Precision studies and searches for New Physics at ISOLDE

+ quantum technologies

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CERN

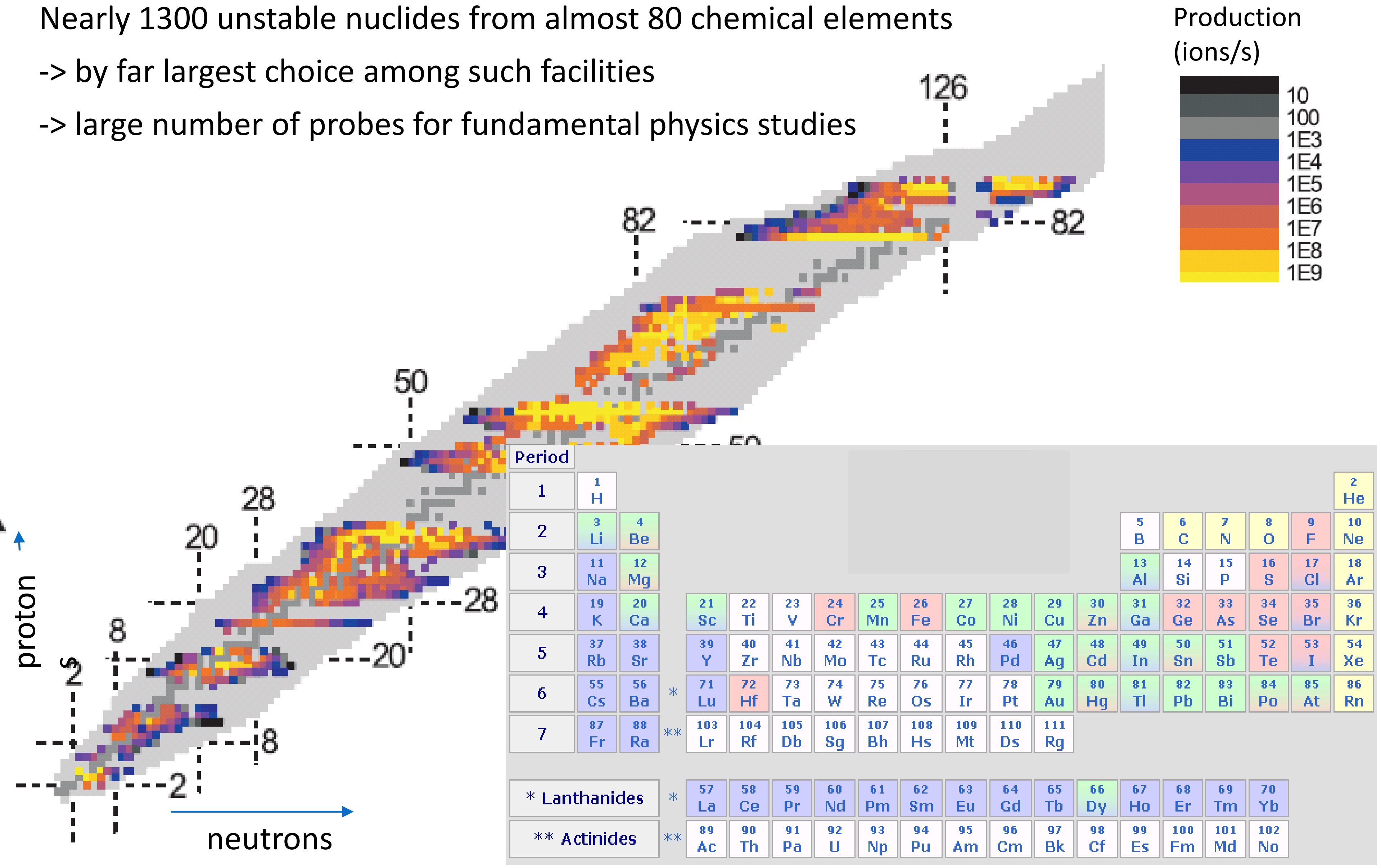
With input from D. Atanasov, B. Blank, R. Garcia Ruiz, S. Malbrunot-Ettenauer, M. Mougeout, S. Sels, P. Van Duppen

ISOLDE radio-nuclei

Nearly 1300 unstable nuclides from almost 80 chemical elements

-> by far largest choice among such facilities

-> large number of probes for fundamental physics studies



Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
** Actinides			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Precision- and New-Physics at ISOLDE

Laser spectroscopy (atoms, molecules)

Optical pumping

Decay spectroscopy

Emission channeling

Branching ratios

Beta spectrum shape

Half-lives

Electric dipole moment

Magnetic dipole moment

Isotope shifts

Weak interaction studies:
V_{ud}, scalar+ tensor terms,
β spectrum

Nuclear clock

Beta-decay mixing ratio

Particle correlations

BSM bosons

Atomic and nuclear excitation energies

Binding energies

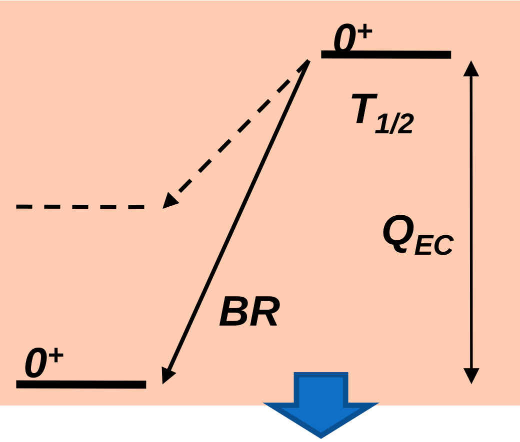
Hyperfine splitting

Mass spectrometry

Penning traps

Multireflection time-of-flight devices

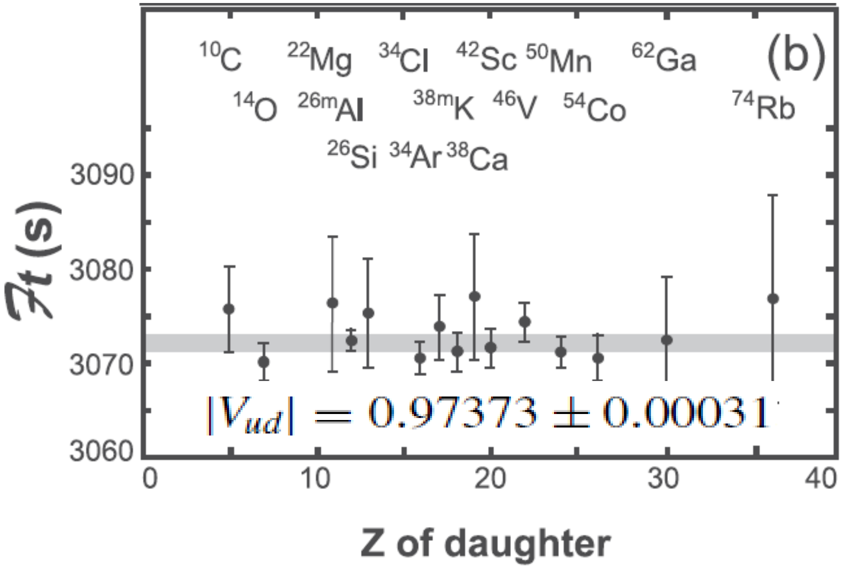
V_{ud} from super-allowed transitions



Transition strength *Ft* ->

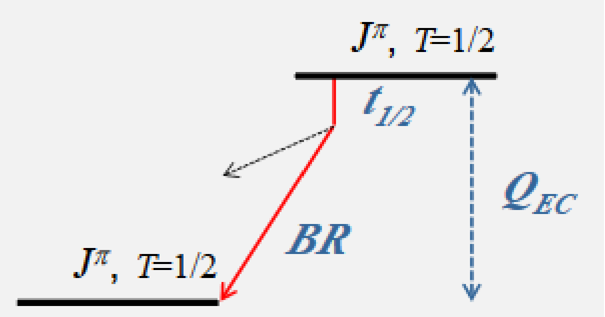
vector coupling constant for semi-leptonic decays G_v -> $\mathbf{V_{ud}}$:

Many of experimental values come from ISOLDE

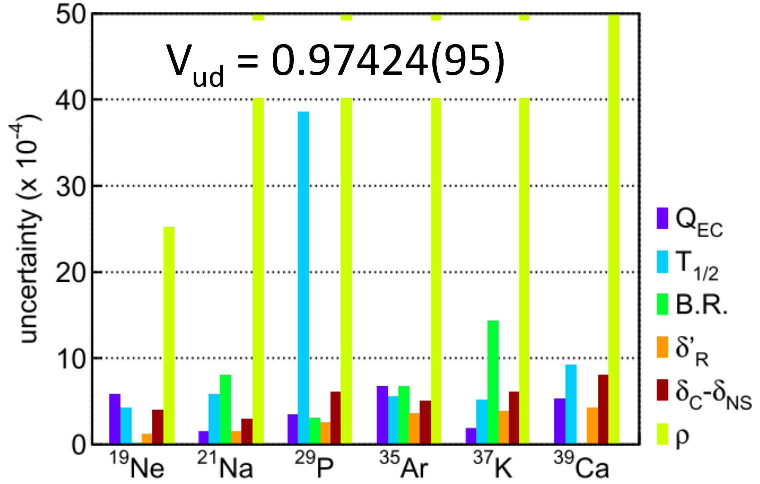


J. C. Hardy and I. S. Towner, Phys. Rev. C 102, 045501 (2020)

Mirror transitions:



+ Gamow-Teller to Fermi mixing ratio ρ

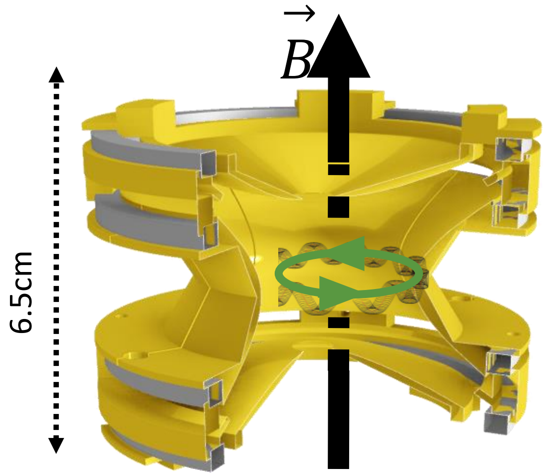


A. Falkowski, M. González-Alonso, O. Naviliat-Cuncic, arXiv:2010.13797 (2020)

=> Search for deviations from Standard Model expectations

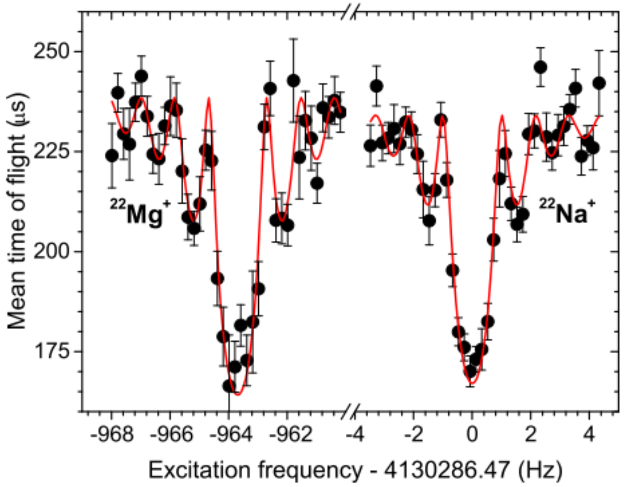
M. González-Alonso, O. Naviliat-Cuncic, N. Severijns, Progr. Part. Nucl. Phys. 104 (2019) 165, N Severijns, B Blank, J Phys G 44, 074002 (2017)

Q_{EC} for superallowed decays

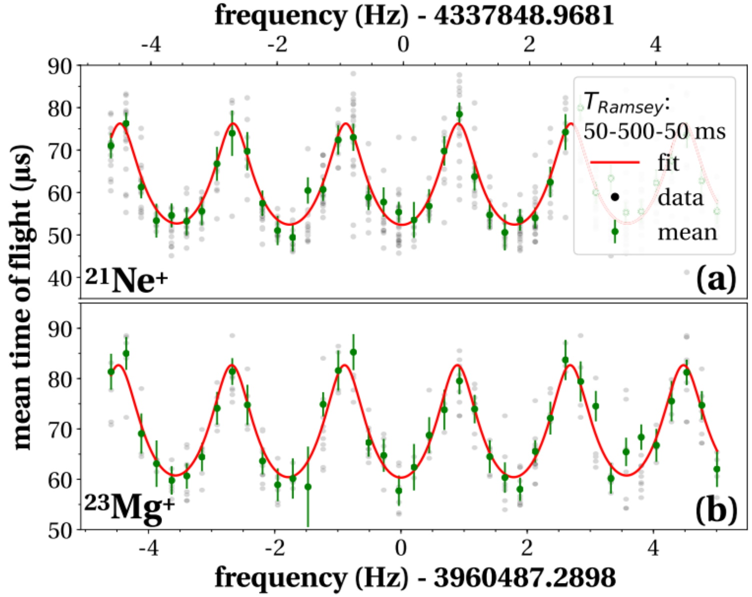


Penning-trap
mass
Spectrometry
With ISOLTRAP

$$\nu_c = \frac{qB}{2\pi m_{ion}} \quad \text{with} \quad \frac{\delta\nu_c}{\nu_c} = \frac{\delta m}{m} \sim 10^{-9}$$

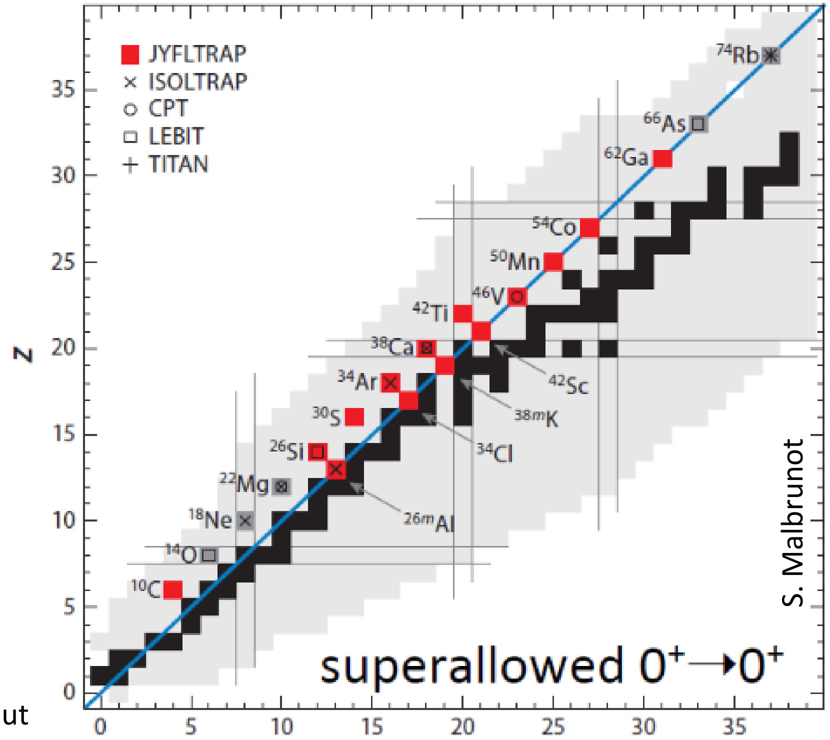


Mukherjee M et al Phys. Rev. Lett. 93 150801 (2004)



J. Karthein et. al., Phys. Rev. C 100, 015502 (2019)

M. Mougeout

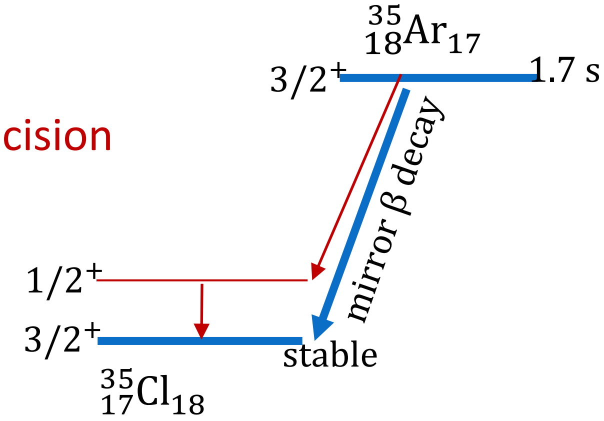


S. Malbrunot

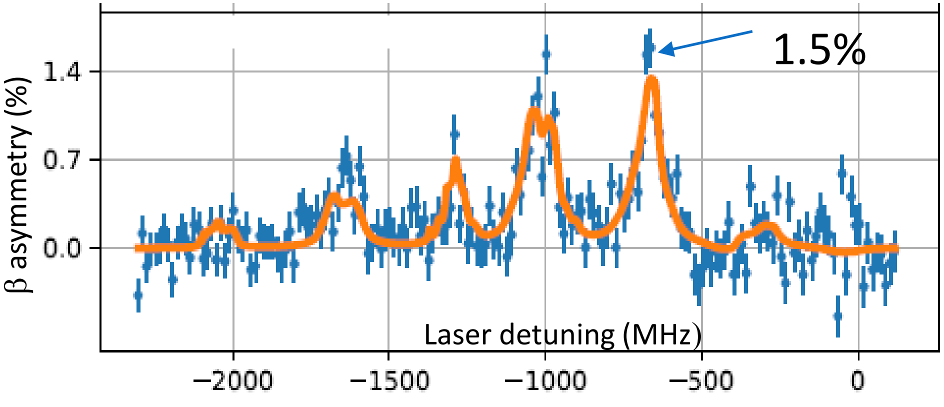
Mixing ratio ρ for ^{35}Ar and ^{23}Mg

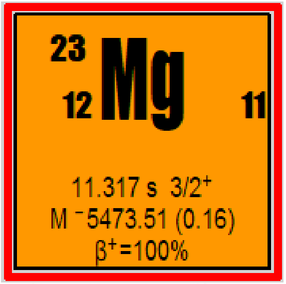
Laser polarisation beamline VITO

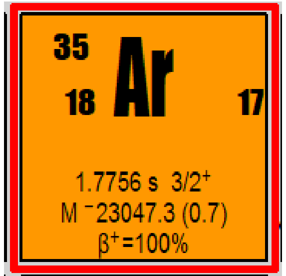
Goal: measure β-decay asymmetry parameter a_β with 0.5% precision
=> determine mixing ratio ρ
=> V_{ud} precision around 5×10^{-4} level

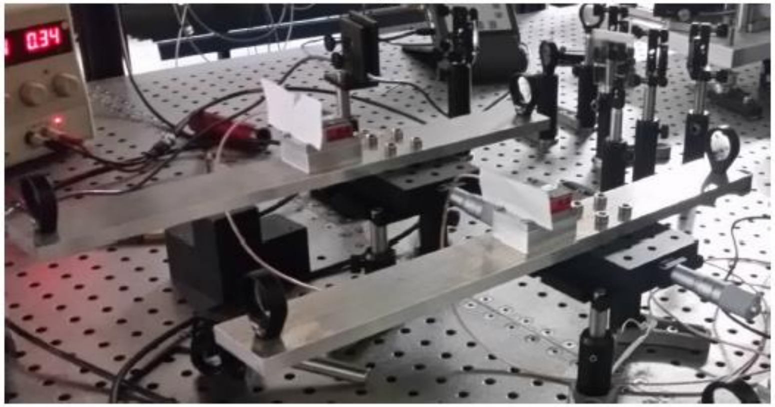


Our 1st results: laser polarisation of ^{35}Ar:







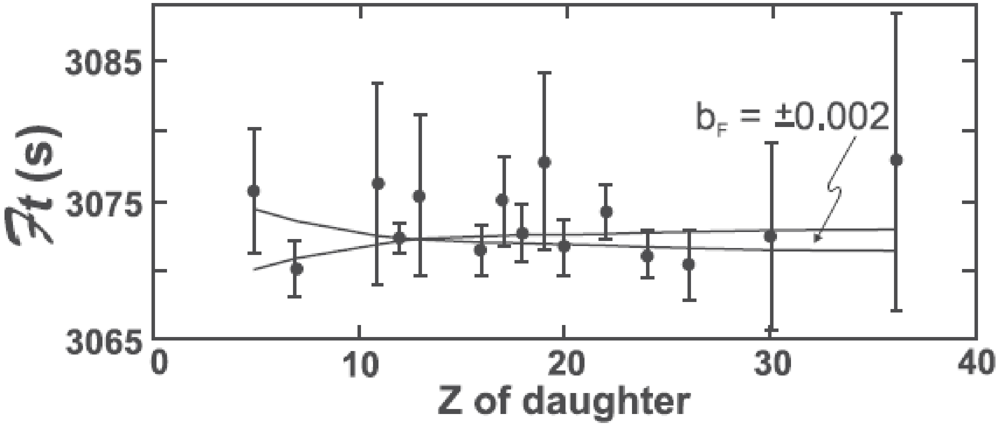


Plans:
-improve polarisation of ^{35}Ar,
-investigate ^{23}Mg feasibility,
-prepare final setup

W. Gins et al, Nucl. Instr. and Meth. A 925, 24 (2019)
W. Gins, PhD thesis KU Leuven cds.cern.ch/record/2654181?ln=en

Search for scalar currents

- Standard Model: only vector current for Fermi transitions
  - ➢ limit on scalar current from term in Fermi function $1 + b\frac{m_e}{E_e}$
- from 0+ → 0+ β decay: $b_f = - 0.0028 \pm 0.0026$

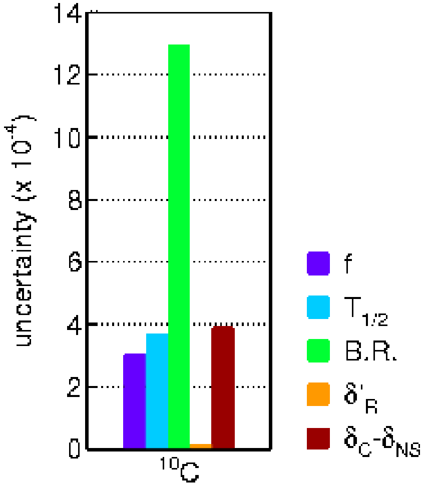


- highest sensitivity for low Q-value

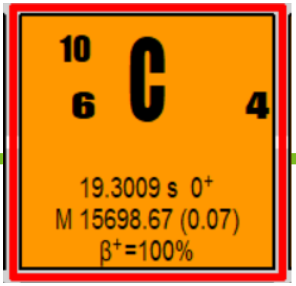
  (= light nuclei) transitions

  ➔ improve on low-Z nuclei

  ➔ improve BR for ^{10}C



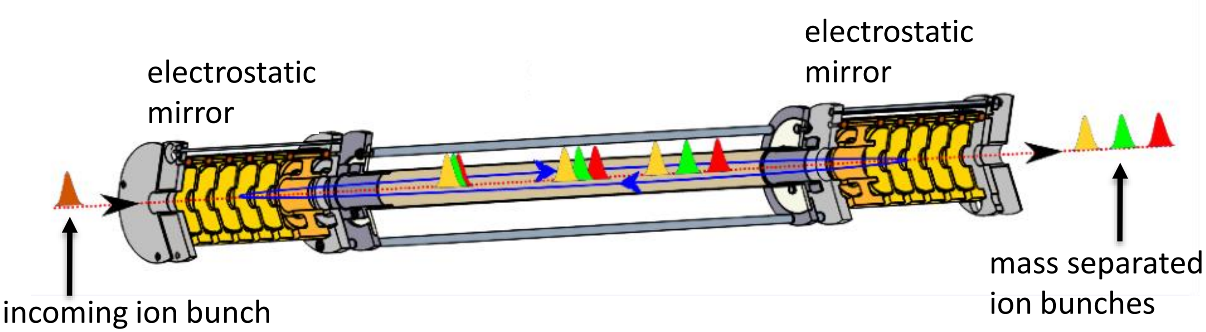
^{10}C and scalar currents



- Decay spectroscopy

- Branching ratio
  Final result: **1.4638(50) %**
  Literature: **1.4646(19) %**

- How to improve?
  - Higher beam intensity
  - Eliminate $^{13}N_2$ contamination:



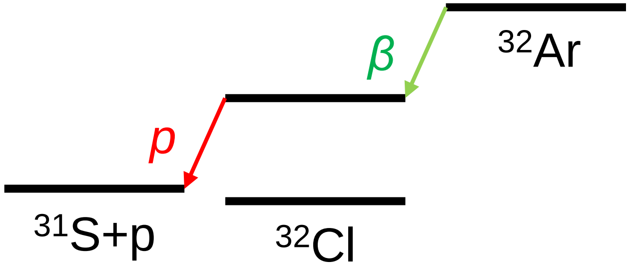
- development of MR-ToF mass separator at MIRACLS

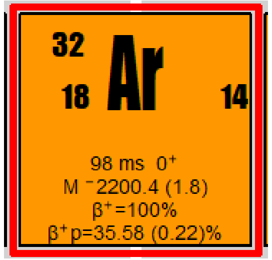
- prototype for general purpose ISOLDE MR-ToF

B. Blank, S. Malbrunot

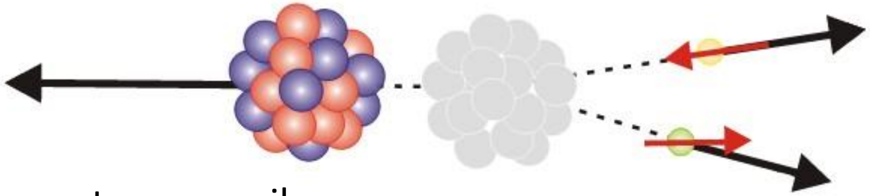
Scalar currents with ^{32}Ar at WISARD

- Aim: search for scalar current contribution in predominantly vector current of β decay via β–ν correlation



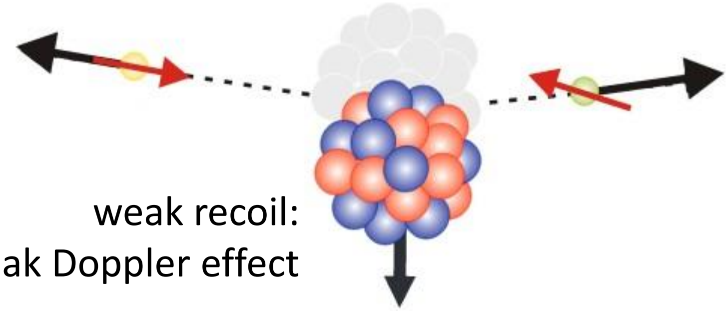


Vector current



strong recoil:
strong Doppler effect

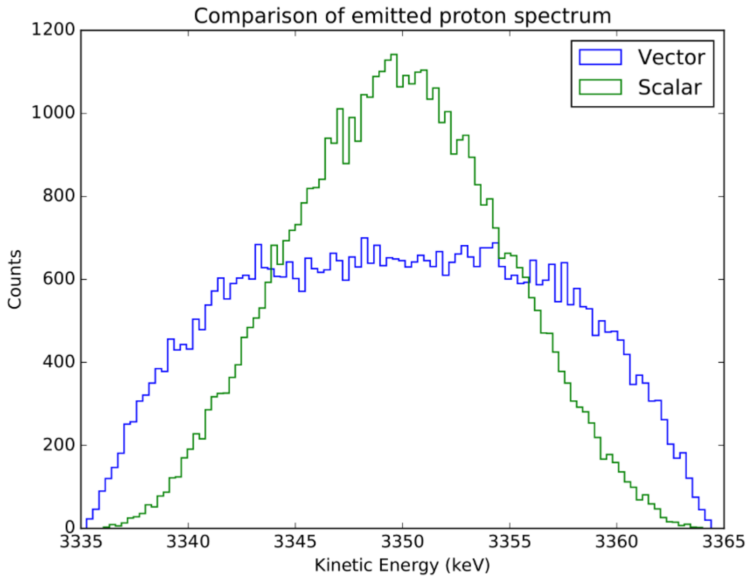
Scalar current



weak recoil:
weak Doppler effect

- Tool: β-delayed p decay of ^{32}Ar, Doppler effect on proton energy

- Present limits on scalar current from βν correlation $a_F = 0.65\%$



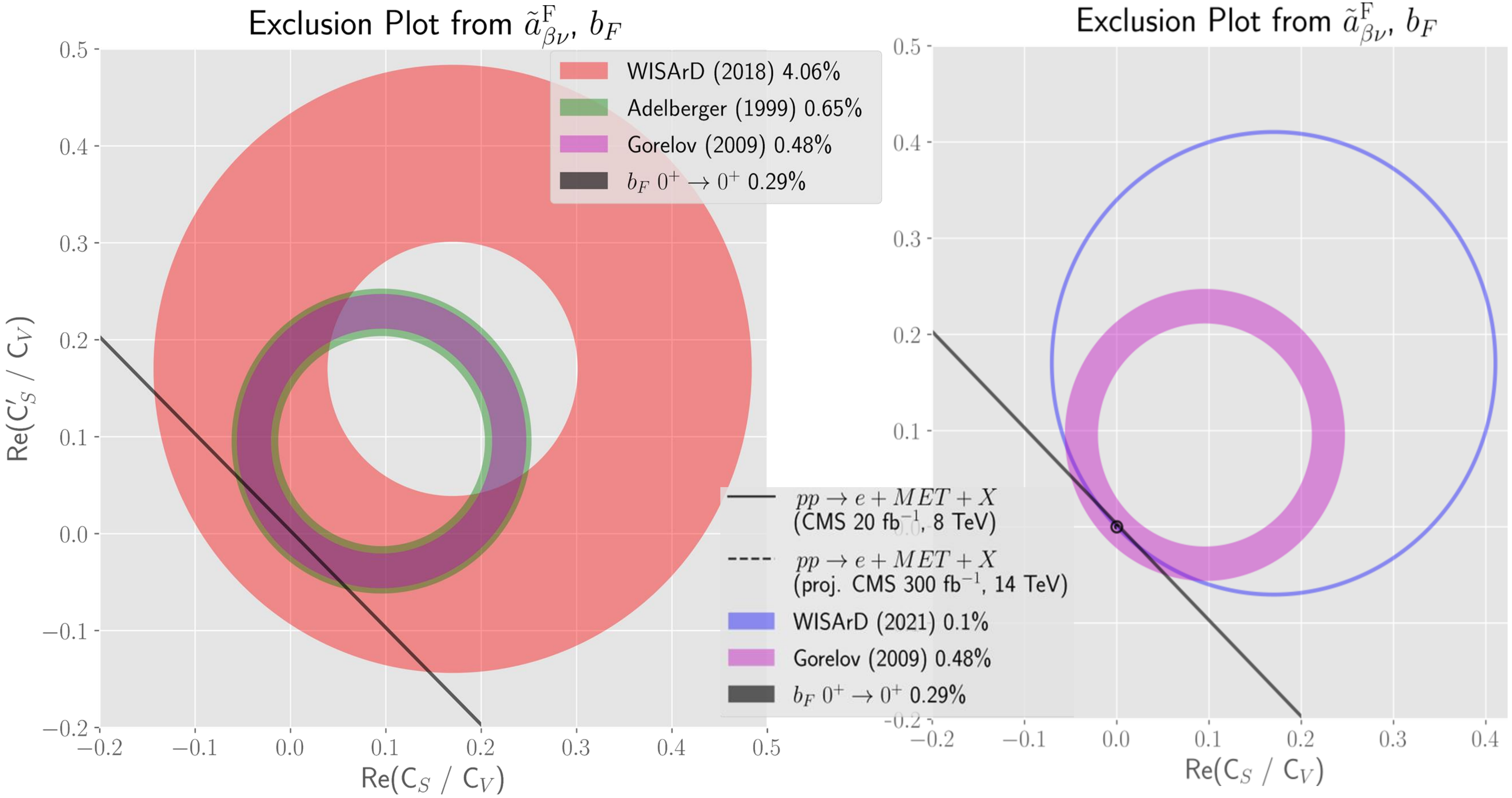
L. Hayen CRADLE++ (https://github.com/leenderthayen/CRADLE)

32Ar and scalar currents

- Proof-of-principle run in 2018
- Final experiments after LS2

$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$

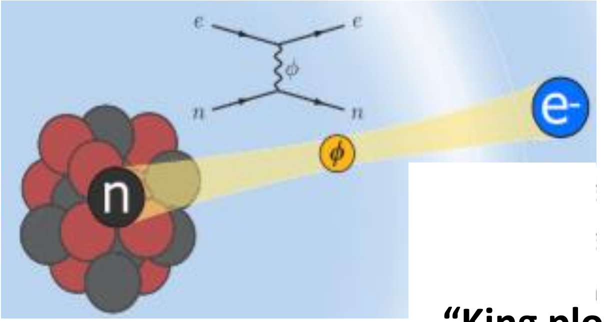
3rd most precise measurement of a_F



V. Araujo-Escalona et al., Phys. Rev. C101, 055501 (2020)

D. Atanasov

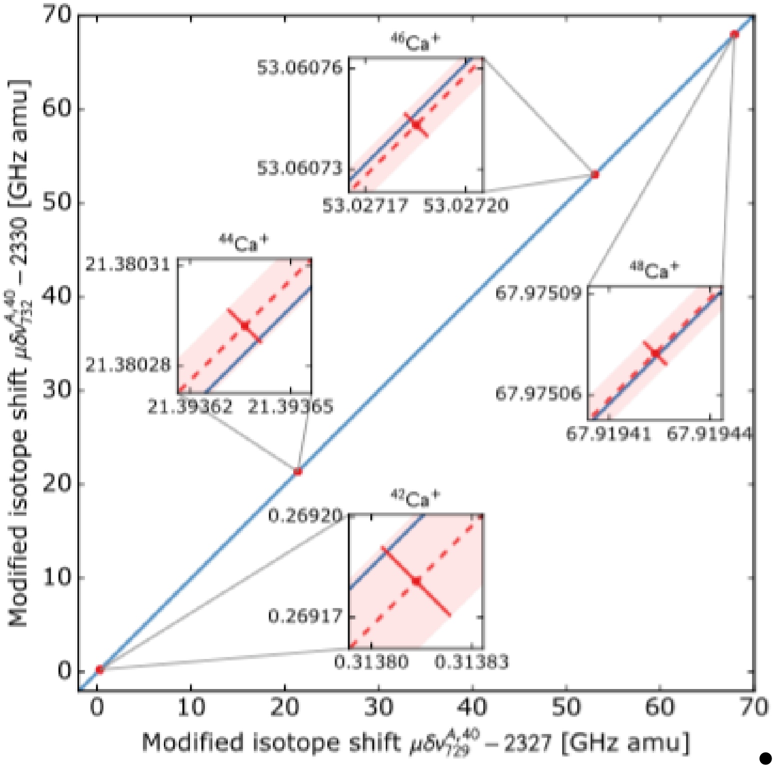
New physics searches with isotope shifts

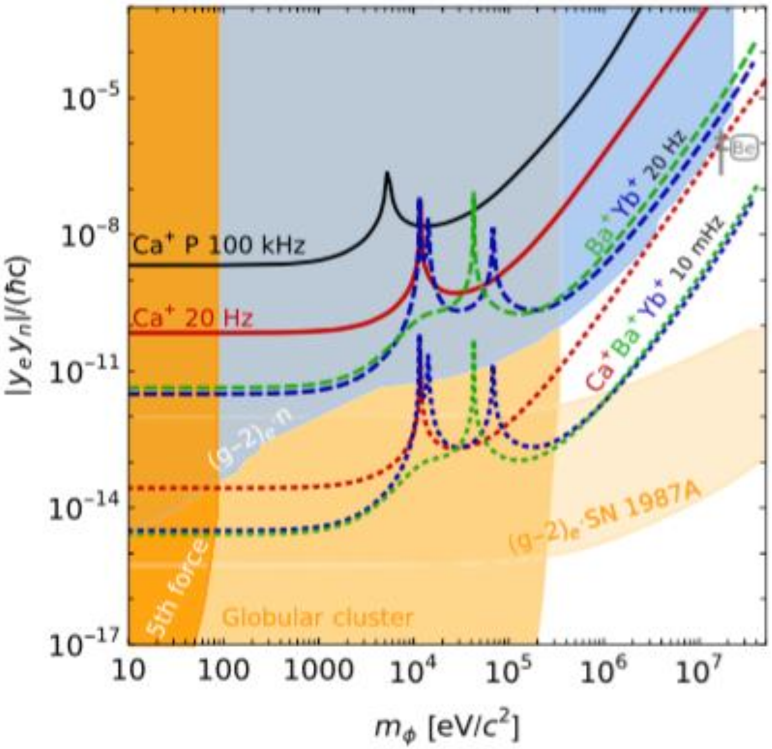


Difference in atomic transition frequency between isotopes,
due to different mass and charge distribution => linear “King plot”
New Physics interaction => deviation from linearity

Constraints coupling between electrons and neutrons by bosons beyond the standard model

“King plot" for stable Ca



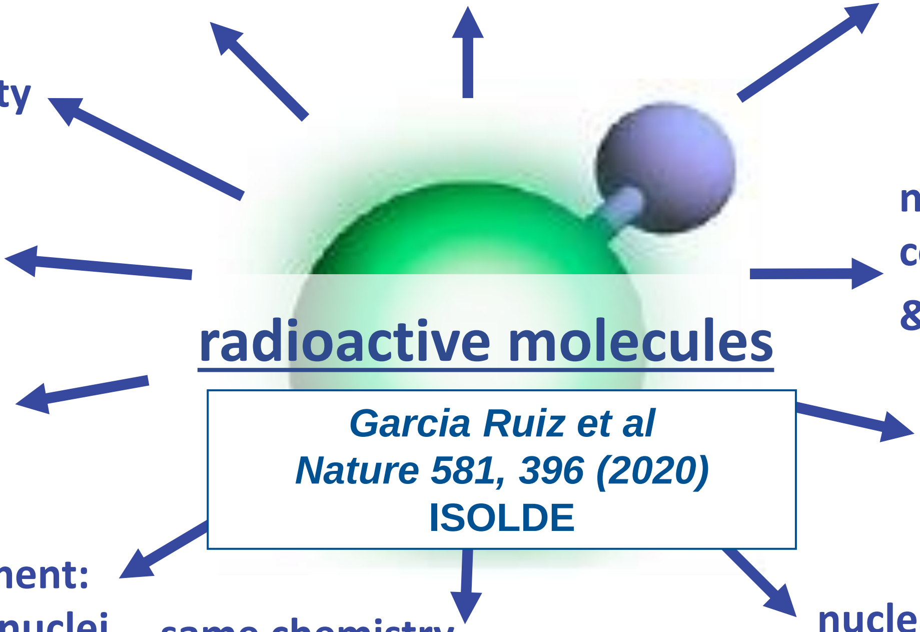


J. C. Berengut et al., PRR 2, 043444 (2020)
I. Counts et al. Phys. Rev. Lett. 125, 123002 (2020)
C. Solaro et al., Phys. Rev. Lett. 125, 123003 (2020)

- **studies could be extended to radionuclides (especially isomers)**
- **requires new precision level for atomic and molecular techniques at ISOLDE**

S. Ettenauer, R. Garcia Ruiz

Radioactive molecules & EDMs



radioactive molecules

Garcia Ruiz et al
Nature 581, 396 (2020)
ISOLDE

laser cooling

long coherence time

complementary physics
- parity violation
- quantum chemistry
- nuclear structure

co-magnetometry
/ B-field insensitivity

close-lying opposite
parity states

nuclear-spin-independent
component
& electron EDM

large E_{eff}
$\propto Z^2 R(Z)$

CP violating nuclear
Magnetic Quadrupole
Moment

ISOLDE

Schiff moment:
deformed nuclei

same chemistry
different physics sensitivity
systematic spin dependence

nuclear-spin-dependent
component
& hadronic EDM

R. Garcia Ruiz
S. Ettenauer

Exotic molecules → Best of all worlds
... BUT, are experimentally unknown!

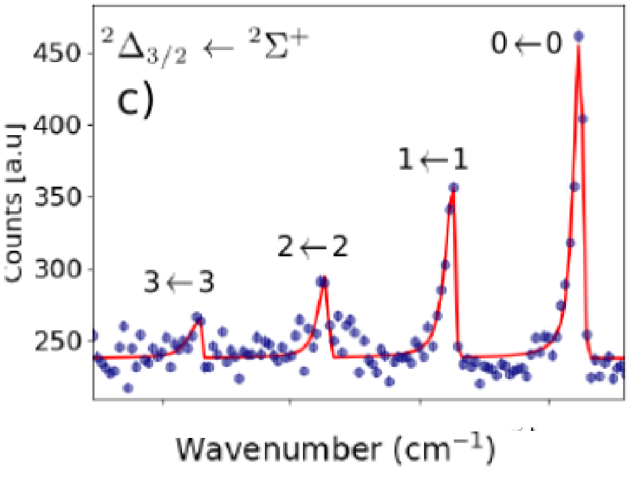
Radium fluoride and EDMs

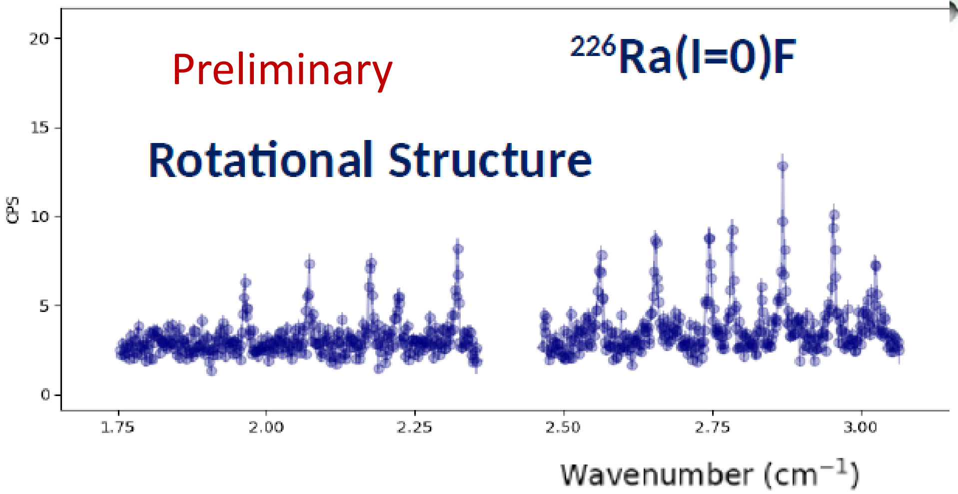
Collinear resonance ionization spectroscopy of RaF molecules

I. Low-lying structure ✓

II. Feasibility of laser cooling?

  1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$ ✓
  2. Short-lived excited state ($T_{1/2}$)? → $T_{1/2} < 50$ ns ✓
  3. Electronic states of lower energy (E)? → 2000 cm^{-1} above ✓





$$\overset{}{H_{mol}} = \overset{\checkmark}{H_e} + \overset{\checkmark}{H_{vib}} + \overset{\checkmark}{H_{rot}} + ... + \overset{\checkmark}{H_{hfs}} + H_{PV} + H_{PTV}$$

R. Garcia Ruiz

Garcia Ruiz et al. Nature 581, 396 (2020)

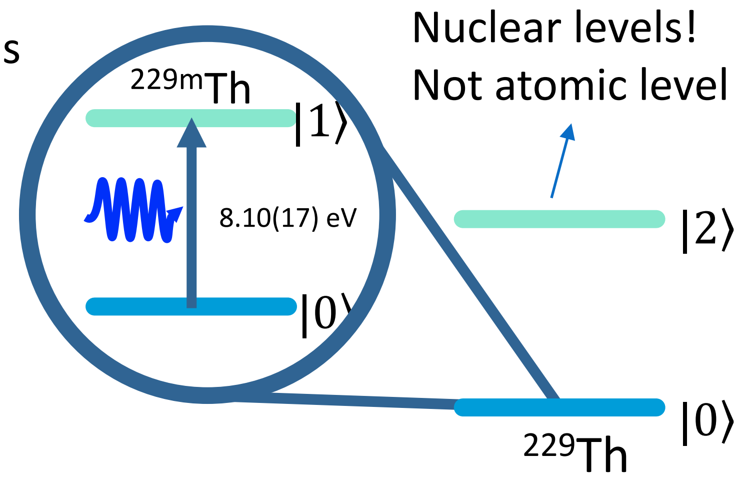
Udrescu et al.,

Plans at ISOLDE:

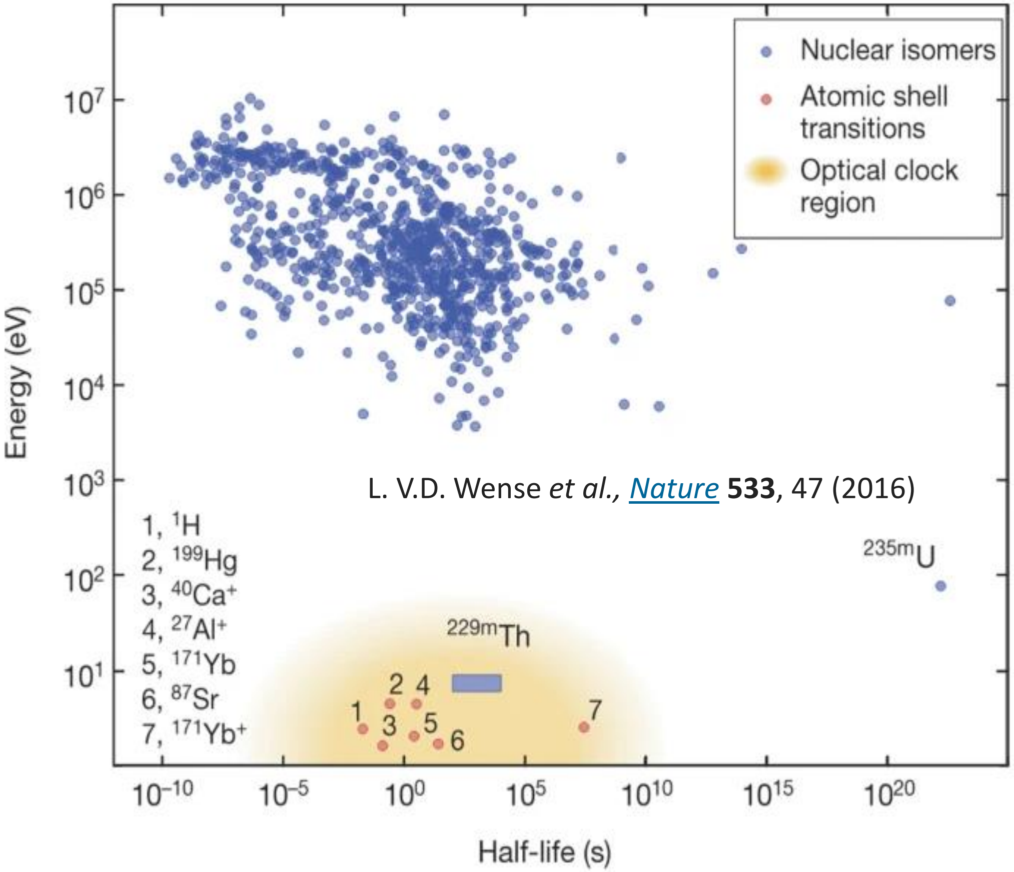
- Precision measurements of RaF + developments for future symmetry-violating properties
- Study of other radioactive molecules of fundamental physics interest, e.g. RaOH

Quantum technologies: nuclear clock

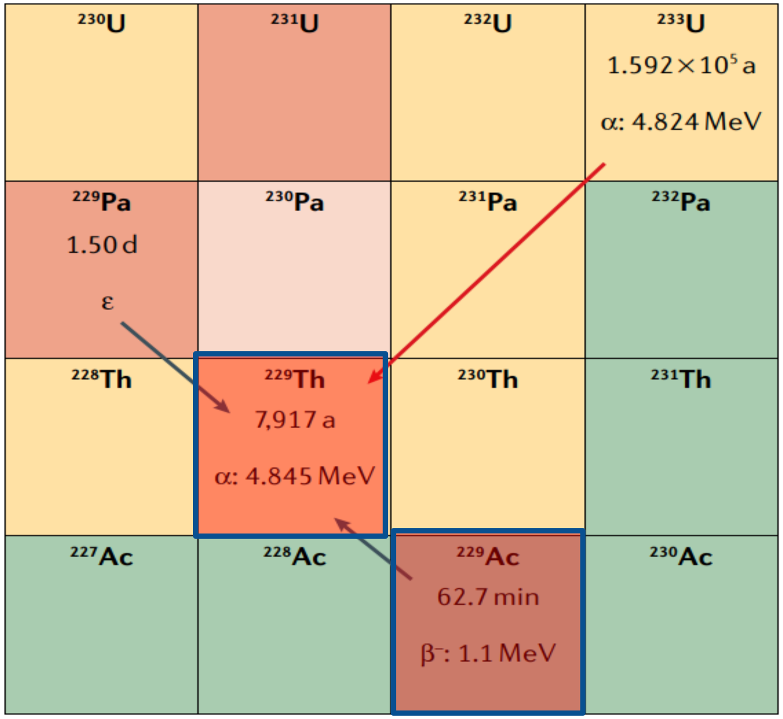
Energy of nuclear excited states >>> Atomic excited states
Exception: ^{229m}Th
Ground-states – First excited level = 8.10(17) eV
~153 nm (VUV laser accessible)



Nuclear levels!
Not atomic level



L. V.D. Wense *et al.*, Nature **533**, 47 (2016)



^{230}U	**^{231}U**	**^{232}U**	**^{233}U** 1.592×10^5 a α: 4.824 MeV
^{229}Pa 1.50 d ε	**^{230}Pa**	**^{231}Pa**	**^{232}Pa**
^{228}Th	**^{229}Th** 7,917 a α: 4.845 MeV	**^{230}Th**	**^{231}Th**
^{227}Ac	**^{228}Ac**	**^{229}Ac** 62.7 min β$^-$: 1.1 MeV	**^{230}Ac**

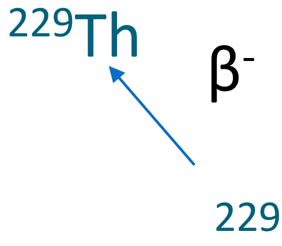
P. Van Duppen, S. Sels

Nuclear clock based on 229mTh

Nucleus is more separated from environment:

- Expected to outperform present-day best clocks
- World-wide effort to created nuclear clock

BUT : Nuclear properties not know with high enough precision!

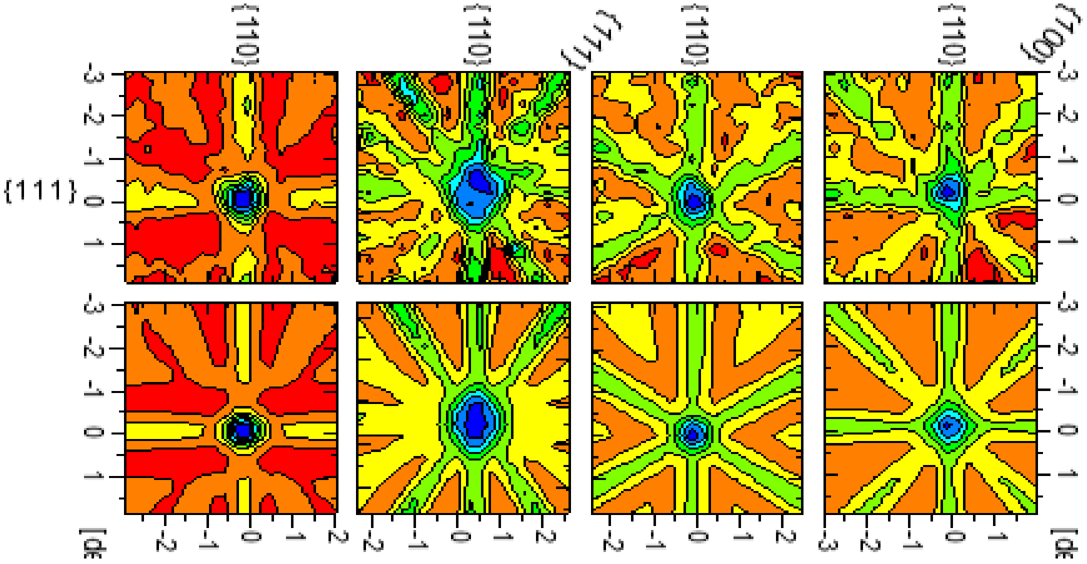


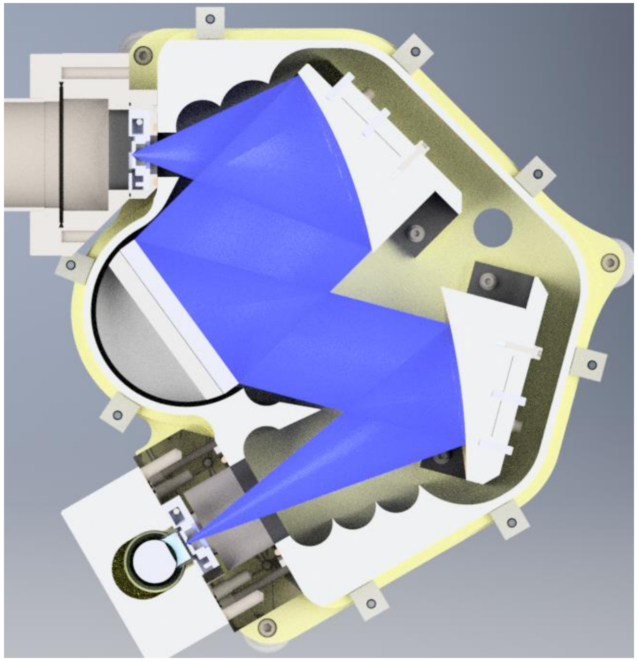
Goal:

- Create ^{229}Ac at ISOLDE, implant it in wide-bandgap CaF crystal at correct site (emission channeling measurement)
- Measure direct photon emission from ^{229m}Th →^{229}Th with high-resolution VUV photon spectrometer with $\Delta\mathrm{E} < 0.1\ \mathrm{nm}$
- prerequisite for direct laser excitation

$$\Delta E = 1\ \mathrm{nm} = 0.05\ eV$$

P. Van Duppen, S. Sels, KU Leuven

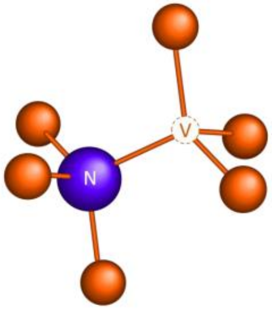


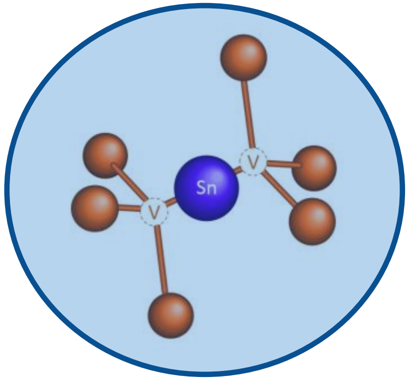


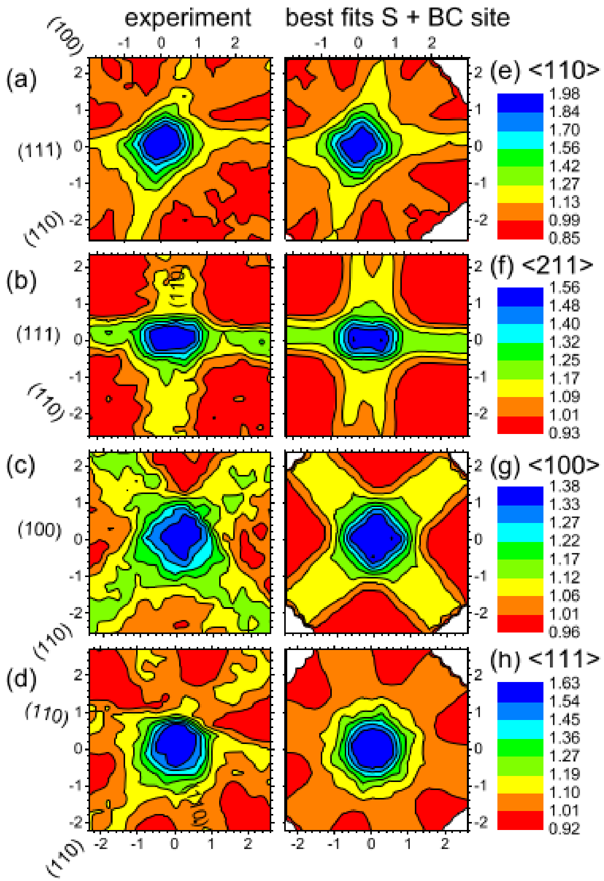
Quantum technologies: quantum emitters

Towards more efficient communications

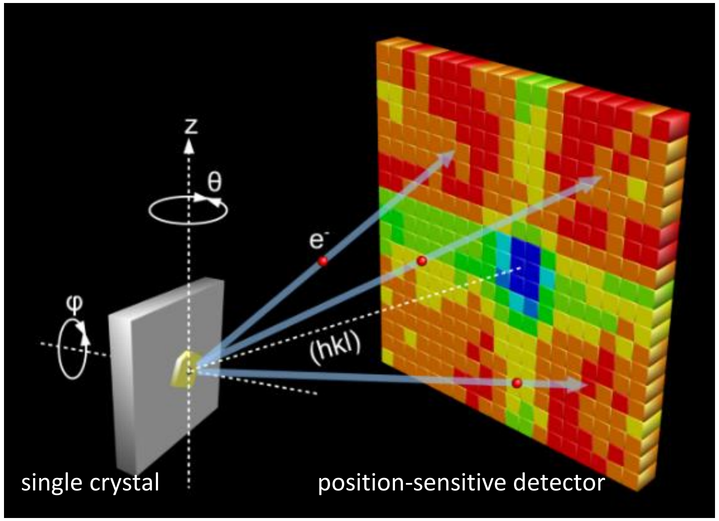
Search for more suitable quantum emitters: beyond NV…identification and control of novel emitters







Material science: Emission channeling



Phys. Rev. Lett. 125, 045301 2020

Outlook

- Experiments planned for the coming running period
- Improved beam purity with 30 keV MR-TOF device

New ideas as part of the ISOLDE-EPIC proposal:

- Exploit accelerator upgrades within LIU project: higher intensities of radio-nuclei
  - Higher proton energy (1.4 -> 2 GeV)
  - Higher proton intensity
- Improved beam purity
- New experimental hall
  - More space for existing and new experimental setups
  - Stable conditions for precision experiments
  - Parallel running and combination of experimental techniques

Wilder ideas: beams from gamma-factory?

Summary

- Precision and New Physics Studies present and intensifying at ISOLDE

- Topics:
  - Weak interaction studies
  - EDMs
  - Quantum techniques – nuclear clock
  - Others not covered in the talk: neutrino mass, precise magnetic moments

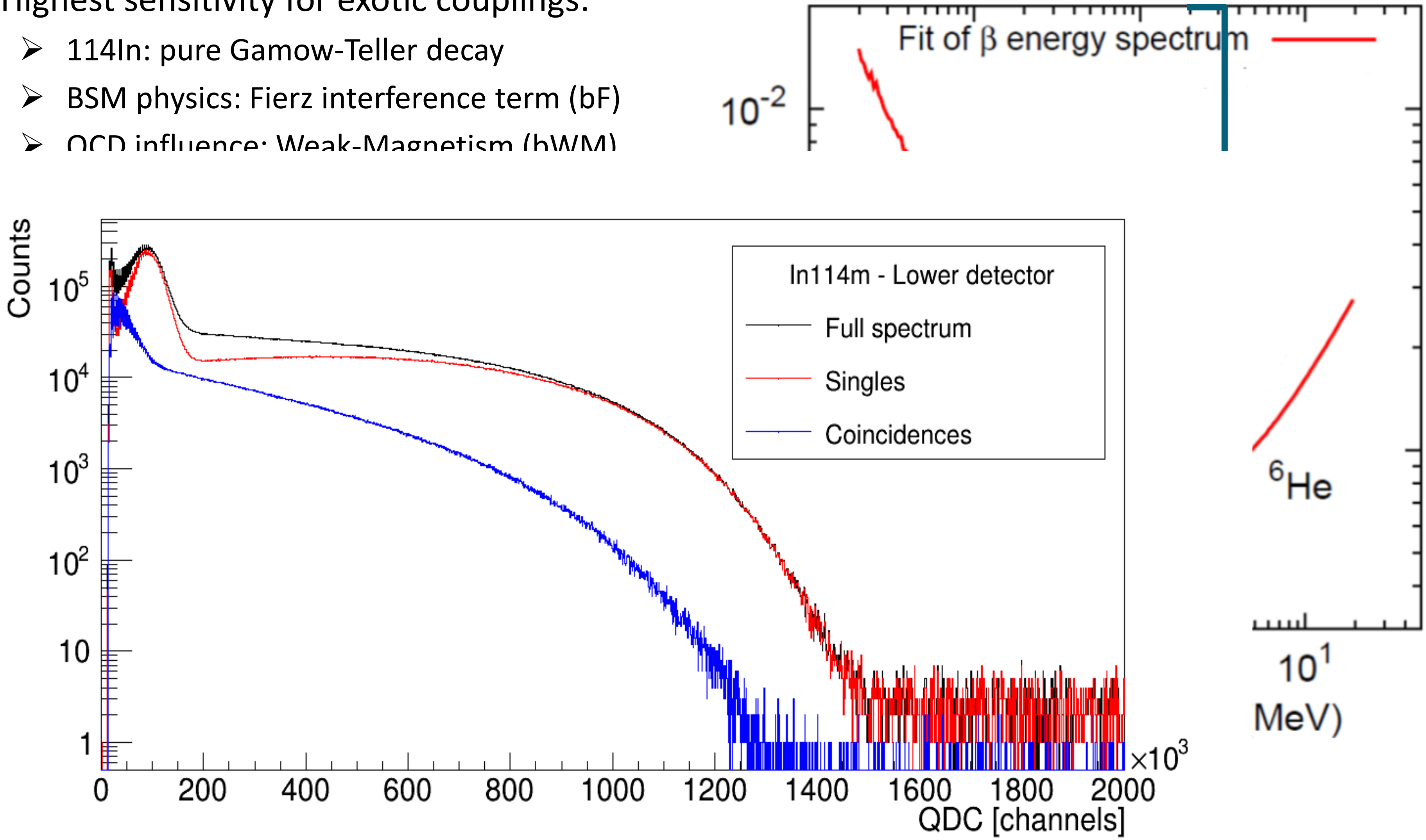
- Techniques
  - Decay spectroscopy, traps, laser spectroscopy, material science

- Outlook:
  - More possibilities given by the EPIC proposal

BACKUP

Beta-energy spectrum

- Highest sensitivity for exotic couplings:
  - 114In: pure Gamow-Teller decay
  - BSM physics: Fierz interference term (bF)
  - QCD influence: Weak-Magnetism (bWM)



L.Hayen and N.Severijns Comp. Phys. Comm. 240, 152-164 (2019)

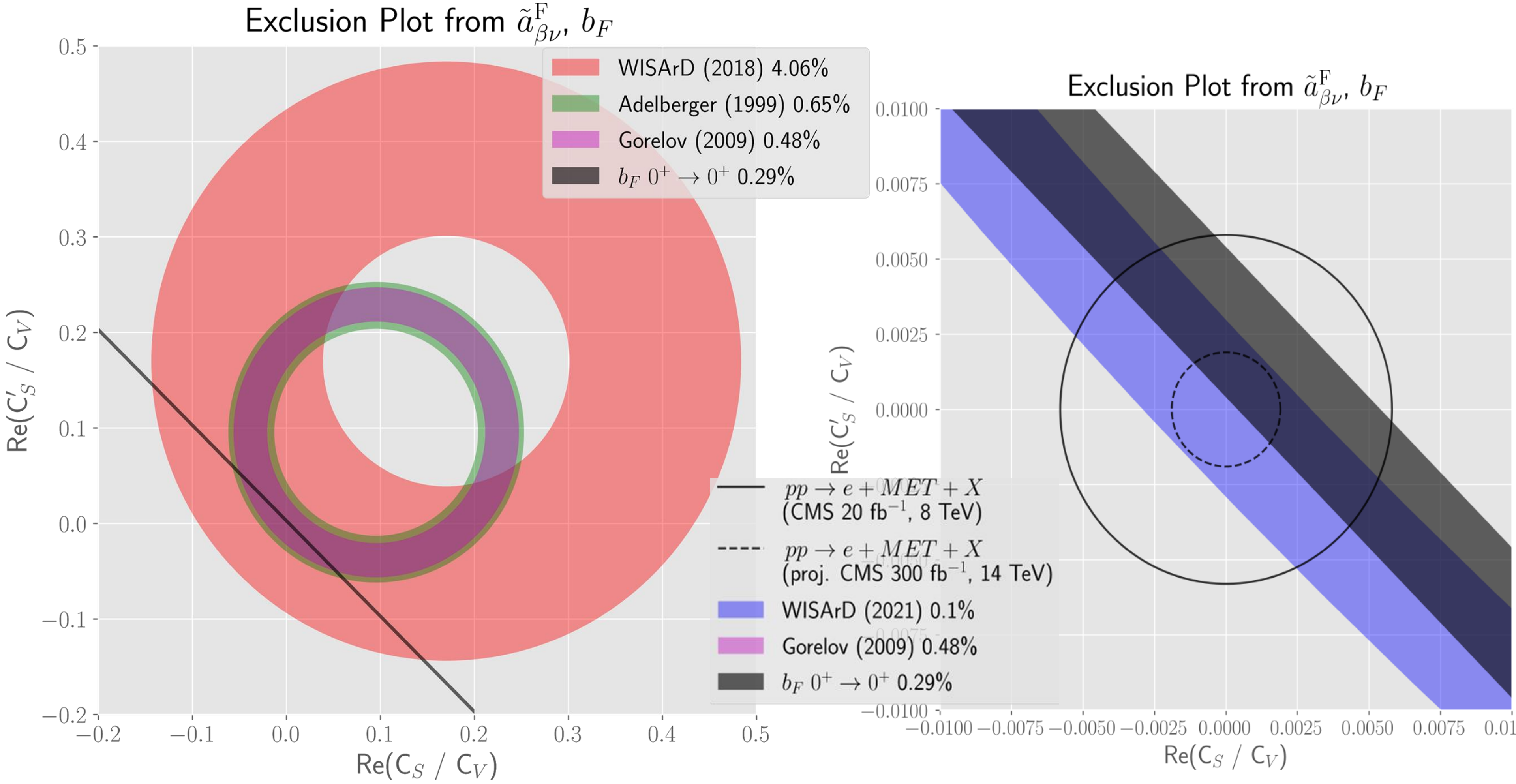
M. González-Alonso and O. Naviliat-Cuncic, Phys. Rev. C 94, 035503 (2016)

32Ar and scalar currents

- Proof-of-principle run in 2018
- Final experiments after LS2

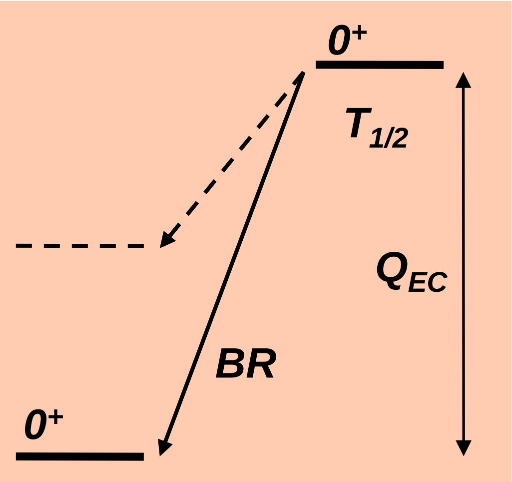
$$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$$

3rd most precise measurement of a_F



V. Araujo-Escalona et al., Phys. Rev. C101, 055501 (2020

V_{ud} from super-allowed transitions



$$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS}) = \frac{K}{\boxed{G_V^2}\,(1 + \Delta_R)\,\langle M_F \rangle^2} = cnst$$

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

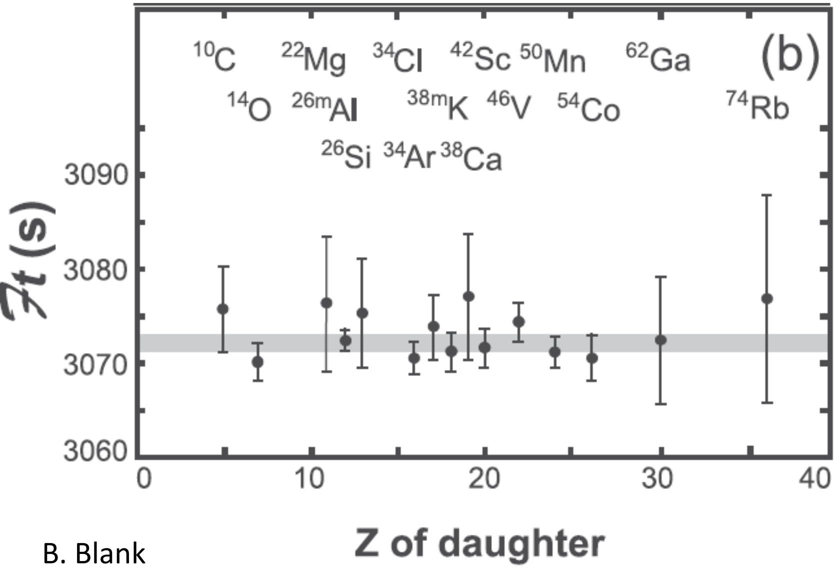
f(nucl. structure) ~ 0.3-1.5%

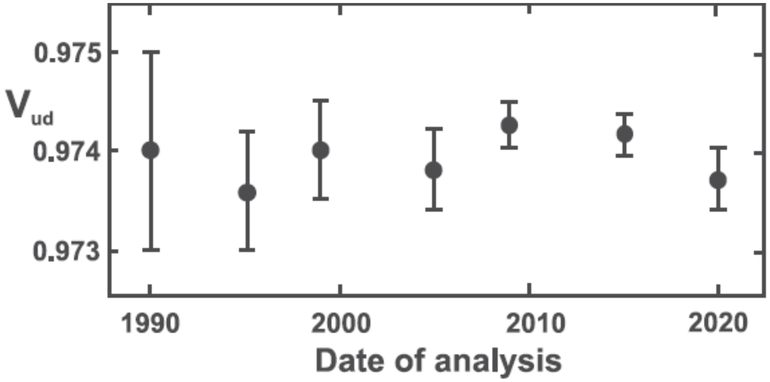
f(weak interaction) ~ 2.4%

Transition strength -> vector coupling constant for semi-leptonic decays -> $\mathbf{V_{ud}}$:

$$\boxed{V_{\mathrm{ud}} = G_{\mathrm{V}}/G_{\mathrm{F}}}$$

Many of experimental values come from ISOLDE





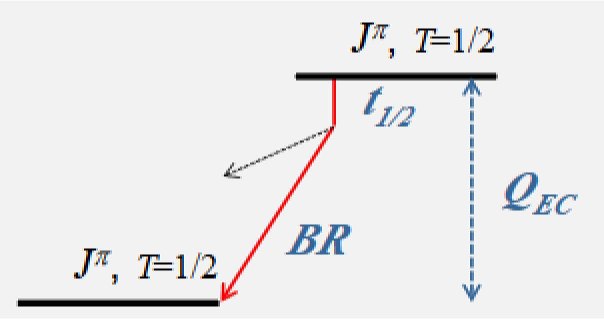
$$|V_{ud}| = 0.97373 \pm 0.00031$$

B. Blank

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

V_{ud} from mirror transitions

- Super-allowed transitions between isobaric analogue states for T=1/2 doublets
  - Between states with same spins & parities in mirror nuclei
  - Involve vector (Fermi decay) and axial (Gamow Teller) parts

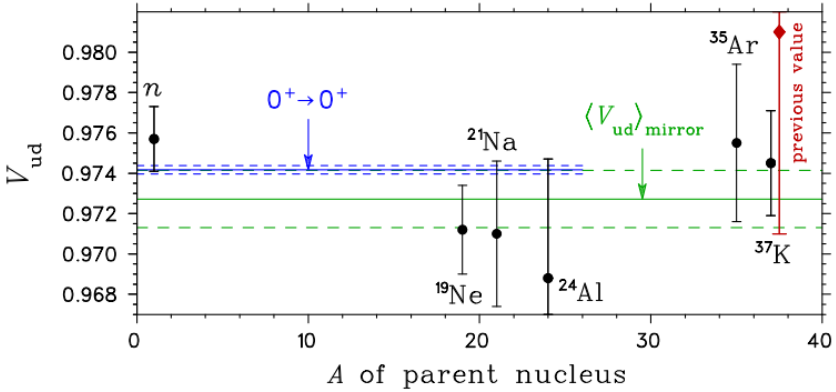


- Connection to V_{ud}:

$$\mathcal{F}t_0 = f_\mathrm{V}\, t\left(1+\boxed{\frac{f_\mathrm{A}}{f_\mathrm{V}}\rho^2}\right)(1+\delta'_\mathrm{R})(1+\delta_\mathrm{NS}-\delta_\mathrm{C})$$

$$= \frac{K}{G_\mathrm{V}^2\langle M_\mathrm{F}\rangle^2(1+\Delta_\mathrm{R}^\mathrm{V})}, \quad \longrightarrow V_\mathrm{ud} = G_\mathrm{V}/G_\mathrm{F}$$

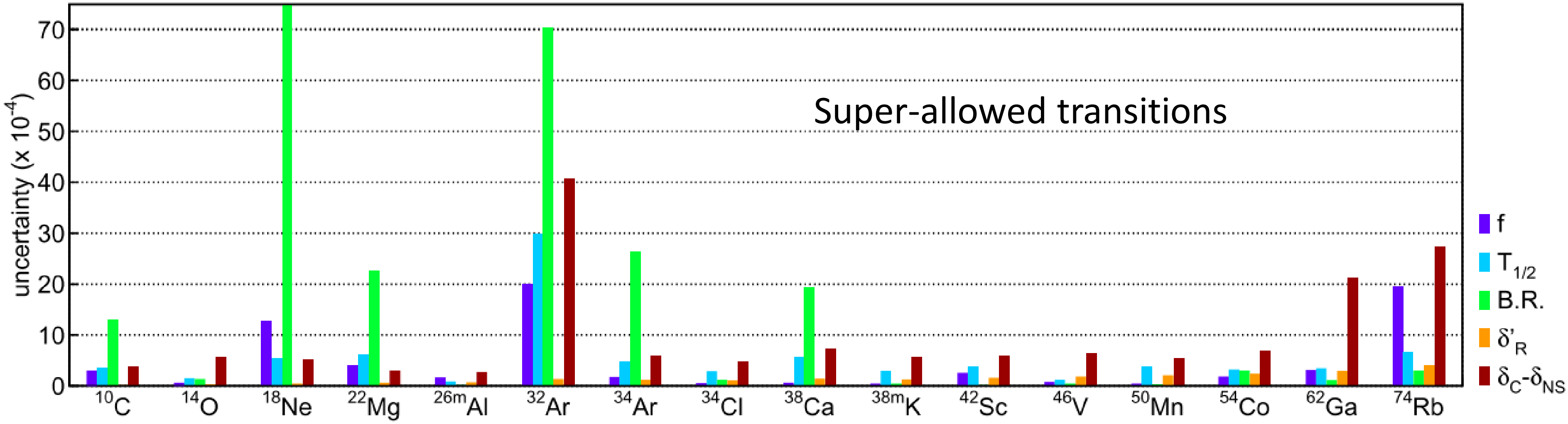
V_{ud} = 0.97424(95)



B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)

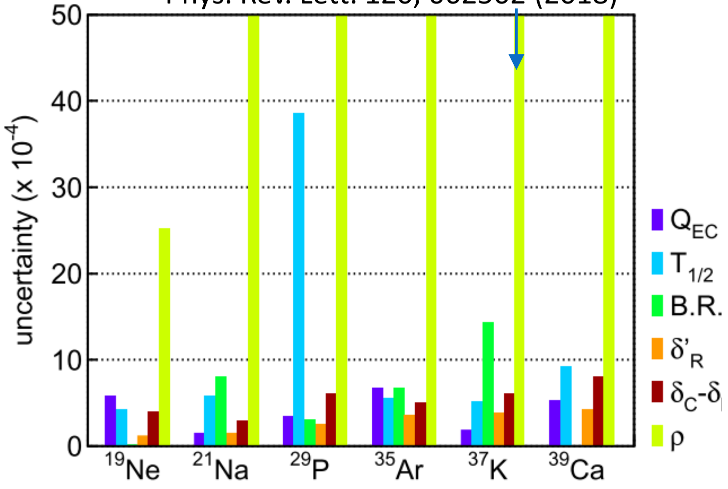
A. Falkowski, M. González-Alonso, O. Naviliat-Cuncic, *Comprehensive analysis of beta decays within and beyond the Standard Model*, arXiv:2010.13797 (2020)

Uncertainties



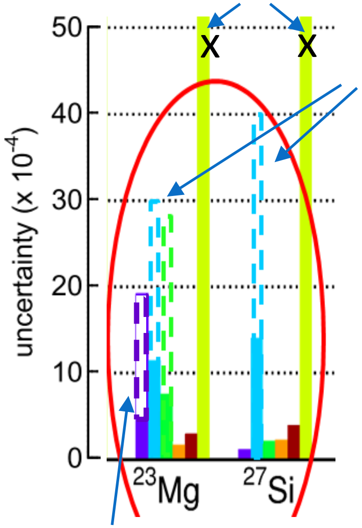
Mirror transitions

400 -> 100e-4; TRIUMF, B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)



no measurement yet

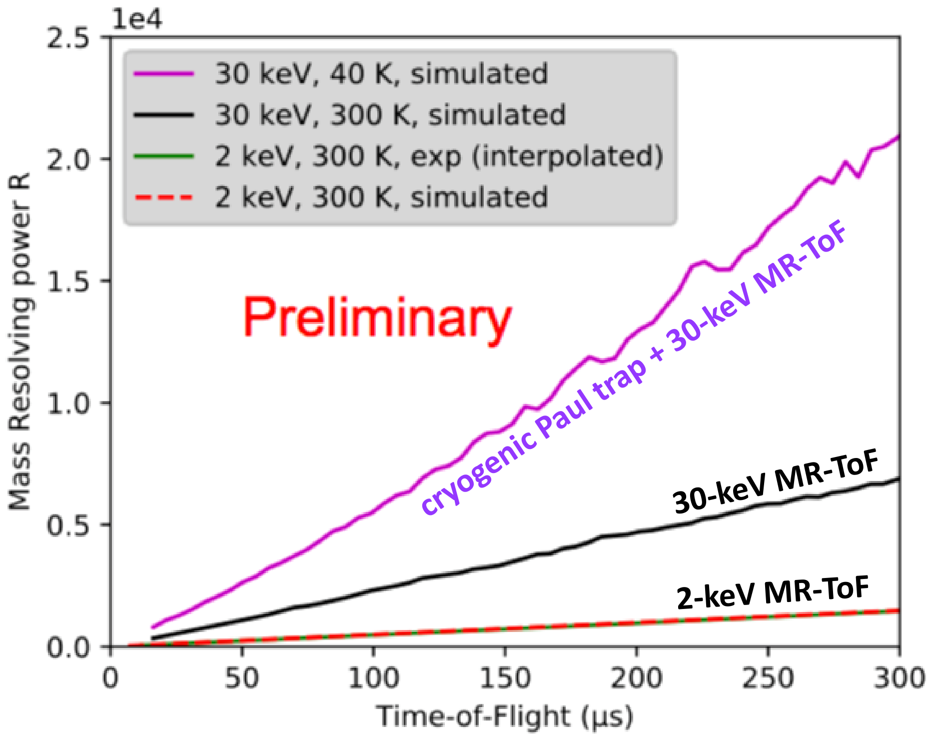
Bordeaux group in Jyvaskyla



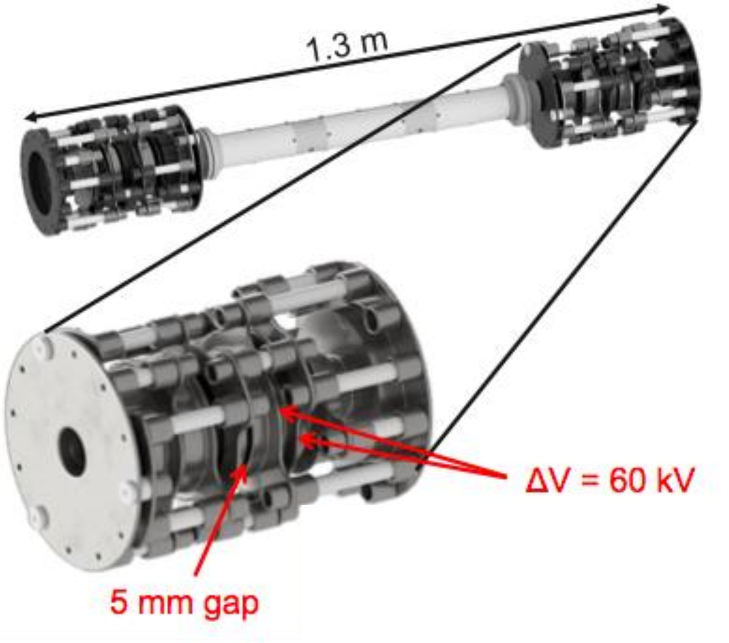
ISOLTRAP, ISOLDE
J. Karthein et. al., Phys. Rev. C 100, 015502 (2019)

N Severijns and B Blank, J. Phys. G: Nucl. Part. Phys. 44 (2017) 074002

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

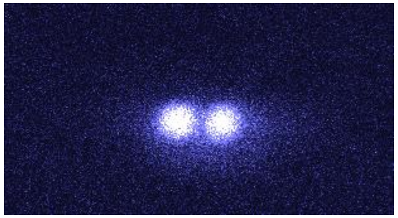


MIRACLS' 30-keV MR-ToF



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)

Future nuclear clock?

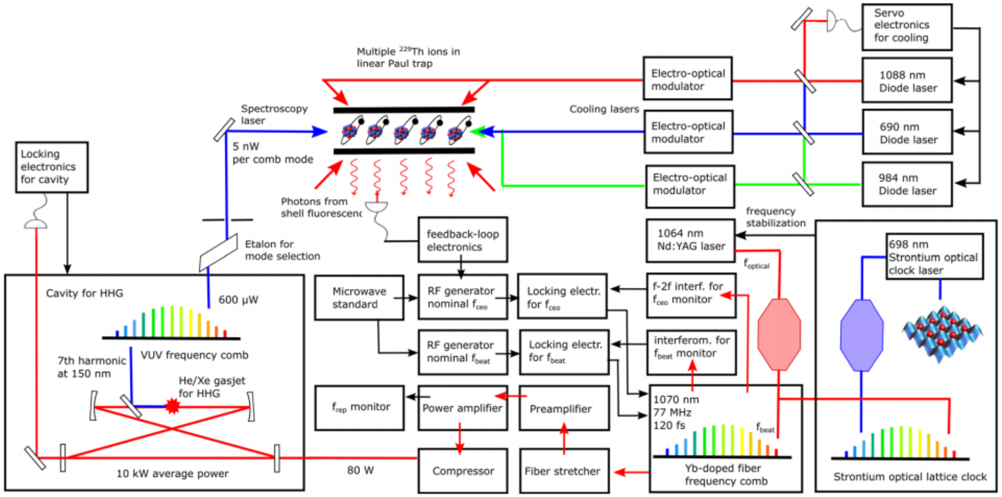


Ion-trap based nuclear clock

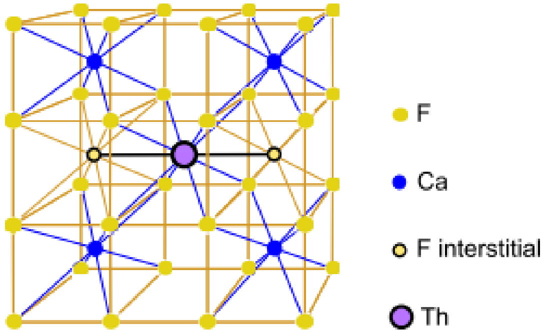
Solid state based nuclear clock

Crystal-Lattice wide-band gap clock

L. VD Wense, Eur. Phys. J. A **56** 277, (2020)



G A Kazakov *et al* 2012 *New J. Phys.* **14** 083019



Exotic molecules and EDMs

$$|s'\rangle = |s\rangle + \frac{\langle s| V_{PV} |p\rangle}{E_- - E_+} |p\rangle$$

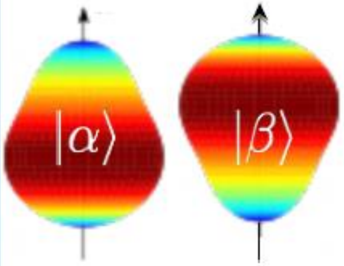
$V_{SV} \sim Z^a A^b Q_2 Q_3 /(E_+^N - E_-^N)$

- → Large Z, A ✓
- → Max. $Q_2 Q_3$ ✓
- → Min. $(E_+ - E_-)$ ✓

Exotic nuclei → Nuclear amplification ($>10^3$)


nature

GOING PEAR-SHAPED



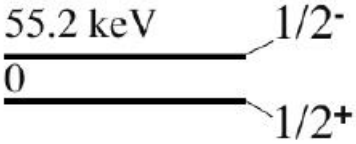
^{225}**Ra**

$\Delta E = 55$ keV

[Gaffney et al. Nature 497, 199 (2013)]

Atoms: $(E_+ - E_-) \sim 1$ eV

Molecules: $(E_+ - E_-) \sim 10^{-5}$ ev

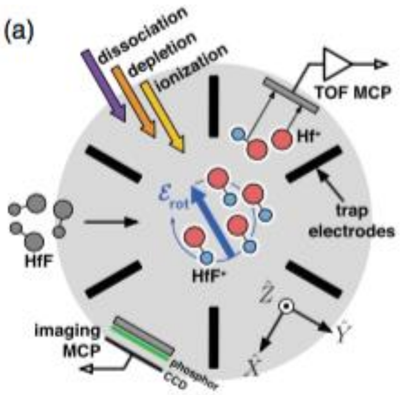


Exotic molecules → Best of all worlds

... BUT, are experimentally unknown!

Ionic (radioactive) molecules

- EDM limit in stable $^{180}Hf^{19}F^+$ confined in an ion trap



trapped ionic molecules

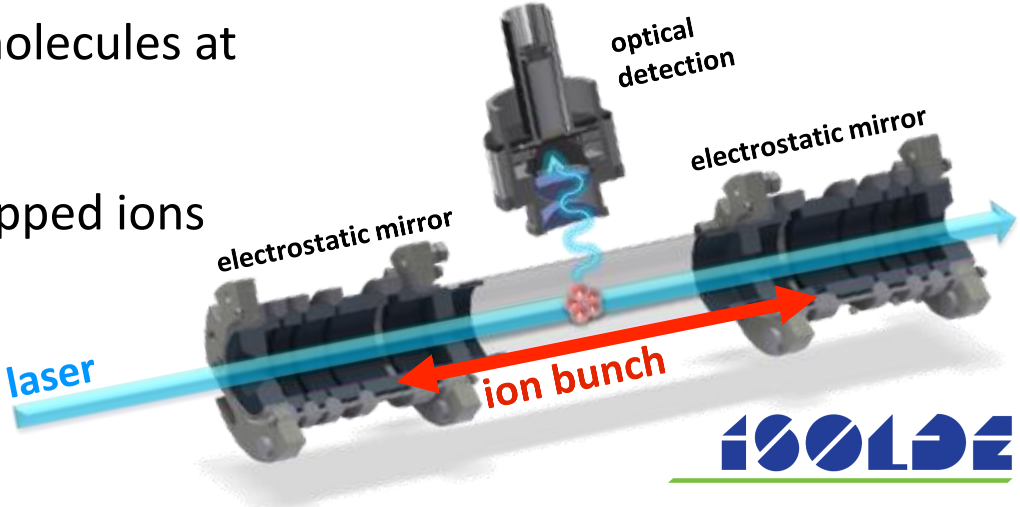
W. B. Cairncross et al., PRL 119, 153001 (2017)

- test fundamental symmetries in molecules including deformed, radioactive nuclei e.g. $^{225}RaOCH_3^+$

P. Yu * and N.R. Hutzler, PRL 126, 023003 (2021)

- spectroscopy of ionic radioactive molecules at MIRACLS

\- high experimental sensitivity for trapped ions



S. Ettenauer