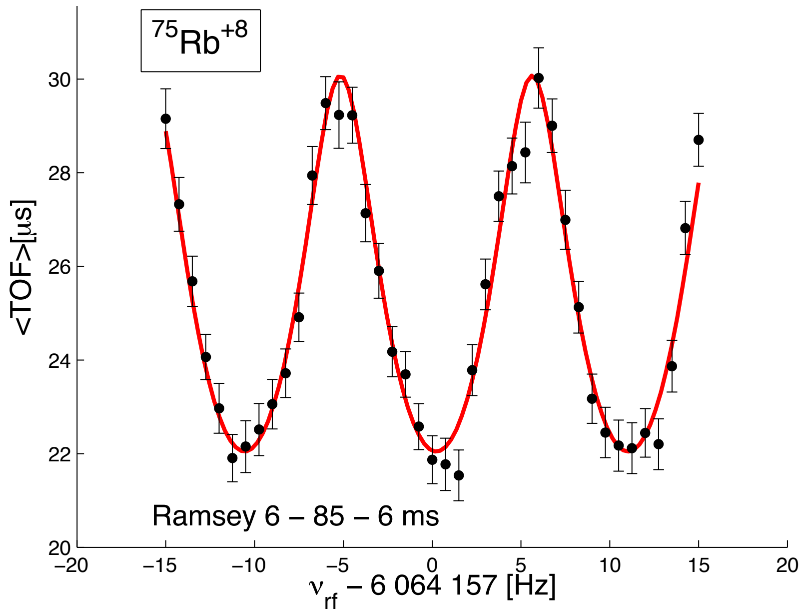
requirements for charge breeding:

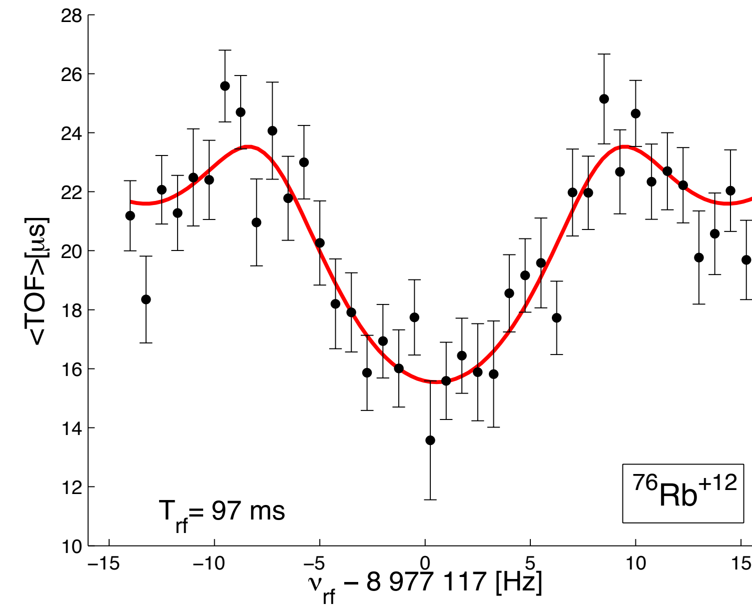
- efficient
- fast (^{74}Rb: $T_{1/2}$=65 ms)



S. Malbrunot-Ettenauer et al., Phys. Rev. Lett. 107, 272501 (2011)
PRC 91, 045504 (2015)

Ramsey excitation of ^{75}Rb





Ramsey excitation:

- 2 excitation pulses
- improves precision by a factor 2 - 3

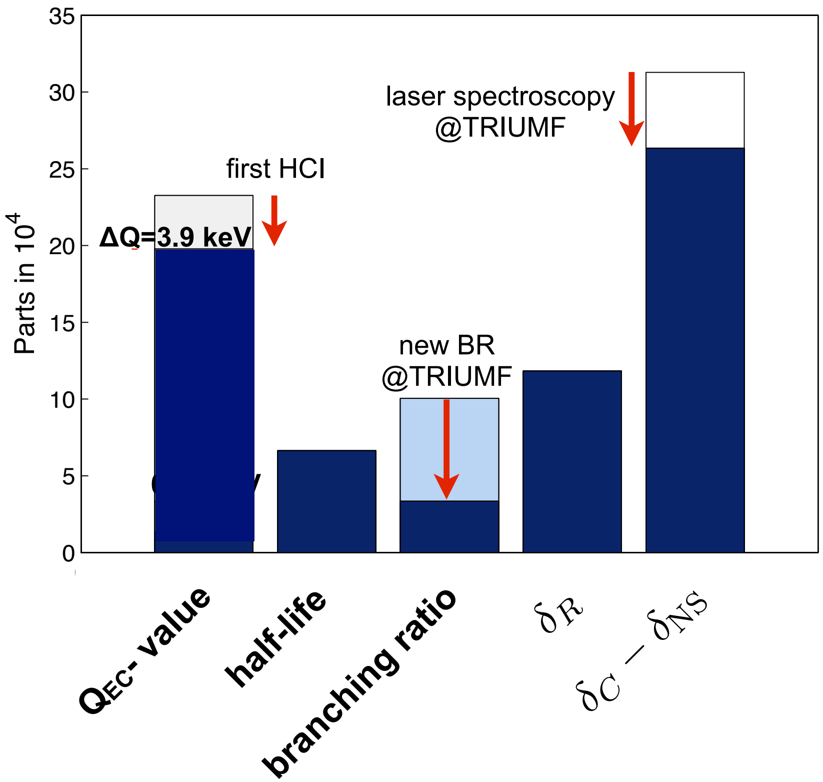
HCI

during this beamtime demonstrated up to q=12+

compared to conventional method: improvement by factor >24

first results ^{74}Rb

- precision already comparable to ISOLTRAP (2007) in < 22 hours
- power outage during ^{74}Rb => reconditioning of EBIT => lower efficiency



S. Malbrunot-Ettenauer et al., Phys. Rev. Lett. 107, 272501 (2011)
PRC 91, 045504 (2015)
E. Mané et al., PRL 107, 212502 (2011)
R. Dunlop et al., PRC 88, 045501 (2013)

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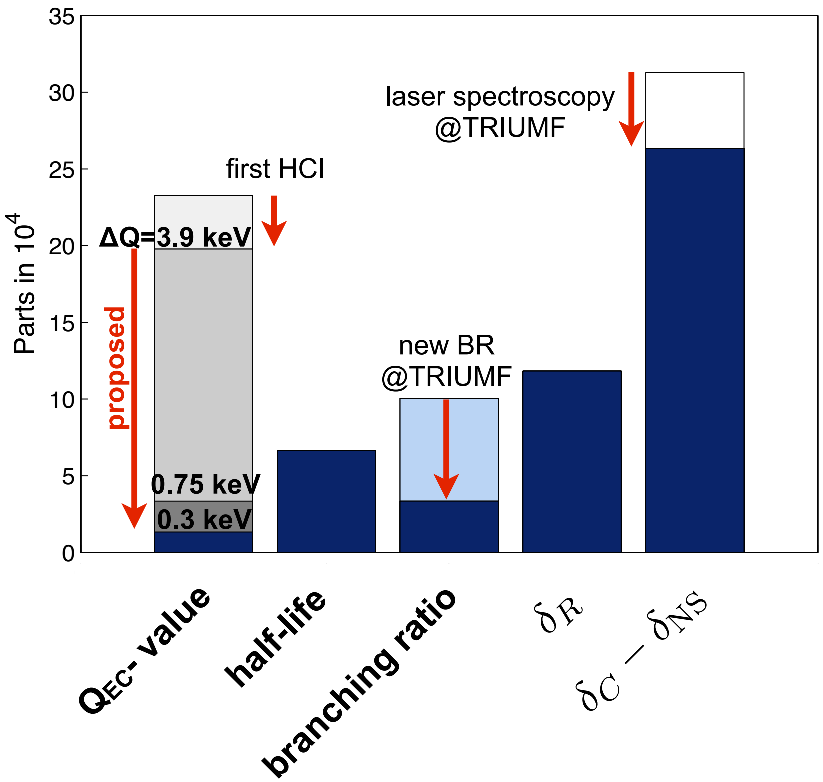

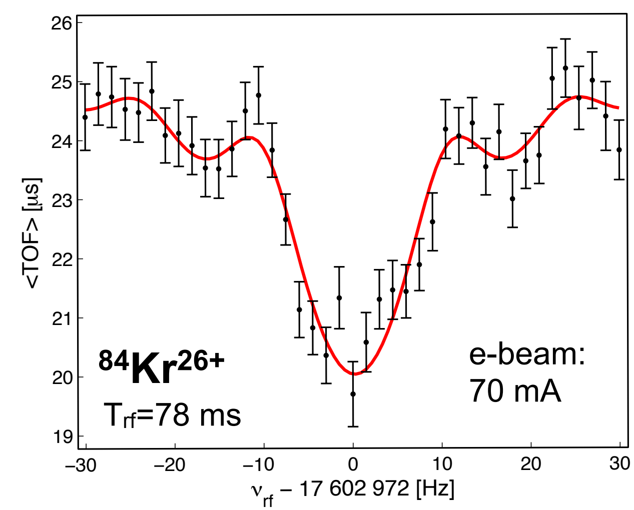

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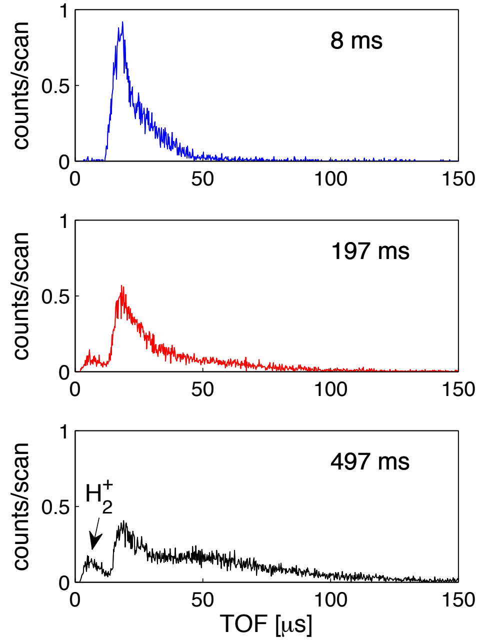
E. Mané et al., PRL 107, 212502 (2011)
R. Dunlop et al., PRC 88, 045501 (2013)

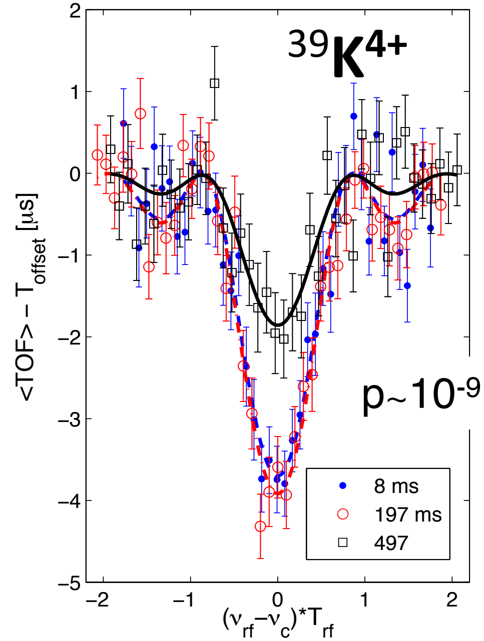
M.C. Simon et al., ICIS proceedings, 2011

potential for second measurement

I_e=400 mA to reach q≈30+

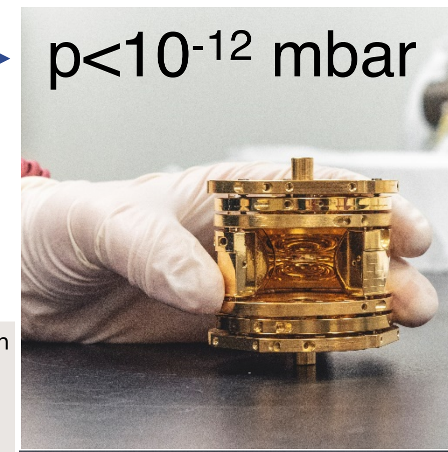
Charge exchange with residual gas

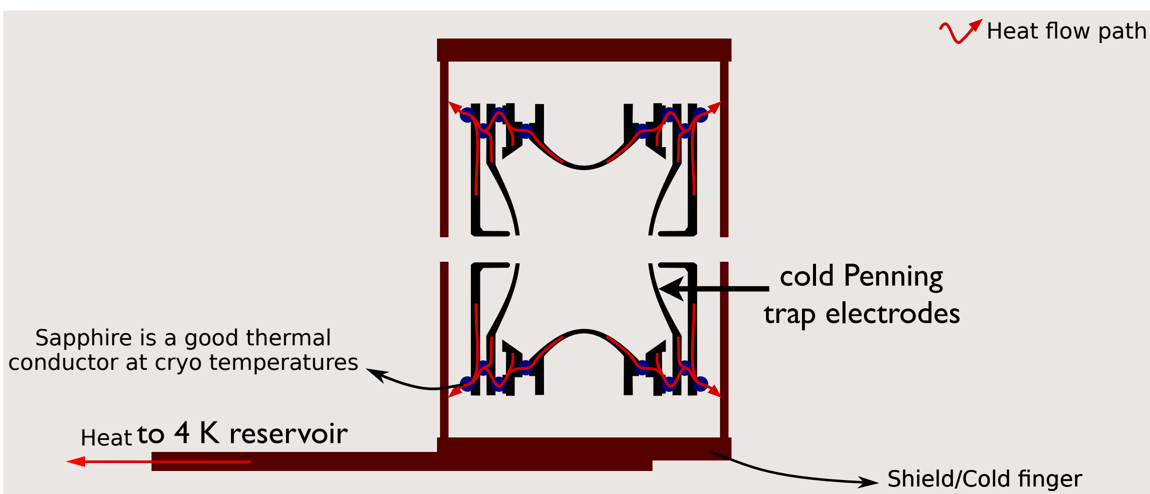


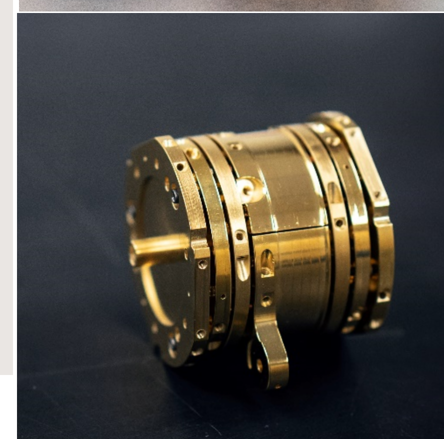


need to eliminate charge exchange
⇒ **cryogenic Penning trap**

p~10^{-9} mbar ⟷

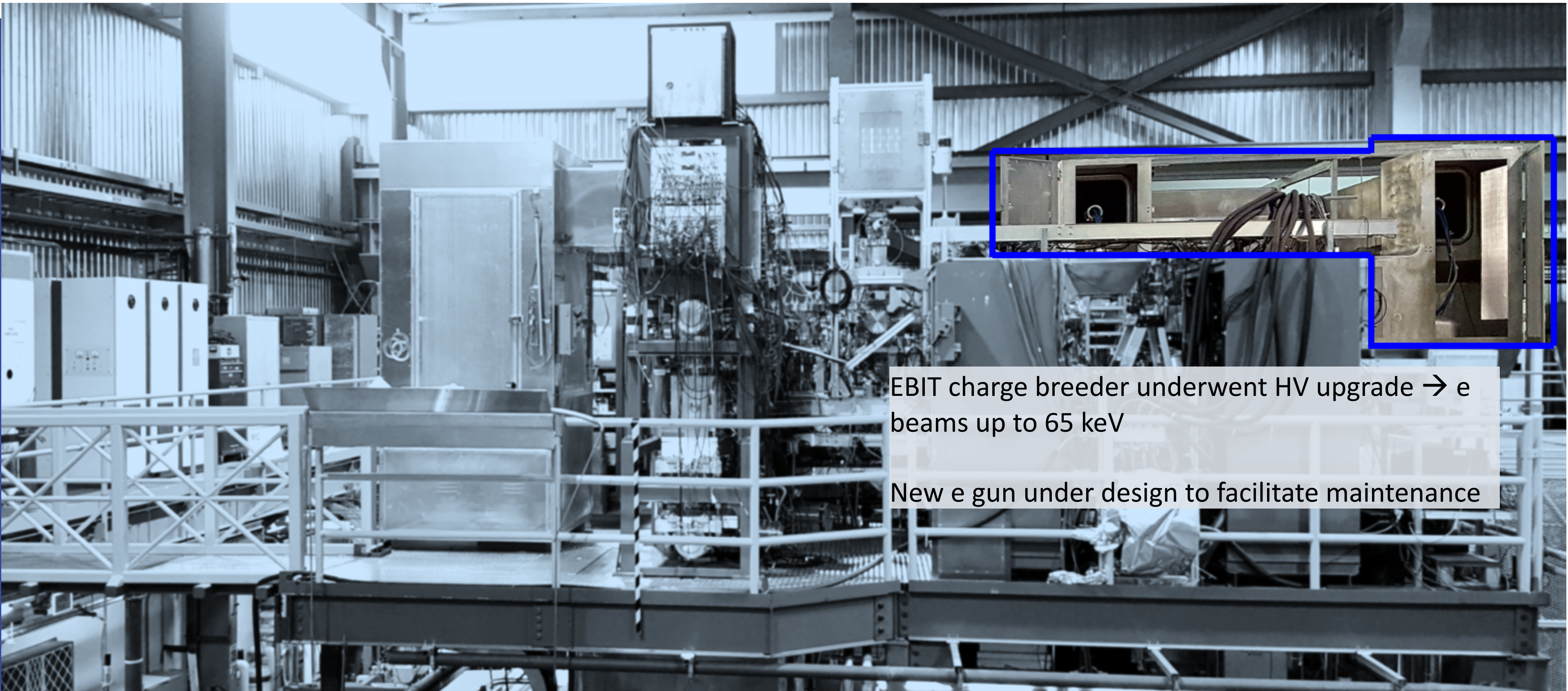






courtesy of A. Kwiatkowski
and E. Leistenschneider

EBIT developments



EBIT charge breeder underwent HV upgrade → e beams up to 65 keV

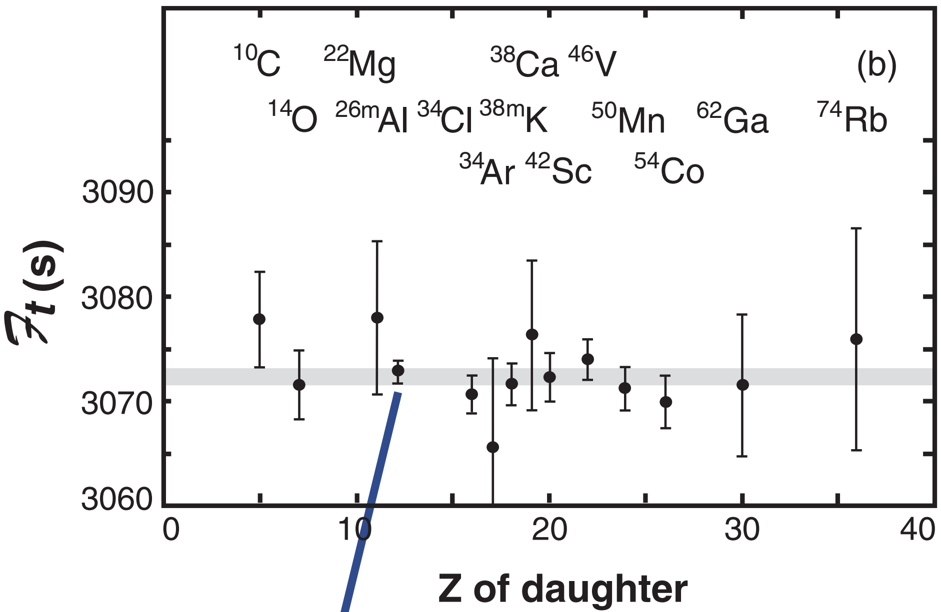
New e gun under design to facilitate maintenance

courtesy of A. Kwiatkowski

Superallowed β decays, V_{ud} & ^{26m}Al's charge radius

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

$$|V_{ud}| = \frac{G_V}{G_F}$$



J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)

- most precisely studied superallowed β emitter
- rivals precision of all other 13 cases combined

Superallowed β decays, V_{ud} & ^{26m}Al's charge radius

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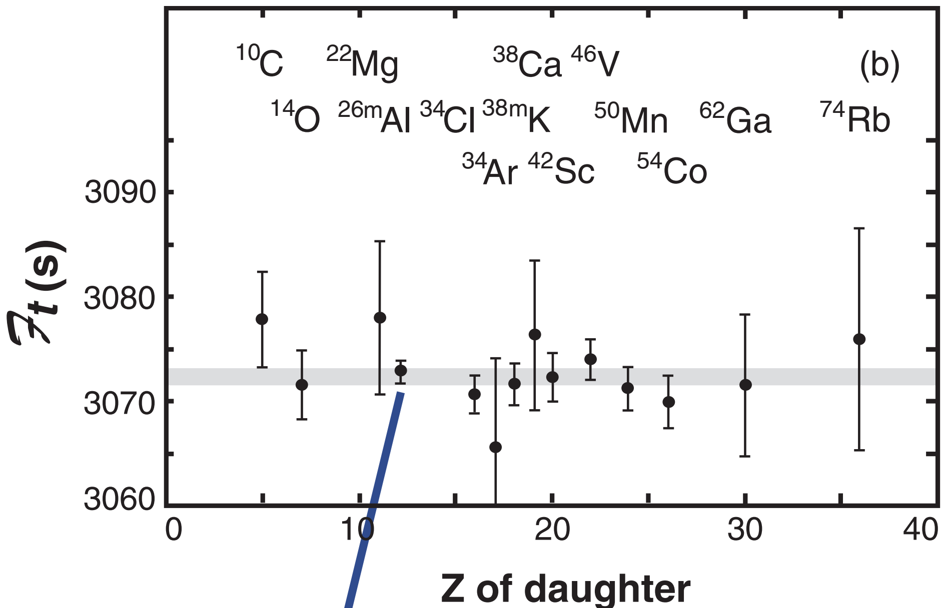

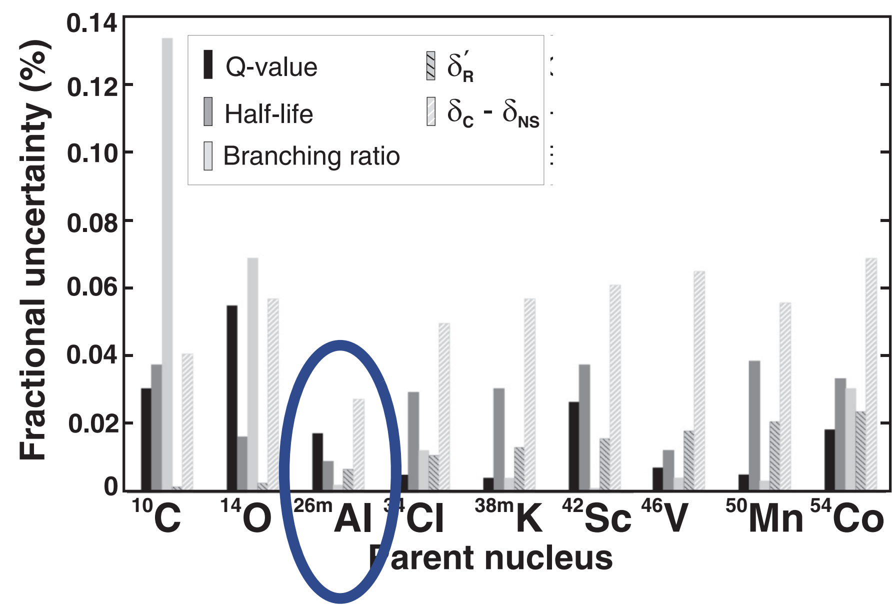

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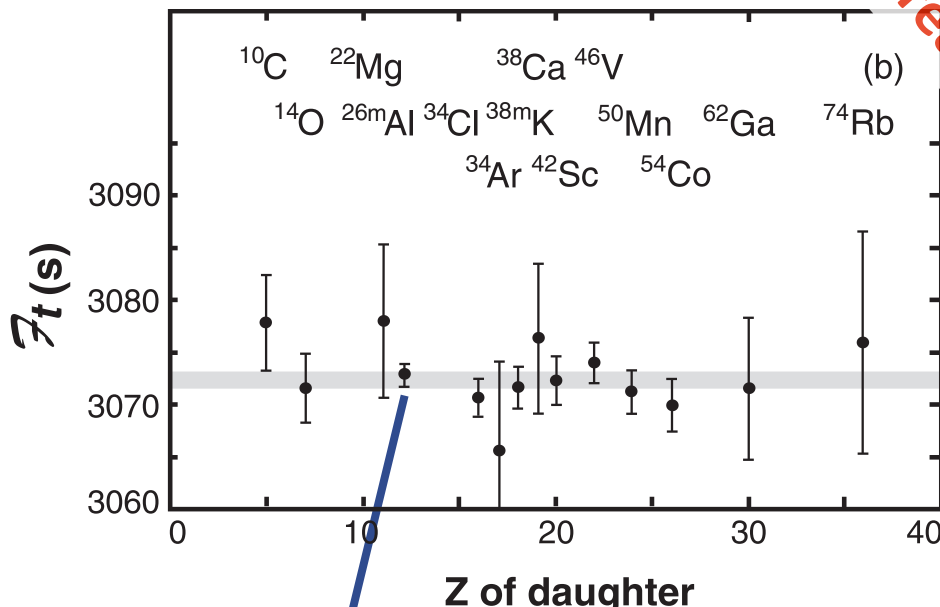
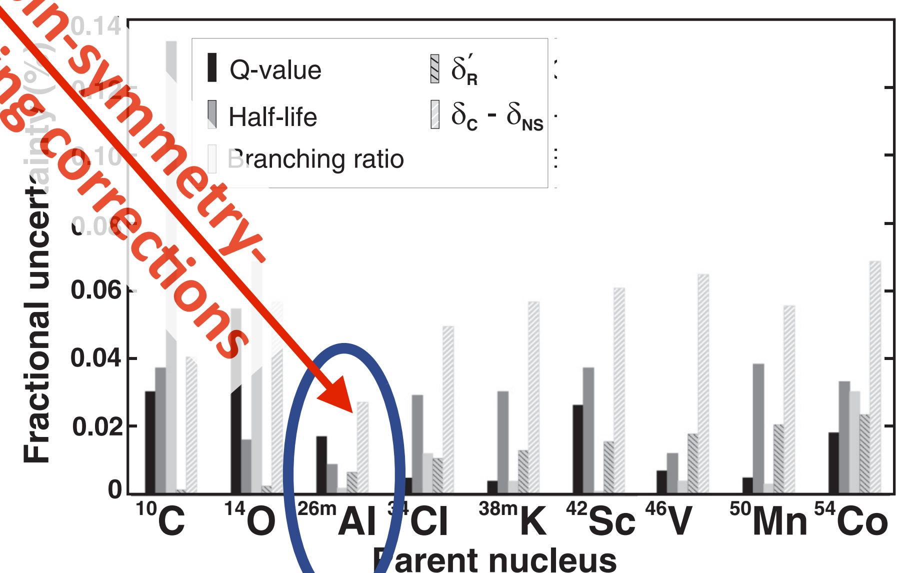
isospin-symmetry-breaking corrections





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ISB corrections δ_c

$$\delta_C = \delta_{C1} + \delta_{C2}$$

configuration mixing within the restricted shell model space (← δ_{C1})

radial overlap correction (← δ_{C2})

^{26m}Al — **δ_{C1} = 0.030(10) %**, **δ_{C2} = 0.280(15) %**

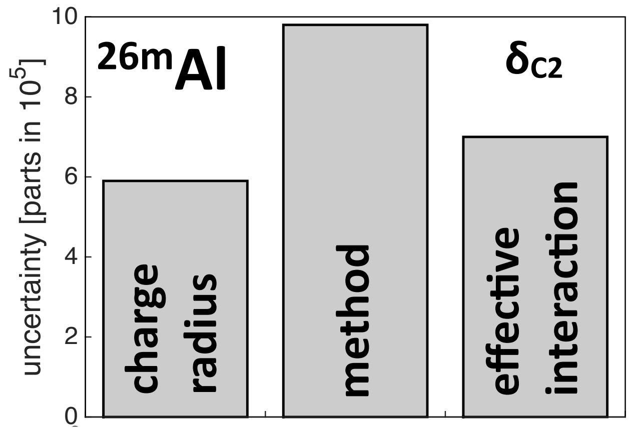
I. S. Towner & J. C. Hardy, PRC 66, 035501 (2002).
I. S. Towner & J. C. Hardy, PC 77, 025501 (2008).

δ_{C2}: shell model based on Saxon-Woods radial functions

$$V_C(r) = Ze^2/r, \quad \text{for} \quad r \geqslant R_c,$$
$$= \frac{Ze^2}{2R_c}\left(3 - \frac{r^2}{R_c^2}\right), \quad \text{for} \quad r < R_c,$$

- nuclear charge radius enters here
- often not known experimentally (e.g. ^{26m}Al)

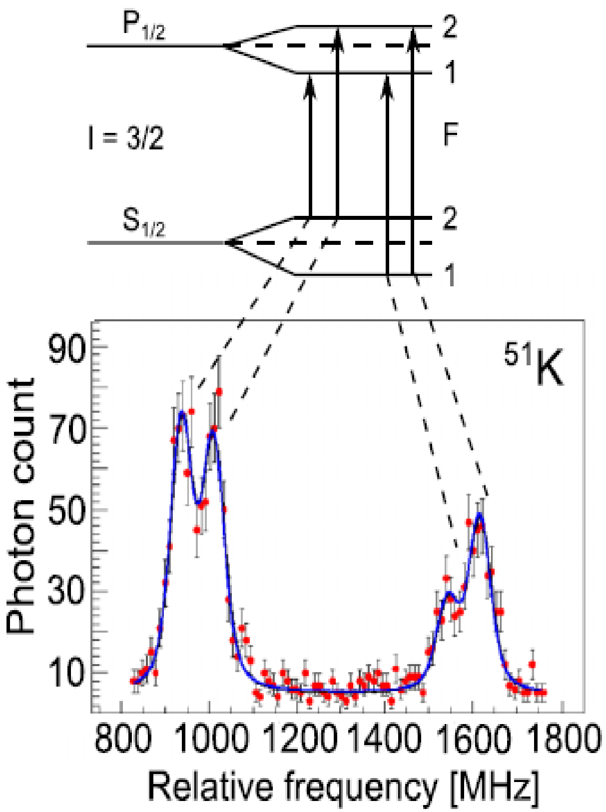
⇒extrapolation based on stable isotopes (and inflated uncertainties)



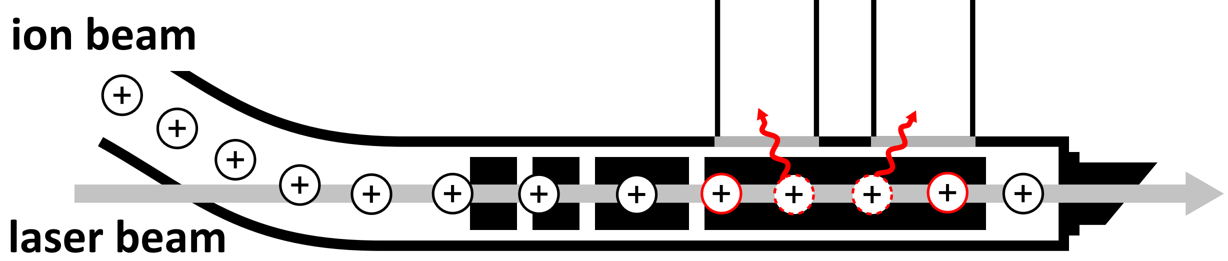
I. S. Towner private communications (2016).

measurement will place $\langle r^2 \rangle$ on solid experimental grounds
and reduce uncertainty on δ_{C2}

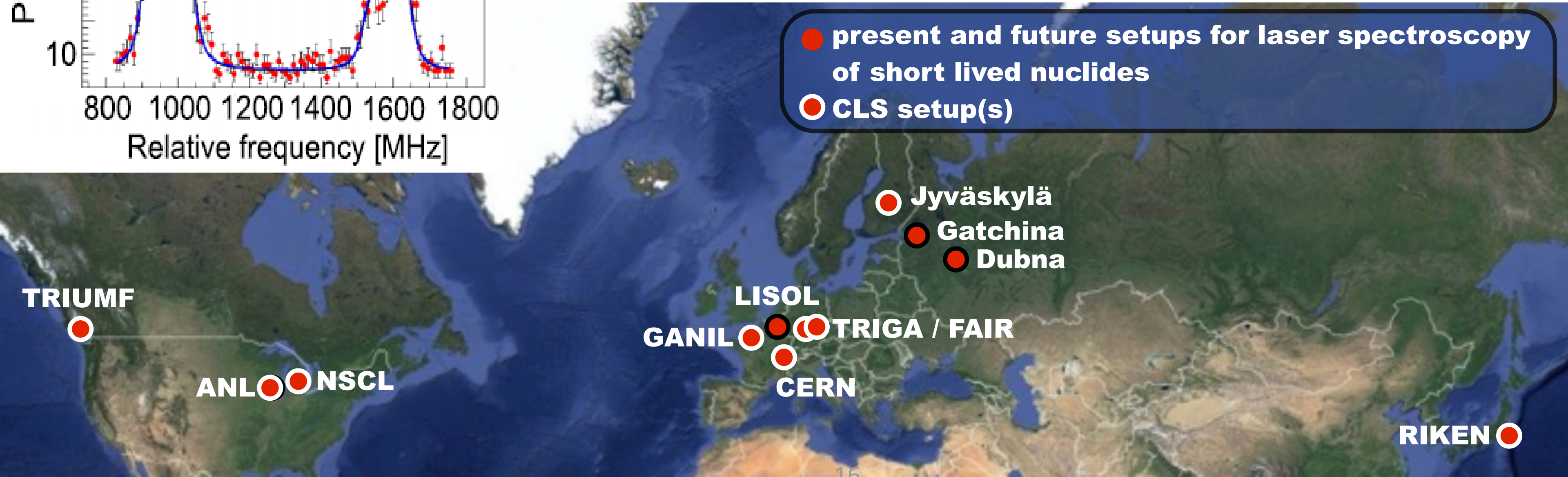
Collinear Laser Spectroscopy (CLS)



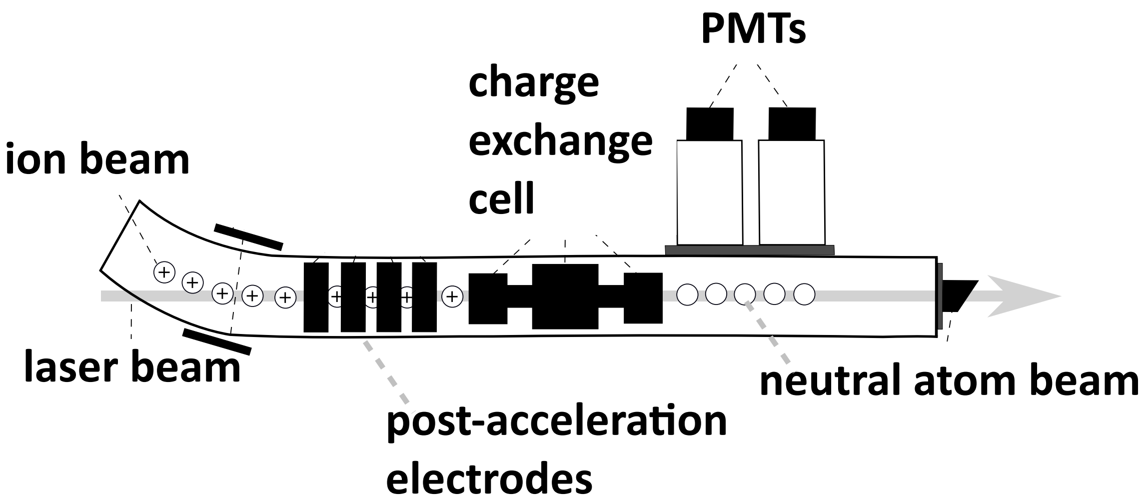
> 30 keV to eliminate Doppler broadening $\delta\nu \propto \frac{\delta E}{\sqrt{E}}$



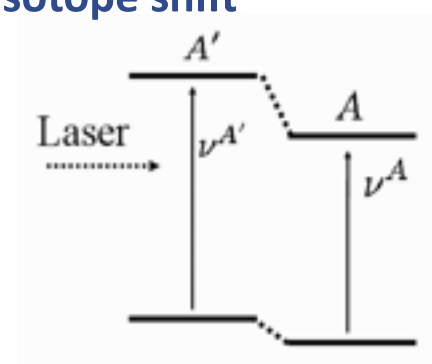
K. Blaum et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)



Measurement at COLLAPS/ISOLDE



isotope shift



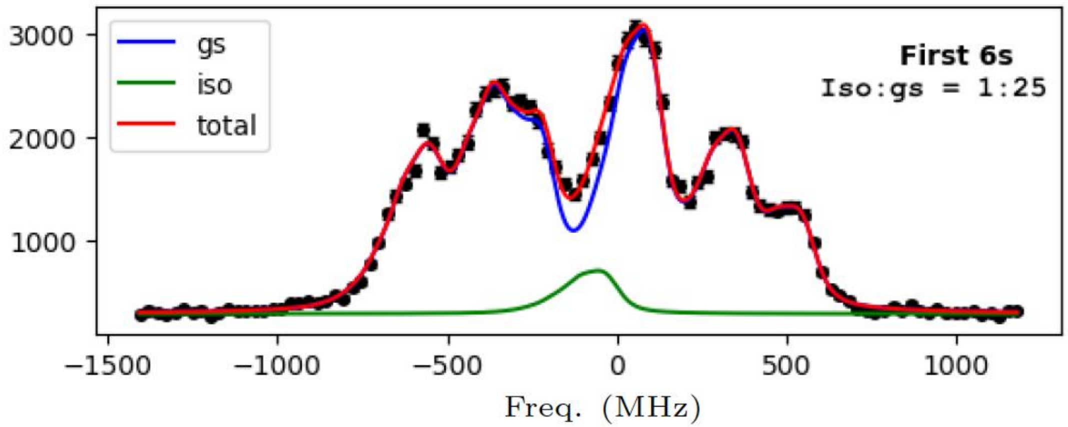
$$\delta\nu^{A,A'} = M\frac{A'-A}{A\cdot A'} + F\delta\langle r^2\rangle^{A,A'}$$

difference in ms charge radii

mass and field shift factors from atomic physics calculation

L. Filippin et al., Phys. Rev. A, 94, 062508 (2016)

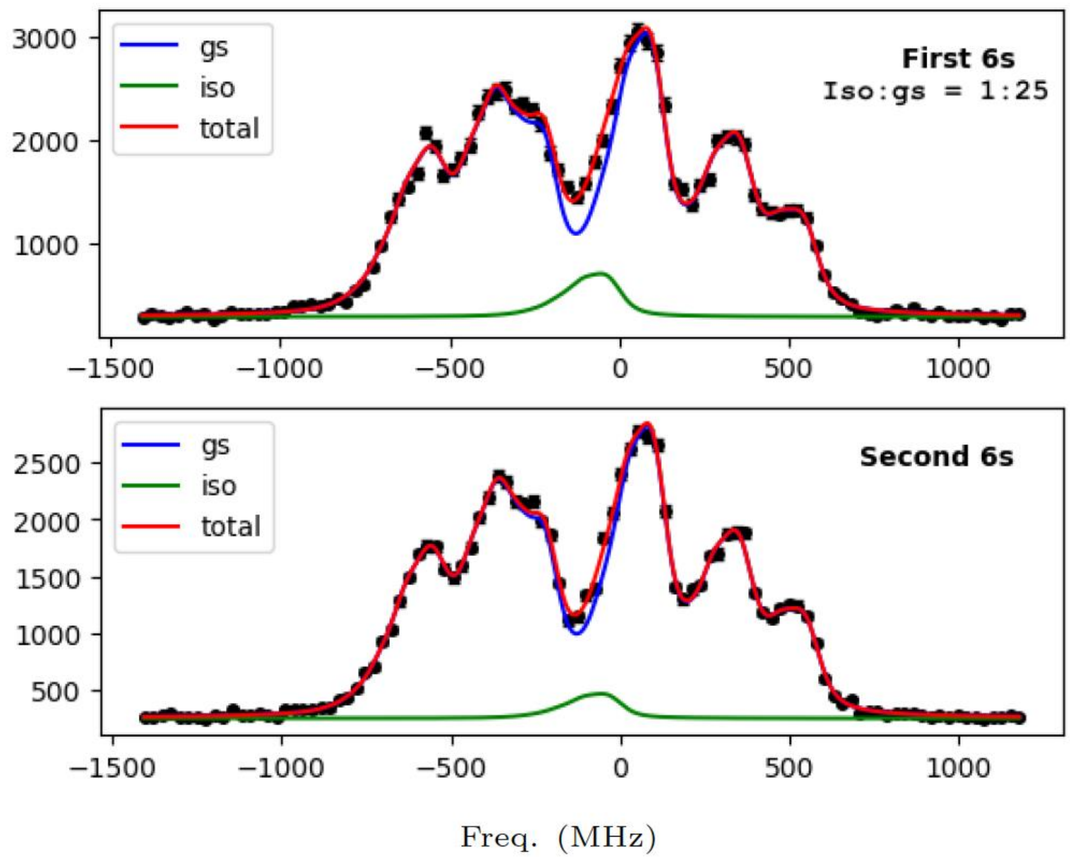
^{26}Al results at COLLAPS



unexpectedly low ratio of isomer to ground state

H. Heylen et al. @ COLLAPS

^{26}Al results at COLLAPS



unexpectedly low ratio of isomer to ground state

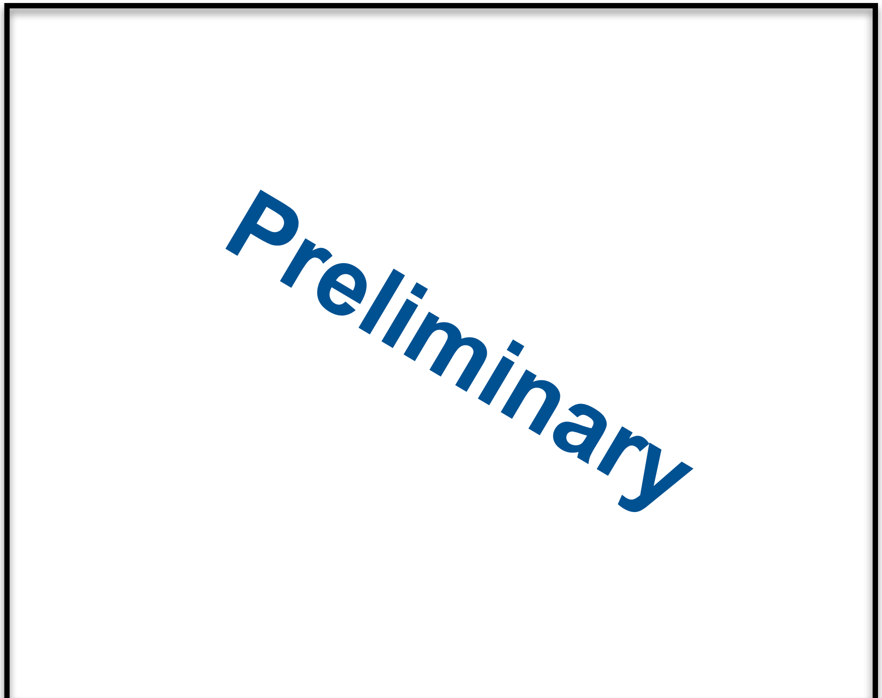
Intensity ratio first 6s/second 6s:

Gs: 0.94(1) [$T_{1/2}$ = 7 x10^5 y]

Iso: 0.56(4) [$T_{1/2}$ = 6.34 s]

H. Heylen et al. @ COLLAPS

Al charge radii



$$\delta\nu^{A,A'} = M\frac{A' - A}{A \cdot A'} + F\delta\langle r^2\rangle^{A,A'}$$

F = [74.0 – 77.5] MHz/fm^2
M = [-239 – -224] GHz u

L. Filippin et al., Phys. Rev. A, 94, 062508 (2016)

what else could be done? **?**

- more accurate M calculation from atomic theory?
- absolute charge radius of ^{26}Al gs ($T_{1/2}$ = 7x10^5 y) ?

H. Heylen et al. @ COLLAPS

^{26m}Al, r_c & δ_c: what do we (not) know?

^{27}Al as reference for absolute charge radius: $R(A') = \sqrt{R^2(A) + \delta\langle r^2\rangle^{AA'}}.$

nuclide	$\langle r_c^2\rangle$ [fm^2]		reference
^{27}Al	9.37(02)	r_c compilation	I. Angeli, At. Data Nucl. Data Tables 87, 185 (2004)
	9.26(18)	weighted average e- scattering	G. Fricke and K. Heilig, Nuclear Charge Radii (2004)

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^{26m}Al	9.24(12)	extrapolation for V_{ud}	Towner & Hardy PRC 66, 035501 (2002)

open questions:

- reliable value of r_c in ^{27}Al (and uncertainty)?
- implications for exp. r_c in ^{26m}Al (and its uncertainty)?

^{26m}Al at JYFL

strong motivation to better access r_c of ^{26m}Al

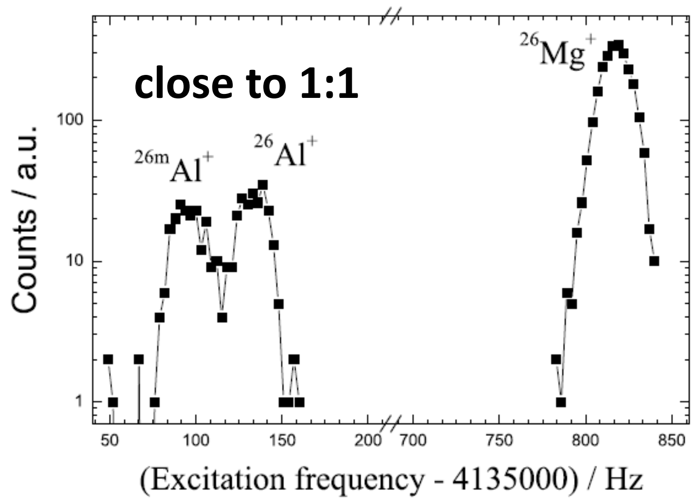
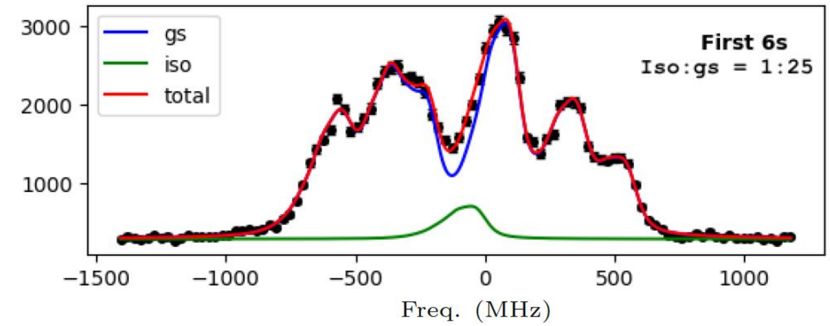


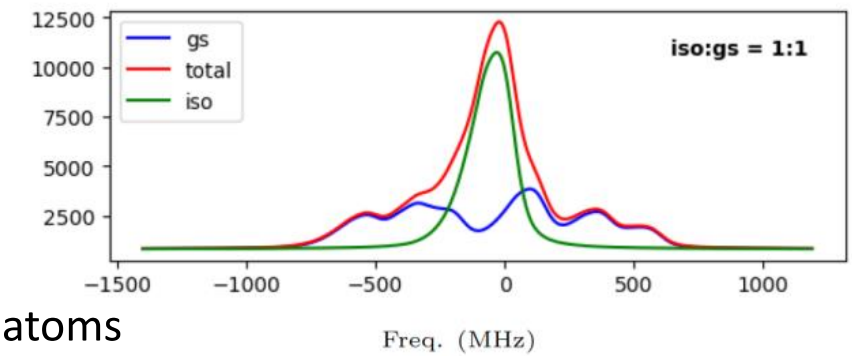
Fig. 1. Purification scan for mass $A = 26$. The excitation time that was employed was sufficient to separate the isomer and the ground state of ^{26}Al having different frequencies by approximately 40 Hz.

T. Eronen et al., NIM B 266, 4527 (2008)

COLLAPS data



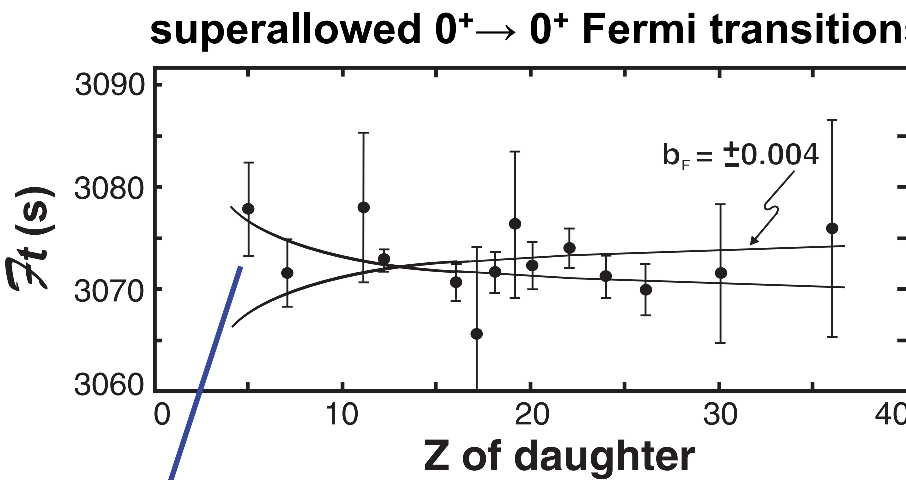
simulation



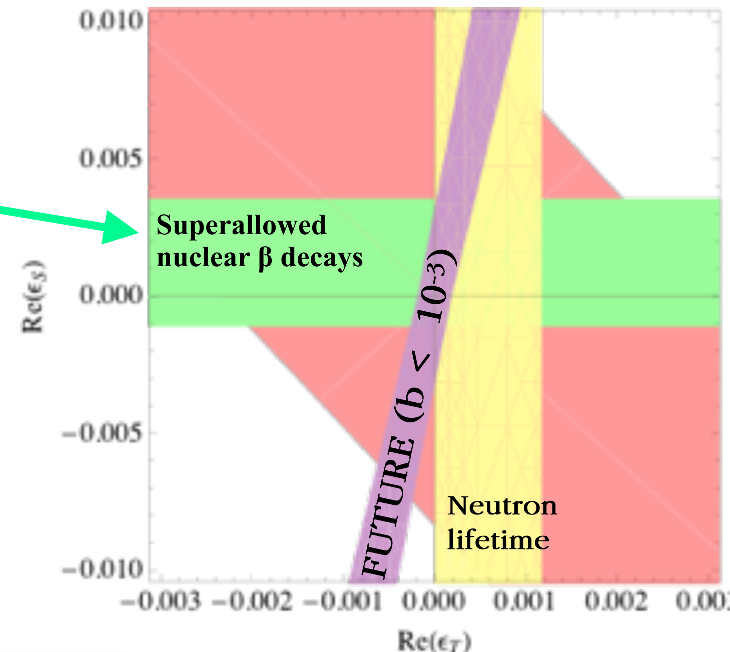
- upgrade of beamline at JYFL for CLS on atoms
- approved proposal ⇒ measurement later this year

Which other methods could calculate δ_c ?

Fierz term, scalar currents, and the case of ^{10}C



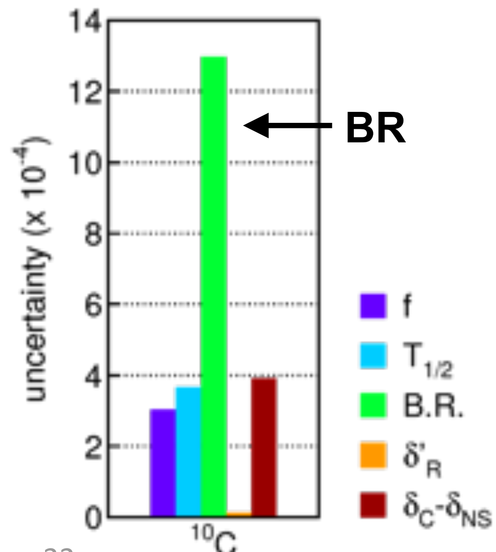
J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)



^{10}C

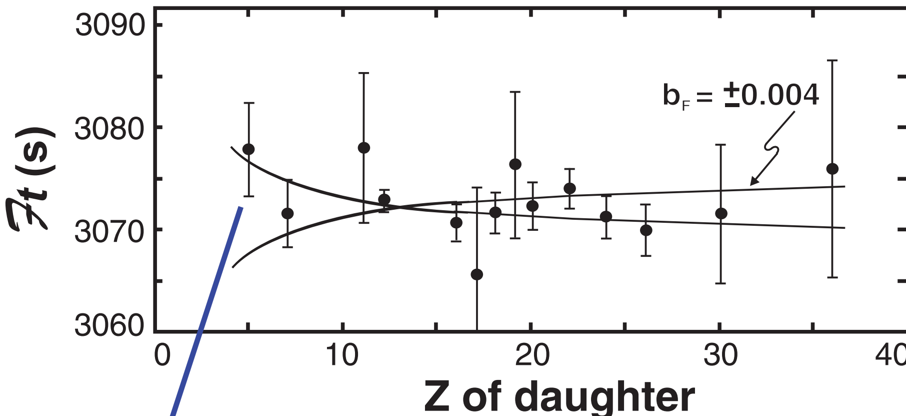
- high sensitivity to scalar currents
- limited by **BR**

G. Savard et al, PRL 74, 1521 (1995)
B.K. Fujikawa et al., PLB 449, 6(1999)

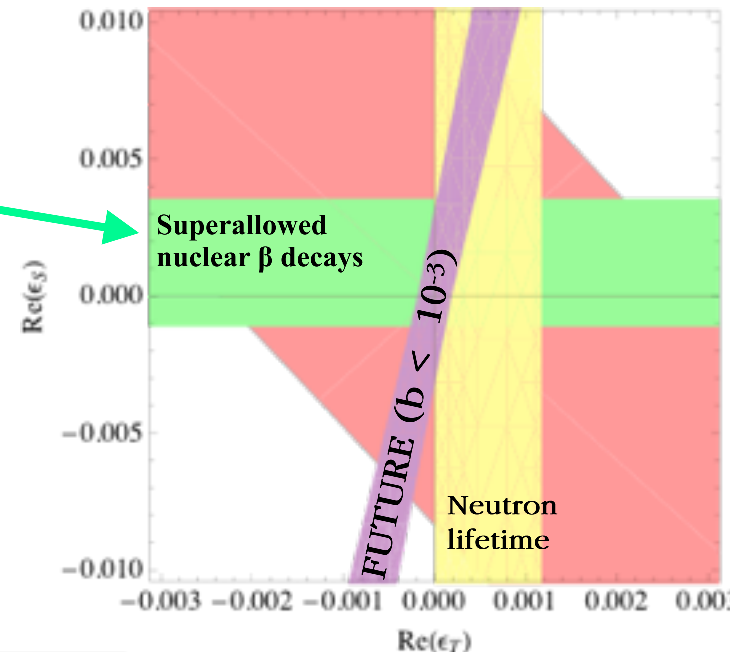


Fierz term, scalar currents, and the case of ^{10}C

superallowed $0^+ \rightarrow 0^+$ Fermi transitions



J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)



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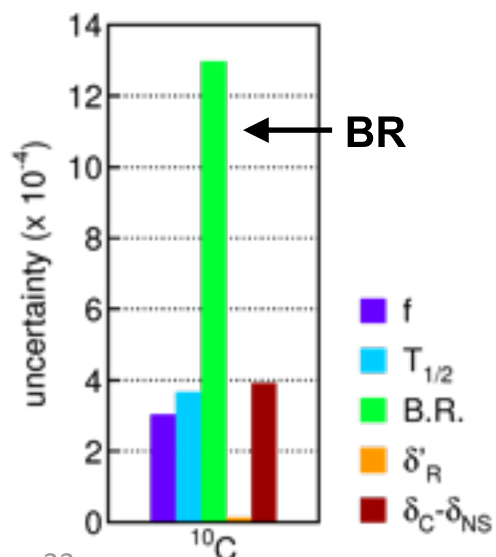
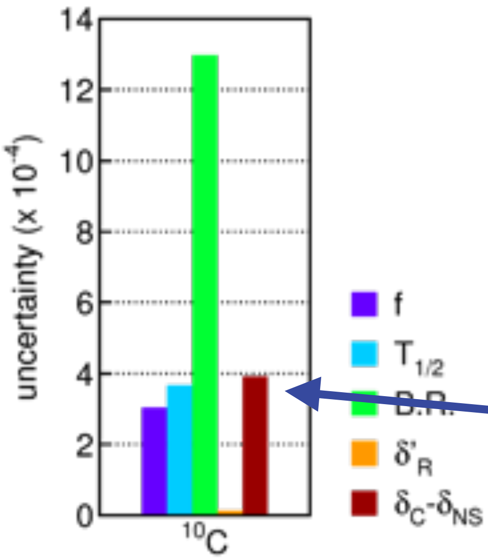
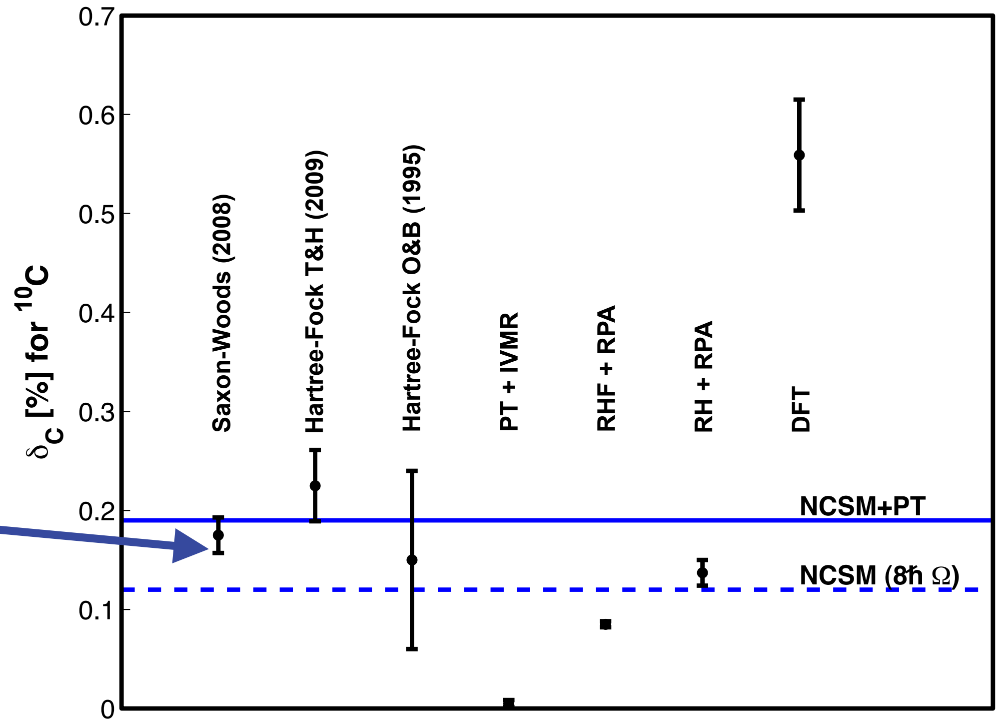


motivates new measurements with state-of-the-art detectors

δ_c in ^{10}C and *ab initio* calculations





NCSM of δ_c in ^{10}C

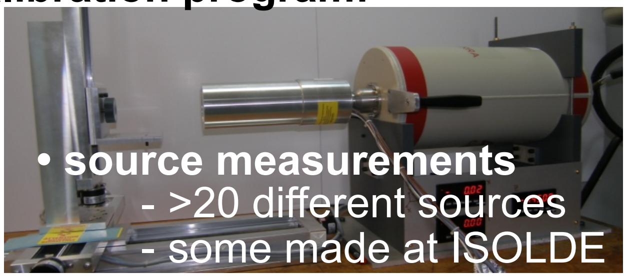
- without 3N forces
- CD-Bonn 2000 NN potential
- not converged
- **what would be possible today?**

?

E. Caurier et al., Phys. Rev. C, 66,024314,(2002)

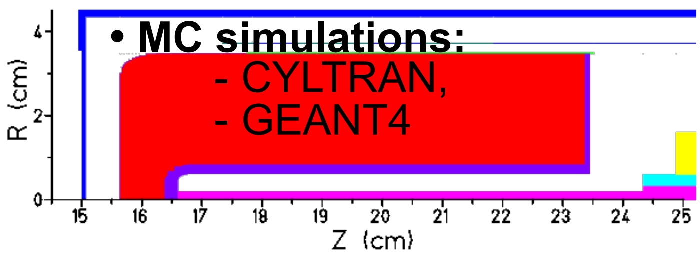
HPGe detector with high precision efficiency

calibration program:



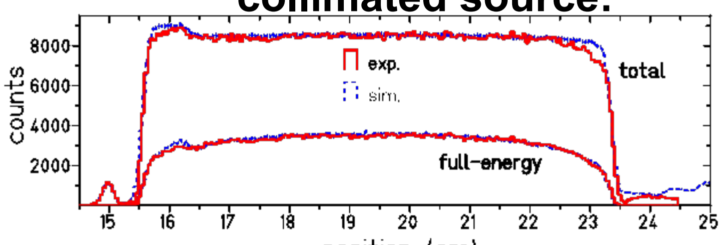
- **source measurements**
  - >20 different sources
  - some made at ISOLDE

- **x-ray photography**

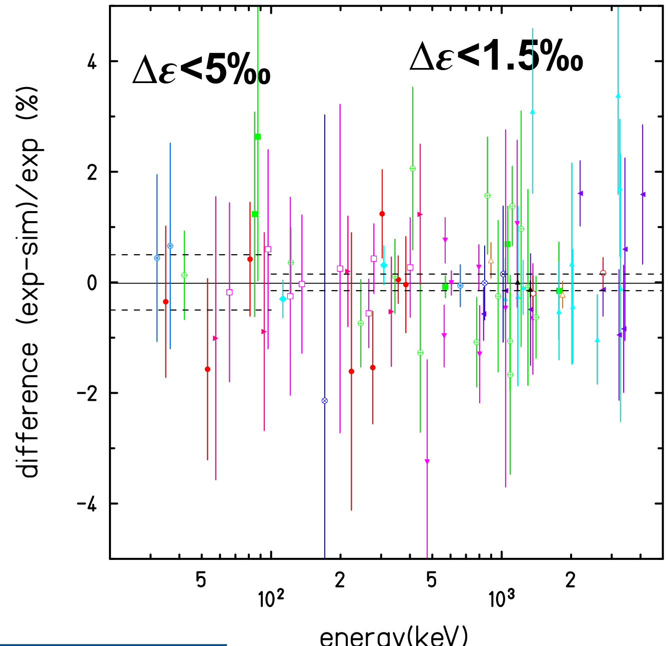


- **MC simulations:**
  - CYLTRAN,
  - GEANT4

- **scan of the crystal with collimated source:**



Results for remaining uncertainty in efficiency



B. Blank et al., NIM A 776, 34 (2015)

HPGe detector with high precision efficiency

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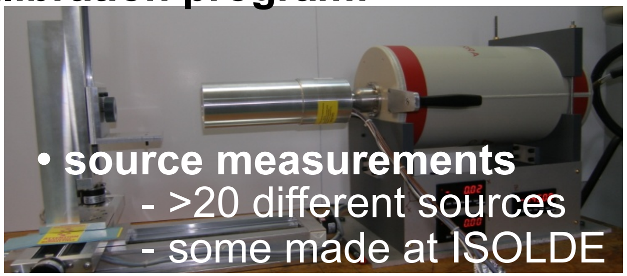

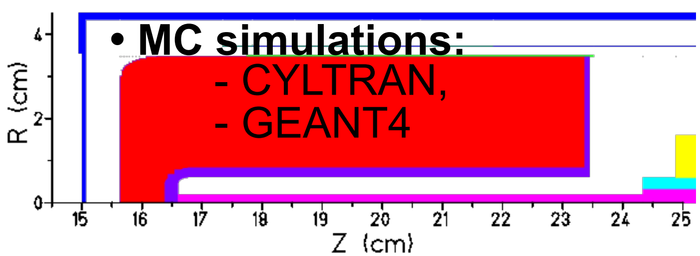

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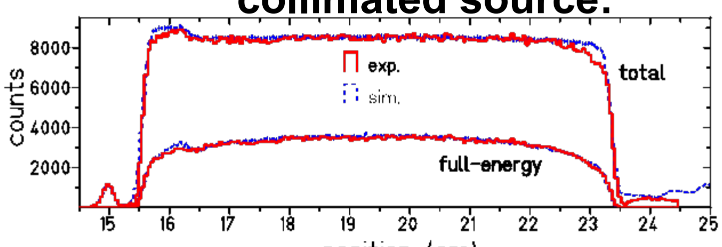

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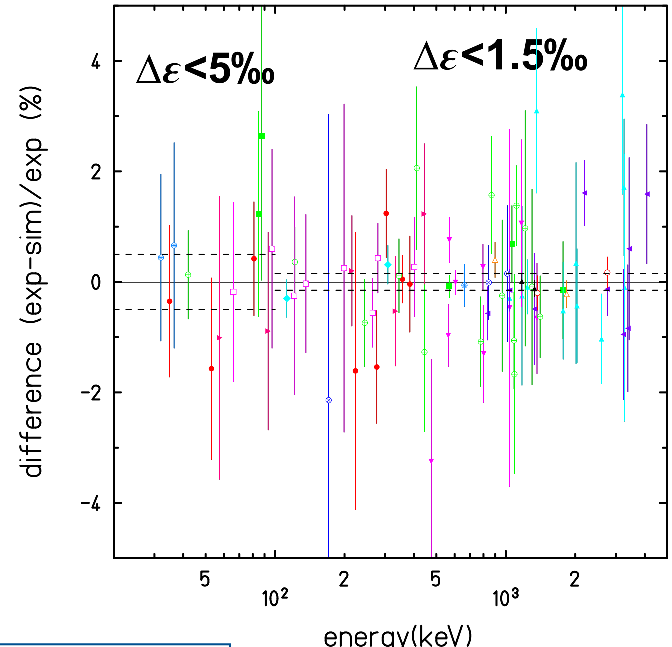
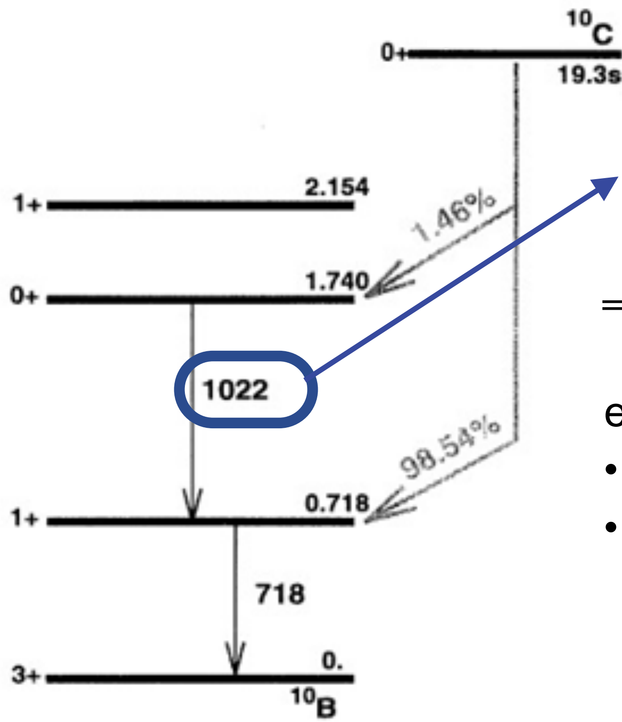


B. Blank et al., NIM A 776, 34 (2015)

status BR of ^{10}C at ISOLDE

- goal: <0.15% in BR
- focus on systematics
- 1st data taking completed at ISOLDE
- analysis ongoing

^{10}C decay scheme



- need to count 1022 keV gammas
- exactly at pile up of 511 keV from e^+ annihilation

⇒ requires excellent understanding/data of pile-up

e^+ form decay of

- ^{10}C
- $^{13}N_2$: strong contaminant in A=26 10C16O beam

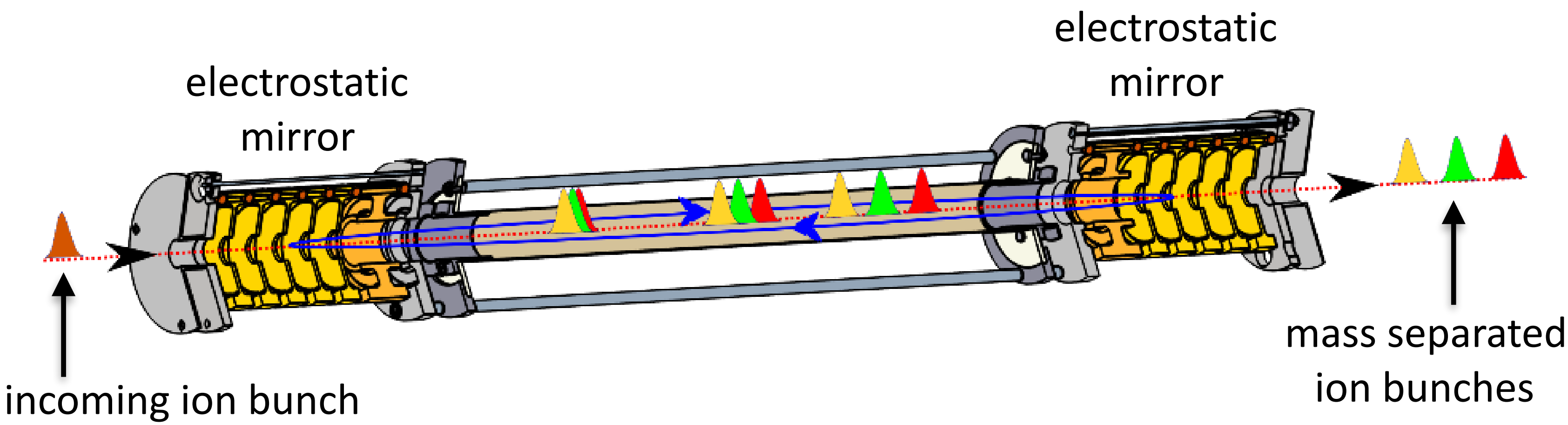
B. Blank et al.,

How to get rid of $^{13}N_2$?

- required mass resolving power $R=M/\Delta M \approx 90'000$
- beyond magnetic separators
- **<u>can we help with ion-trap techniques?</u>**

Mass separation of radionuclides

Mass separation of radionuclides



fast

highly selective

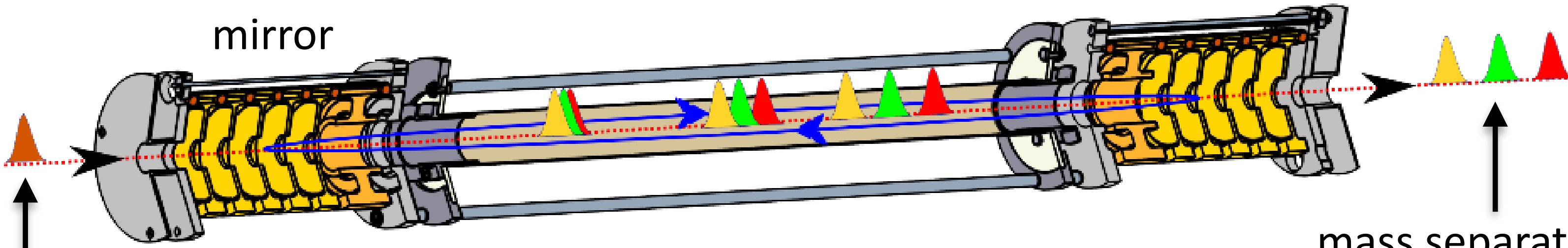
magnetic separators

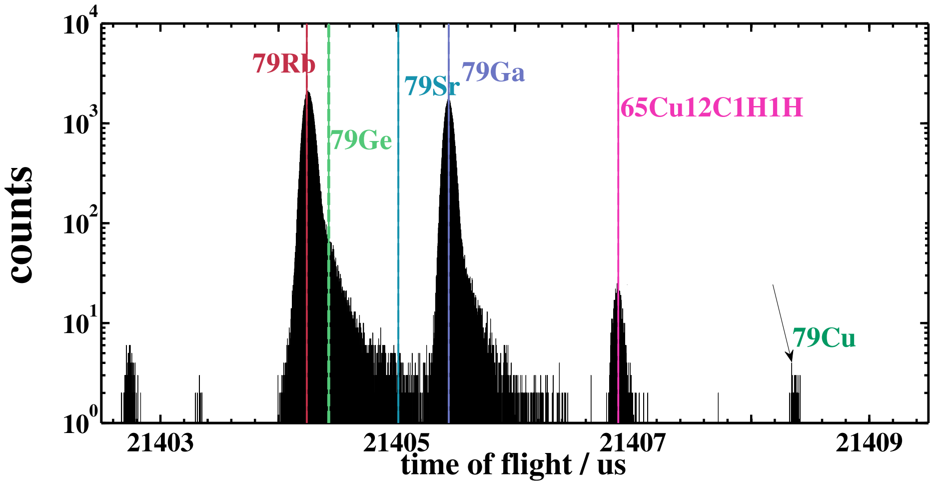
MR-ToF

Penning traps

F. Wienholtz et al., Nature 498, 346-349 (2013)
R. N. Wolf et al., Int. J. Mass Spectrom. 349-350, 123-133 (2013)
F. Wienholtz et al., Phys. Scr. T166 014068, (2015)

MR-ToF device at ISOLTRAP / ISOLDE





<u>**ion beam energy**</u>:

2.3 keV

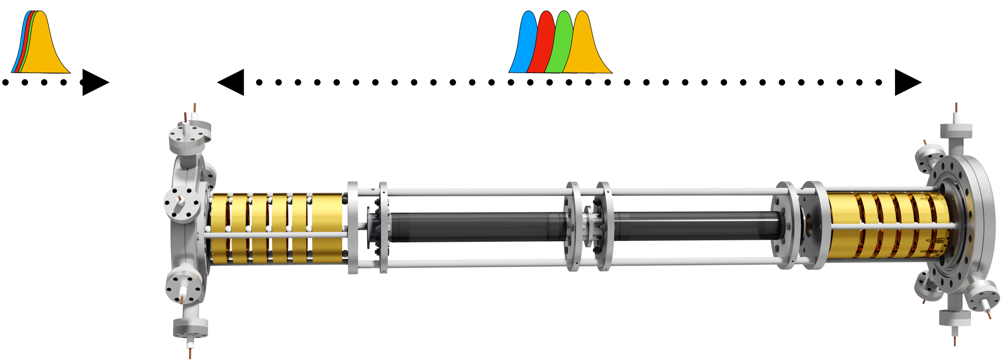
<u>**Mass resolving power**</u> (FWHM):

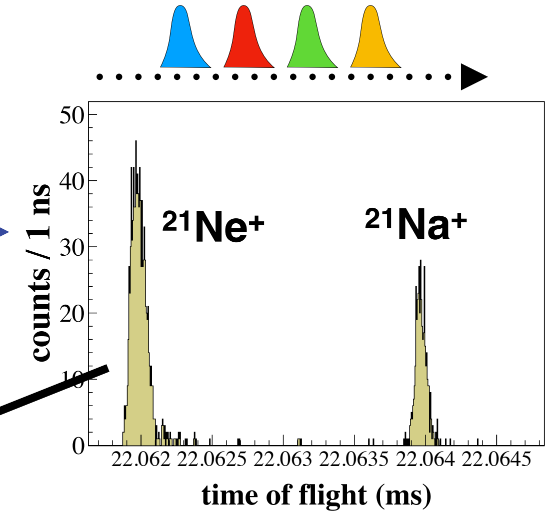
m/Δm=120 000 in 22ms ($^{85}Rb^{+}$)

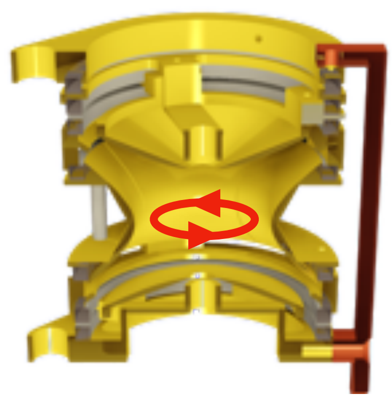
compared to a few 1000 at magnetic separator

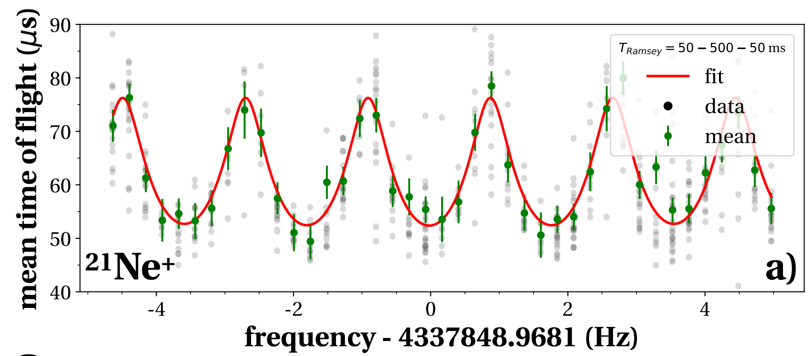
F. Wienholtz et al., Nature 498, 346-349 (2013)
R. N. Wolf et al., Int. J. Mass Spectrom. 349-350, 123-133 (2013)
F. Wienholtz et al., Phys. Scr. T166 014068, (2015)

MR-ToF & BSM measurements









Q-Value of ^{21}Na and ^{23}Mg with $\delta m/m \approx 1\cdot10^{-9}$

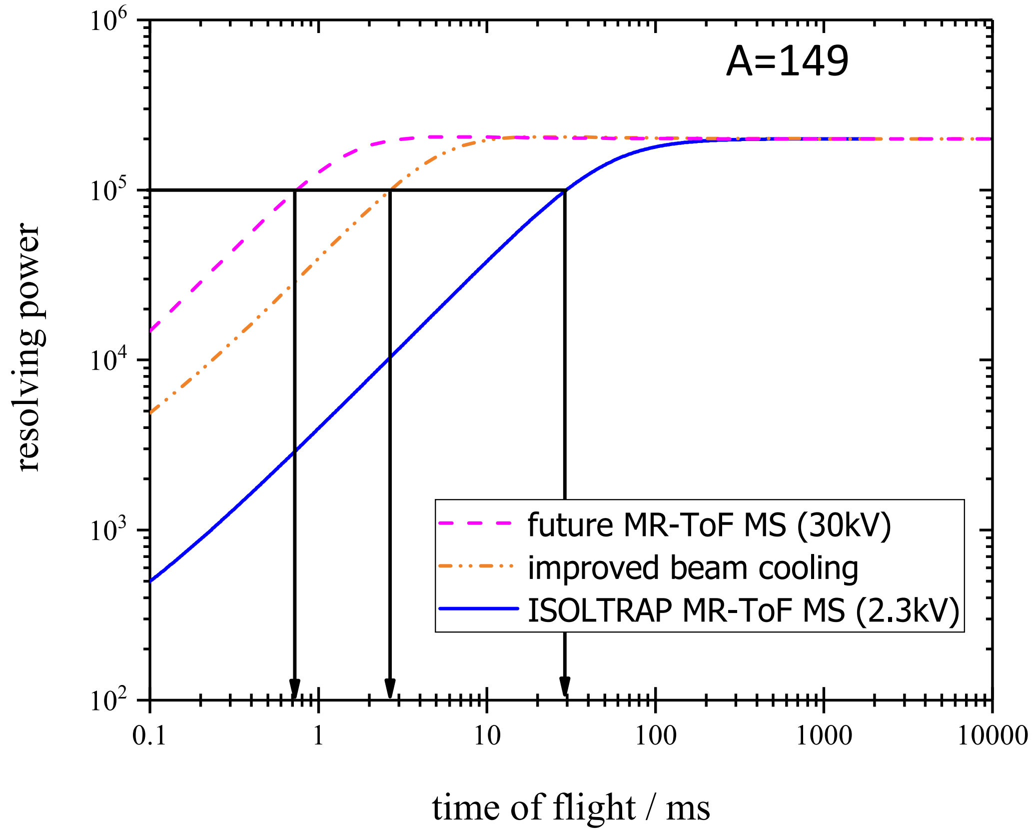
<u>MR-ToF challenges</u>:

- accessibility
- limit in ion# to be processed ⇒ space charge

J. Karthein et al., submitted to PRC

Slide courtesy of Jonas Karthein (CERN, MPIK)

30 keV MR-ToF:
new opportunities for purified ISOLDE beams



faster isobaric separation in MR-ToF while keeping high mass resolving power

➡ higher ion flux through MR-ToF device ('bypass' space-charge limits)

➡ initial goal: a few pA (ultimate goal: >100 pA)

➡ synergy with MIRACLS erc

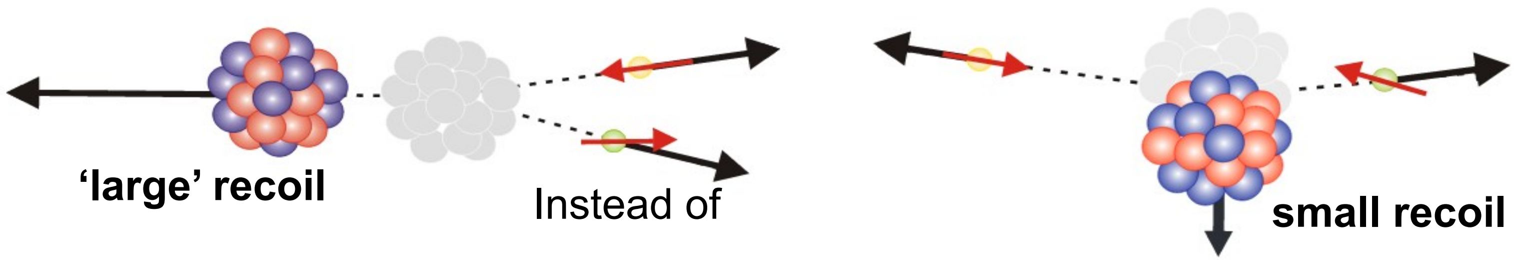
WISArD: Weak-interaction studies with ^{32}Ar decay

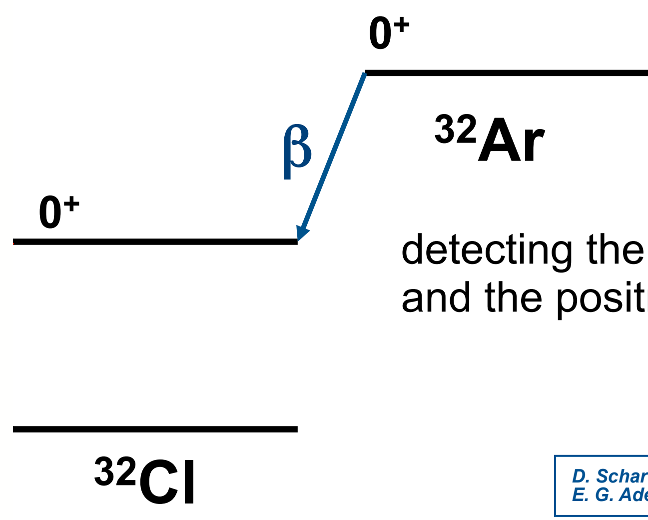
Standard Model
Vector currents

$$\frac{dW}{d\Omega} = 1 + \frac{p_e \cdot p_\nu}{E_e E_\nu}$$

New Physics
Scalar currents

$$\frac{dW}{d\Omega} = 1 - \frac{p_e \cdot p_\nu}{E_e E_\nu}$$





detecting the recoil
and the positron

D. Schardt and K. Riisager, ZPA 345, 265 (1993)
E. G. Adelberger et al., PRL 83 (1999) 1299

WISArD: Weak-interaction studies with ^{32}Ar decay

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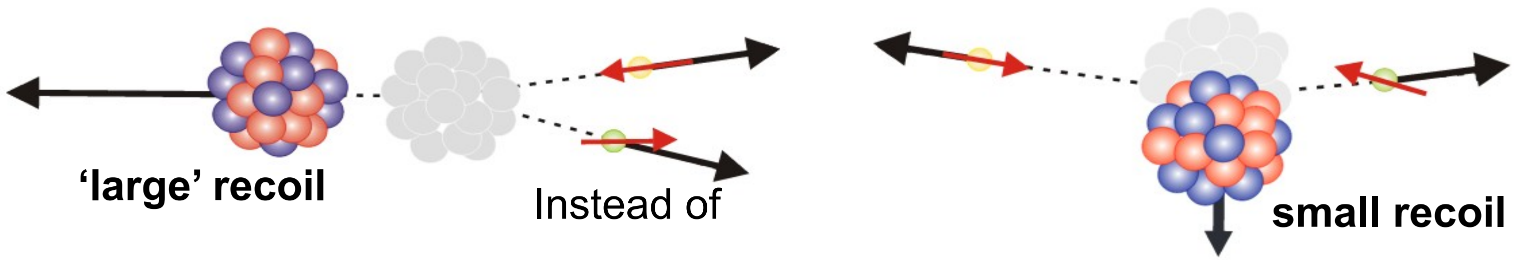
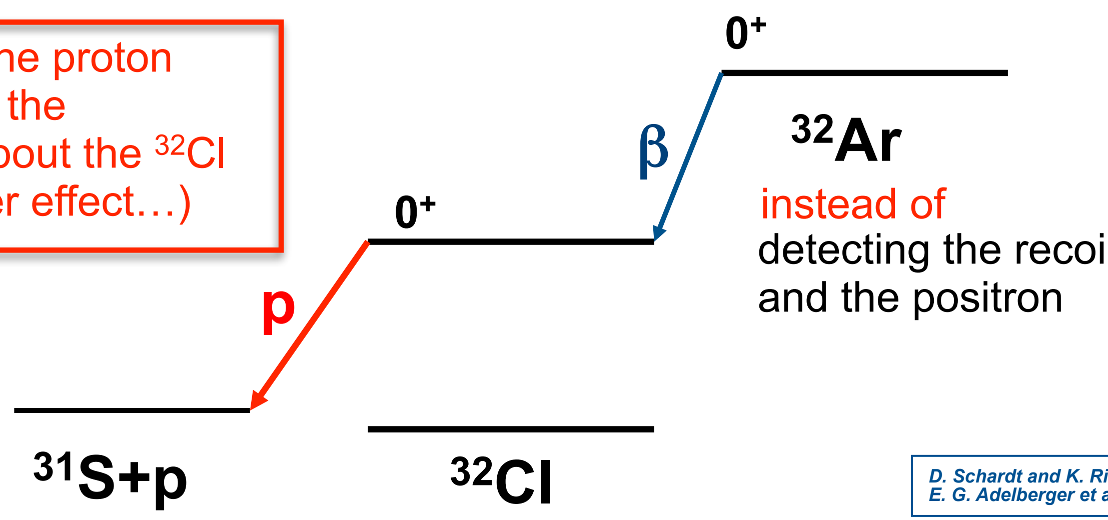


Detection of the proton that contains the information about the ^{32}Cl recoil (Doppler effect…)



D. Schardt and K. Riisager, ZPA 345, 265 (1993)
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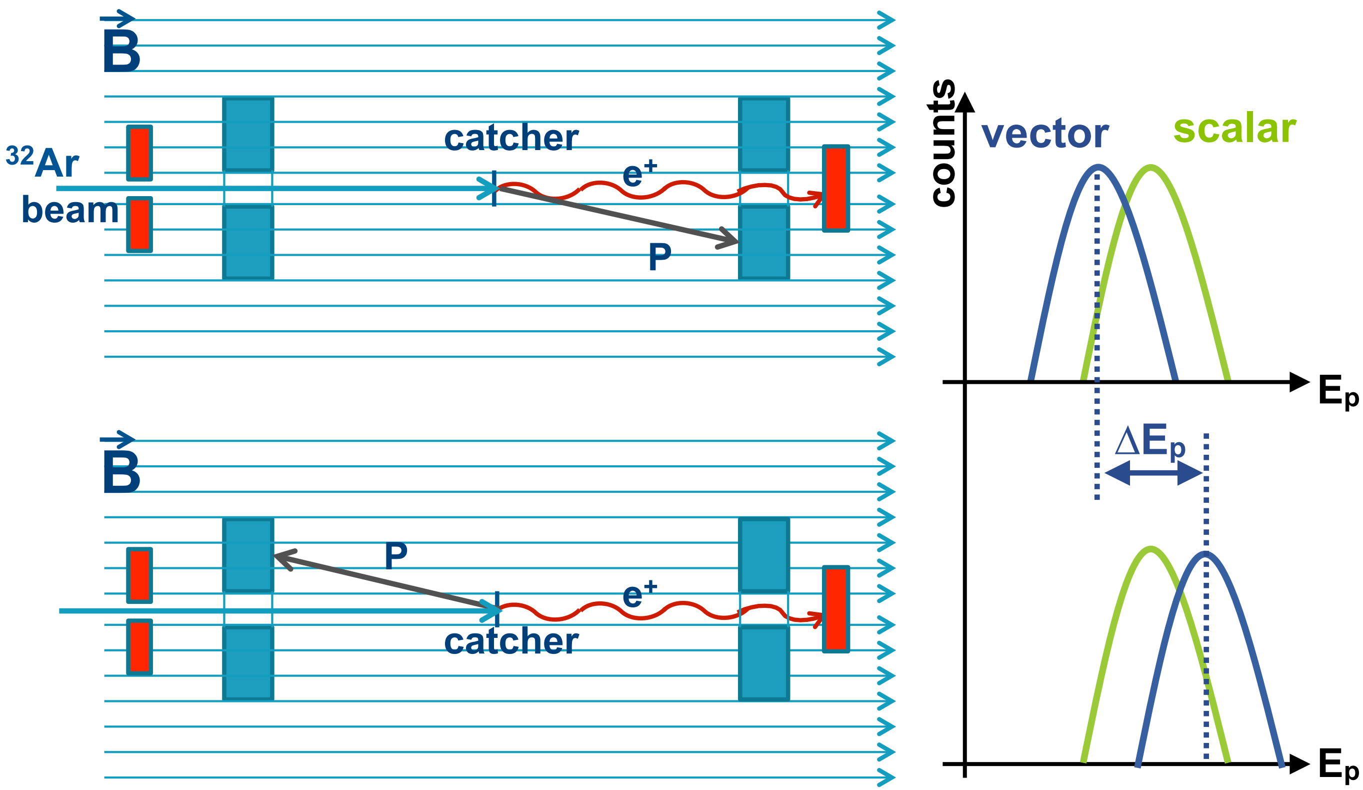
WISArD: Weak-interaction studies with ^{32}Ar decay



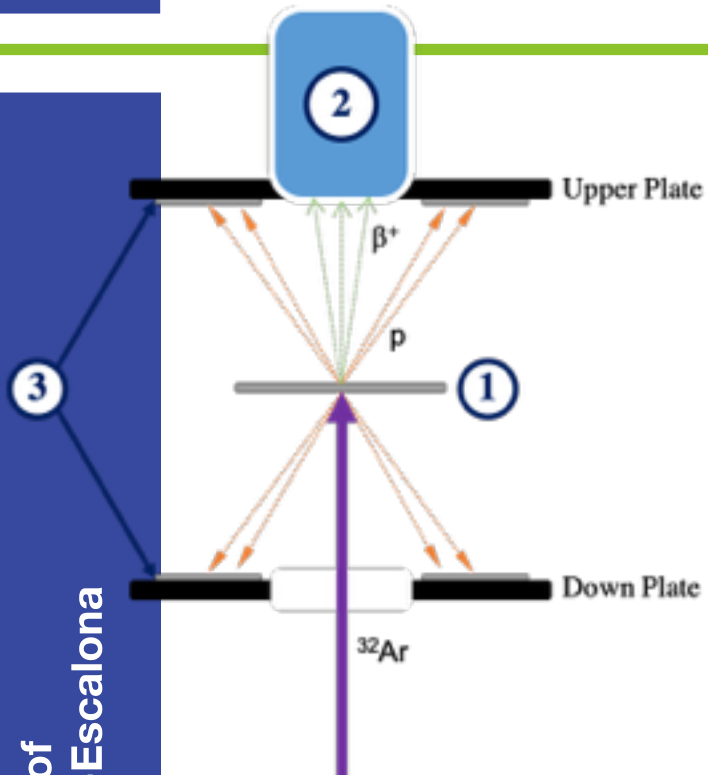
- major advance over previous experiments: ΔE_p measurement (instead of E_p)
- goal: limit on **$a_{\beta\nu}$ of the order of 0.1%** (factor ~6 improvement)
- timeline: proof-of-principle before LS2, data taking after LS2

collaboration. Bordeaux, Leuven, LPC Caen, NPI-Prague

N. Severijns and B. Blank, CERN-INTC-2016-050 / INTC-I-172 (2016)

Preliminary Results (Nov. 2018)

Slide courtesy of
B. Blank and V. Araujo-Escalona

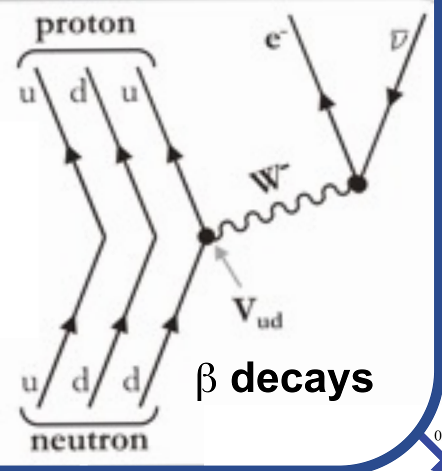


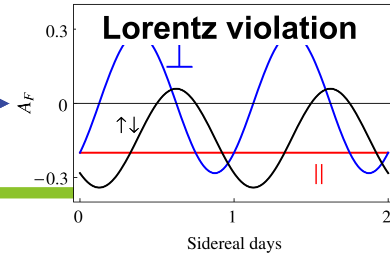
B. Blank, V. Araujo-Escalona, et al.

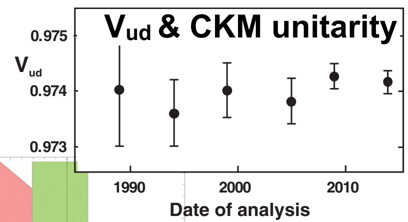
1. ▸ Mylar foil (6 μm)
2. ▸ Plastic scintillator (BC-408)
3. ▸ Silicon detectors (thick 300 μm/ 30mm diamete r)

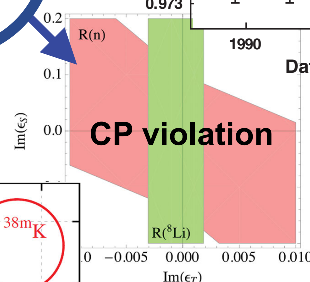
Preliminary

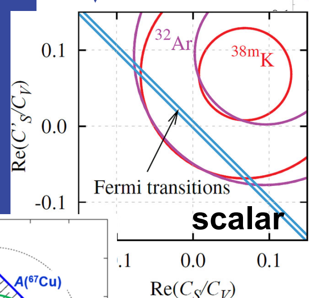
weak interaction studies in β decays

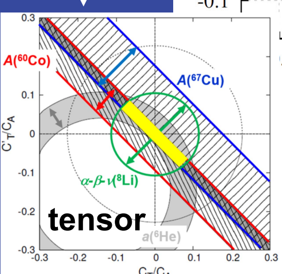












- … offer **high sensitivity** for BSM
- … provide **unique bounds on vertex corrections (V_{ud})**
- … are **complementary for contact interact** (eeqq) with similar sensitivity as LHC
- … **precision measurements of ground state properties** play a central role
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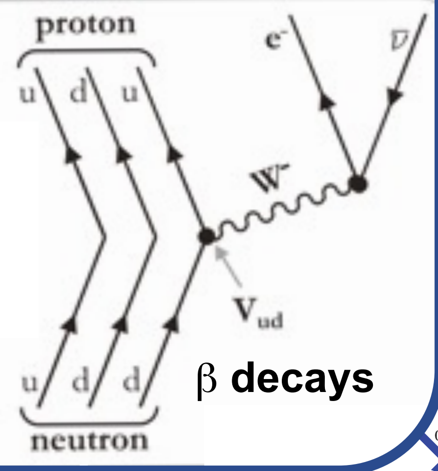
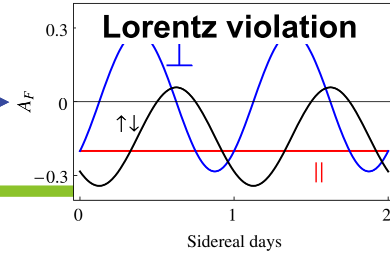
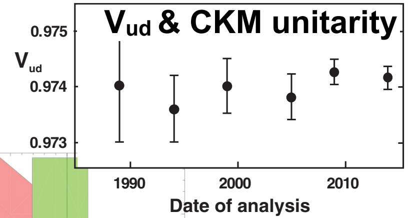
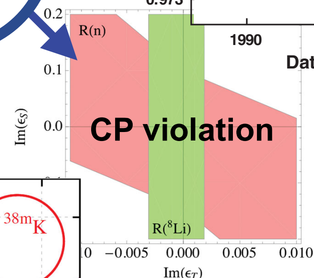
J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)
N. Severijns and O. Naviliat-Cuncic, Phys. Scr. T152, 014018 (2013)
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71, 93 (2013)
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 600 (2013)
K. K. Vos et al., Rev. Mod. Phys. 87, 1483 (2015)

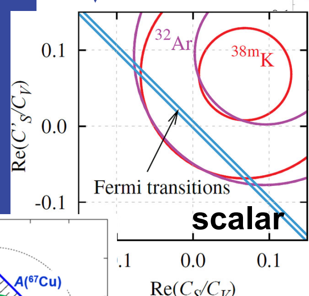
weak interaction studies in β decays

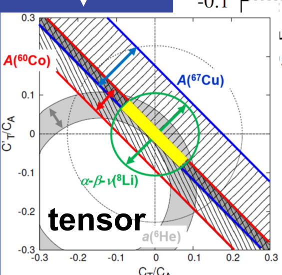












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future exp. work and δ_c: going heavier??

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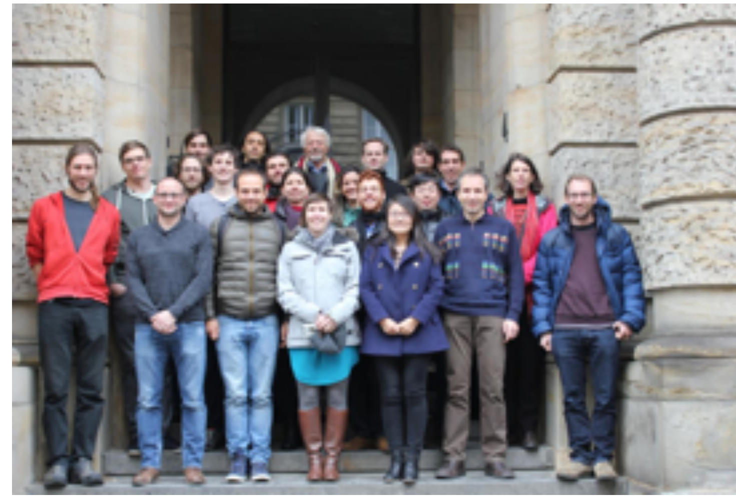
Thank you!

TITAN collaboration
Update on cyroMPET by A. Kwiatkowski and E. Leistenschneider

COLLAPS collaboration



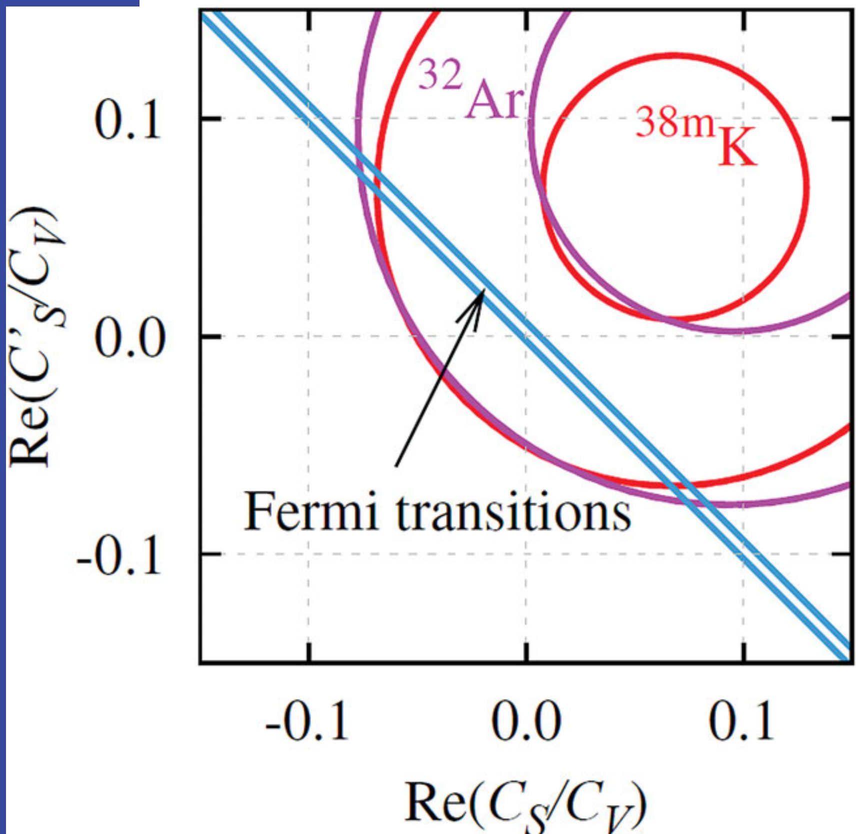
ISOLTRAP collaboration
Slides from J. Karthein

^{10}C
Slides from B. Blank

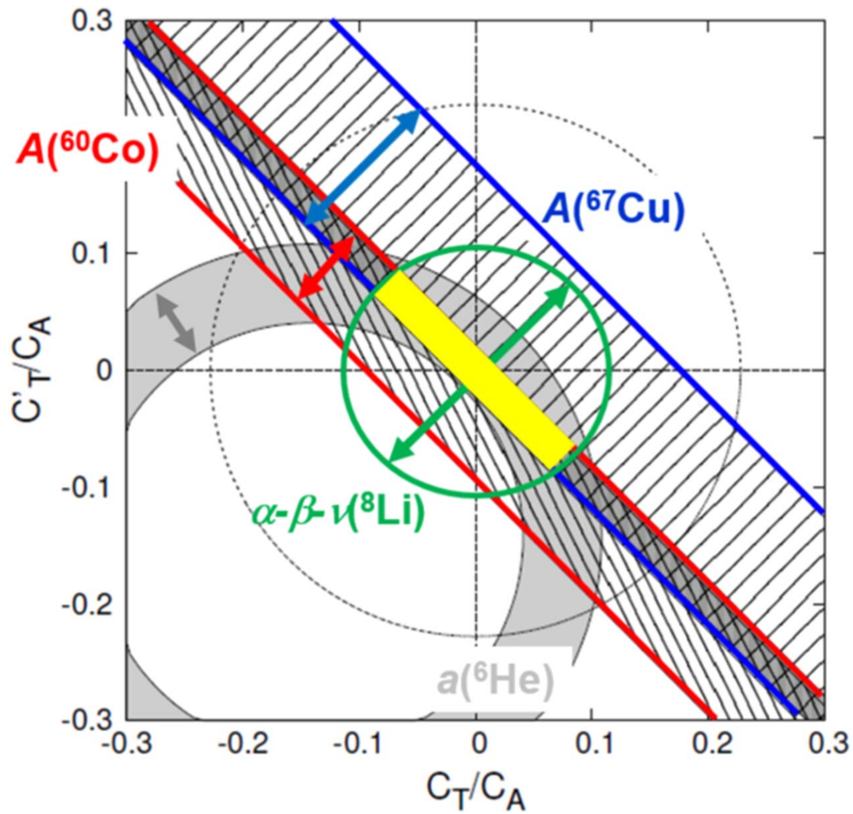
WISArD
Slides from
B. Blank and V. Araujo-Escalona

BACKUP

scalar



tensor



Charge radii

PHYSICAL REVIEW A 94, 062508 (2016)

Multiconfiguration calculations of electronic isotope shift factors in Al I

Livio Filippin,[1,*] Randolf Beerwerth,[2,3,†] Jörgen Ekman,[4,‡] Stephan Fritzsche,[2,3,§]
Michel Godefroid,[1,||] and Per Jönsson[4,¶]

The present work reports results from **systematic multiconfiguration Dirac–Hartree–Fock calculations** of electronic isotope shift factors for a set of transitions between low-lying levels of neutral aluminium. **Two computational approaches** are adopted for the estimation of the mass- and field-shift factors. Within these approaches, **different models for electron correlation** are explored in a systematic way to determine a reliable computational strategy and to estimate theoretical error bars of the isotope shift factors.

F = [74.0 – 77.5] MHz/fm2
M = [-239 – -224] GHz u