Milad Alanssari
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Precision mass measurements in the context of neutrino-nuclear physics

----- $0\nu\beta\beta$ decay and g_A -----

Erice, September, 2017,

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Outline

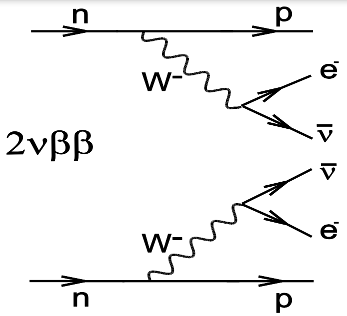
- Double beta (ββ) decay
  - → neutrinoless double beta (0νββ) decay NME
  - → the specialties of ^{96}Zr/ ^{96}Nb for β and ββ decay

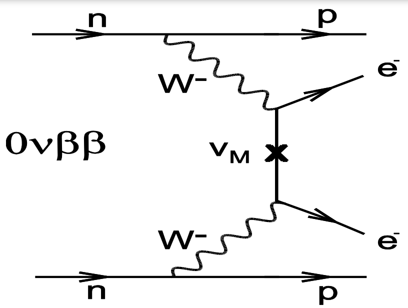
- Mass measurements using the JYFLTRAP ion trap

- Results and the issue of the axial vector coupling g_A

- Proposal for a μ-capture experiment at RCNP to "measure" g_A

Double beta decay





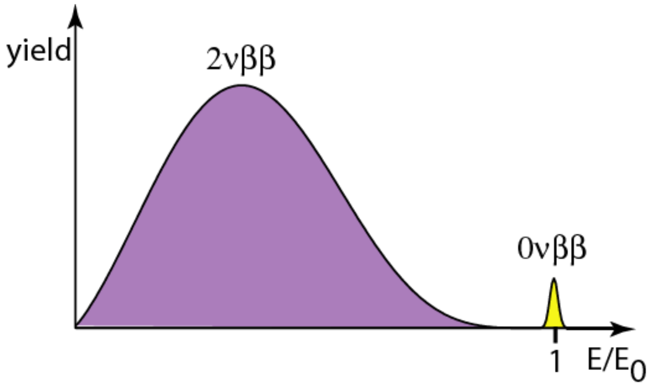
$$A(Z,N) \rightarrow A(Z+2,N-2)+2e^- + 2\bar{\nu}_e$$

- allowed in Standard Model (ΔL=0)
- observed experimentally
- NME can be measured (charge-exchange)
- no dependence on ν mass
- low-q phenomenon (q_{tr} ~ 0.01 fm^{-1})

$$A(Z,N) \rightarrow A(Z+2,N-2)+2e^-$$

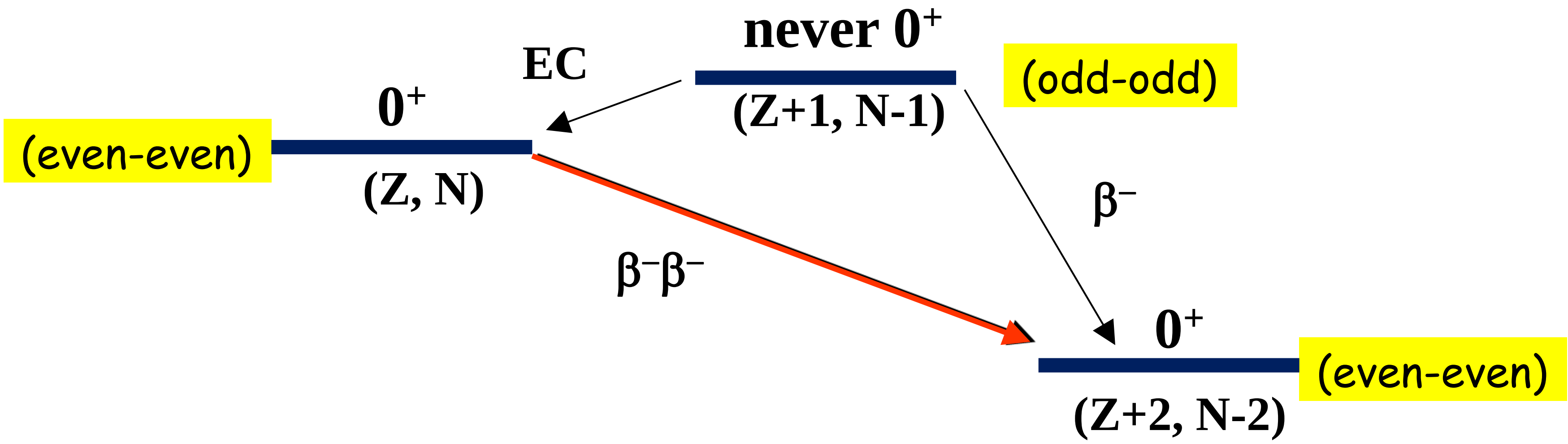
- forbidden in Standard Model (ΔL=2)
- not observed yet
- NME only calculated
- ν has Majorana mass
- high-q phenomenon (q_{tr} ~ 0.5 fm^{-1})

2νββ-decay



0νββ-decay

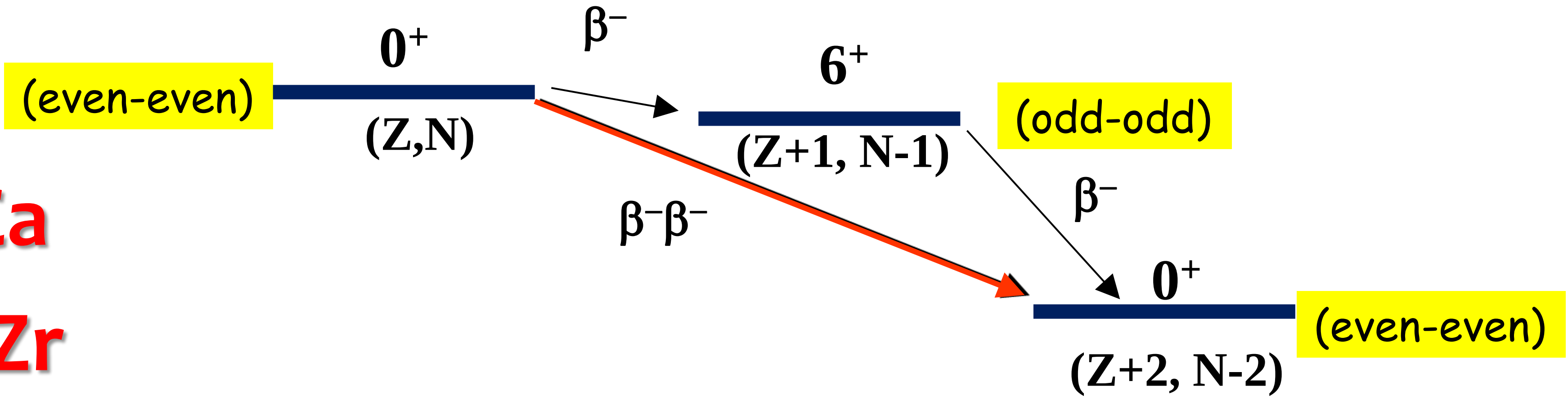
$\beta^-\beta^-$ decay



1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
4. ^{100}Mo
5. ^{82}Se
6. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

the β-β- decay candidates with Q-value > 2 MeV

$\beta^-\beta^-$ decay



(even-even)

0^+

(Z,N)

β^-

6^+

(Z+1, N-1)

(odd-odd)

$\beta^-\beta^-$

β^-

0^+

(Z+2, N-2)

(even-even)

^{48}Ca

^{96}Zr

1. ^{48}Ca
2. ^{150}Nd
3. ^{96}Zr
4. ^{100}Mo
5. ^{82}Se
6. ^{116}Cd
7. ^{130}Te
8. ^{136}Xe
9. ^{124}Sn
10. ^{76}Ge
11. ^{110}Pd

the β-β- decay candidates with Q-value > 2 MeV

$\beta^-\beta^-$ decay rate

$2\nu\beta^-\beta^-$ decay:

$$T_{1/2} \approx 10^{19-21}\,y$$

$$\Gamma = \underset{\text{5-body}}{G(Q,Z)} \times g_A^4 \times \left| \underset{\text{allowed (GT)}}{NME} \right|^2$$

$\propto Q^{11}$

from charge exchange reactions

$0\nu\beta^-\beta^-$ decay:

$$T_{1/2} > 10^{24}\,y$$

$$\Gamma = \underset{\text{3-body}}{G(Q,Z)} \times g_A^4 \times \left| NME \right|^2 \times \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

$\propto Q^5$

calculated within models

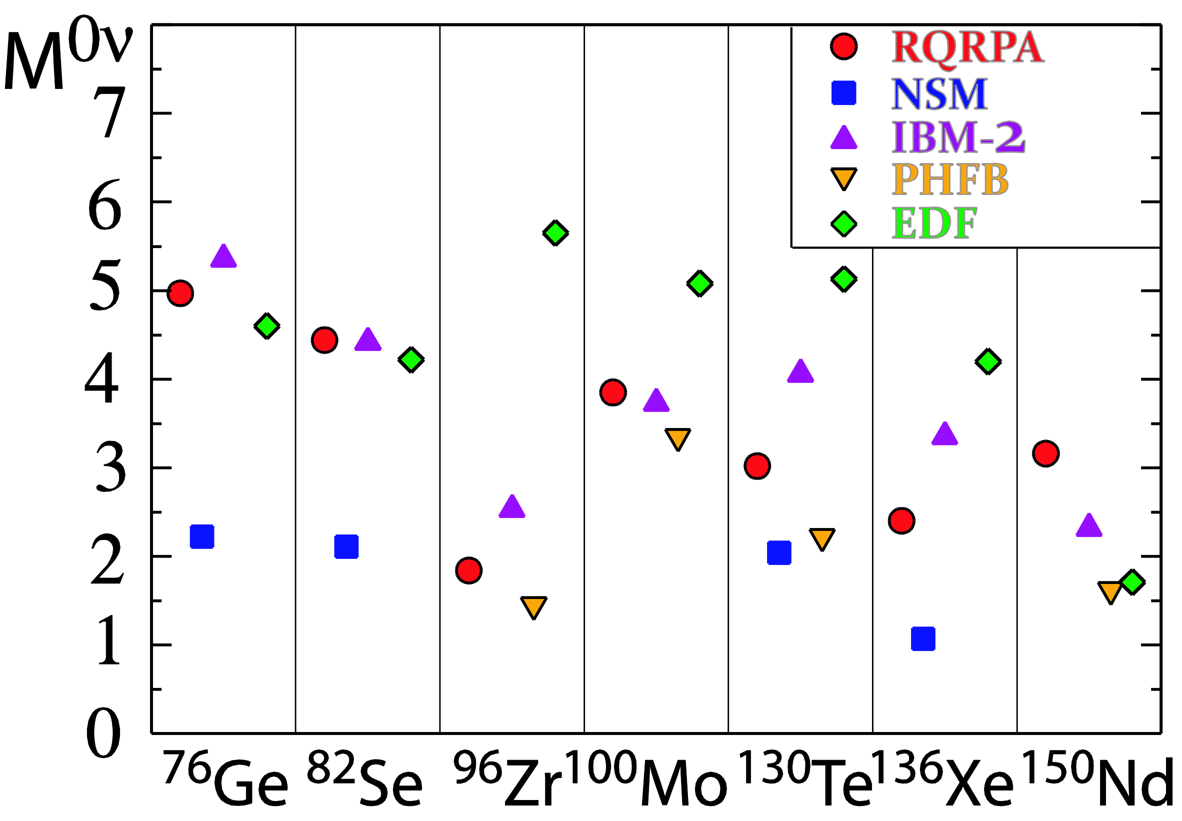
effective Majorana ν mass, $m_{\beta\beta}$

favorable:

1. high Q-value
2. large Z

$0\nu\beta^-\beta^-$ N_{ucl.} M_{atrix} E_{lement}

P.Vogel, J. Phys. G, NPP39, 2012



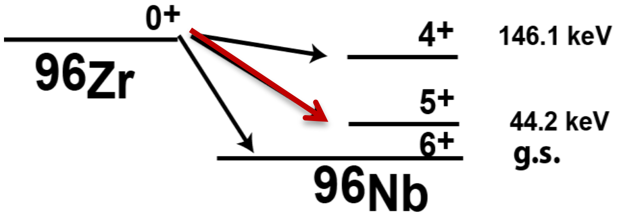
The calculated 0νββ decay NME via different models differ by more than a factor of 2-3 (i.e. half-life 4-9)

Idea for ^{96}Zr

- (i) measure **Q-value** for ^{96}Zr $\longrightarrow$ ^{96}Nb **single β-decay** by precision mass measurement and

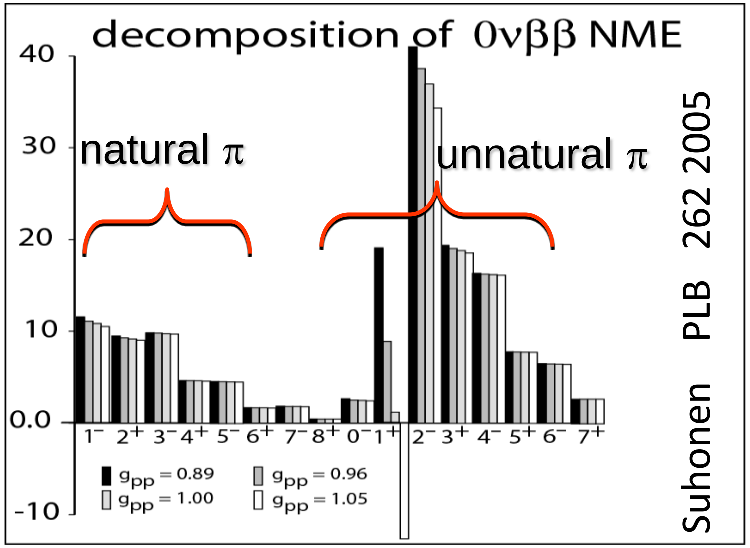
  (ii) measure the **single β-decay** rate

  (iii) → ft-value



- determine the ^{96}Zr **4-fold forbidden β-decay NME** and confront with theory

- confront with same theories aimed at calculating **0νββ-decay NME for the same nucleus!!**



Suhonen PLB 262 2005

Competition between β & ββ decay of ^{96}Zr

two conflicting half-lives:

NEMO-3: $T^{2\nu\beta\beta}_{1/2} = (2.3 \pm 0.2) \times 10^{19}\,\text{y}$

geo-chem: $T_{1/2} = (0.94 \pm 0.32) \times 10^{19}\,\text{y}$ ①

can this difference be reconciled ?
yes, if single β competes with ββ decay

$$\left(T_{1/2}\right)^{-1} = \left(T^{2\nu\beta\beta}_{1/2}\right)^{-1} + \left(T^{\beta}_{1/2}\right)^{-1}$$

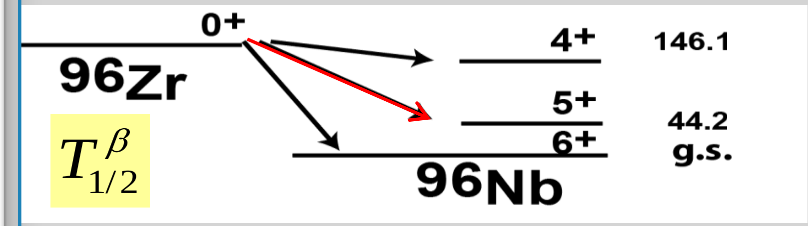
expected $T^{\beta}_{1/2} = (1.6 \pm 0.9) \times 10^{19}\,\text{y}$

experiment $T^{\beta}_{1/2} > 2.6 \times 10^{19}\,\text{y}$ ②

pred. (QRPA) $T^{\beta}_{1/2} = 24 \times 10^{19}\,\text{y}$ ③

BUT

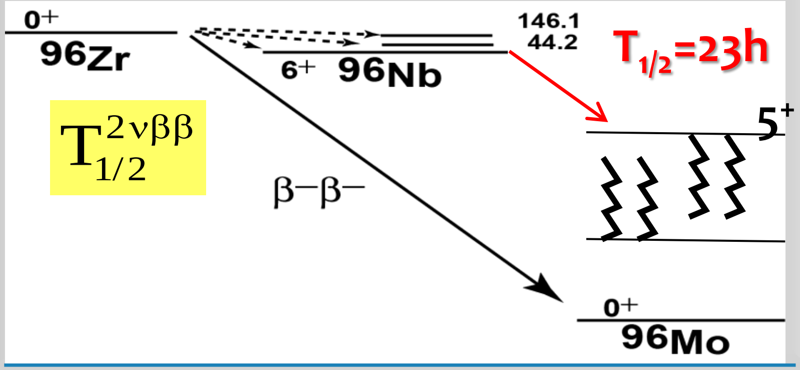
$$(T^{\beta}_{1/2})^{-1} \propto o(Q^{13})\, g_A^2 \left\langle M^{4u}_{\beta} \right\rangle^2$$



0⁺ → 6⁺ 6-fold non-unique (unobservably long)

0⁺ → 5⁺ 4-fold unique (possible)

0⁺ → 4⁺ 4-fold non-unique (no phase space)



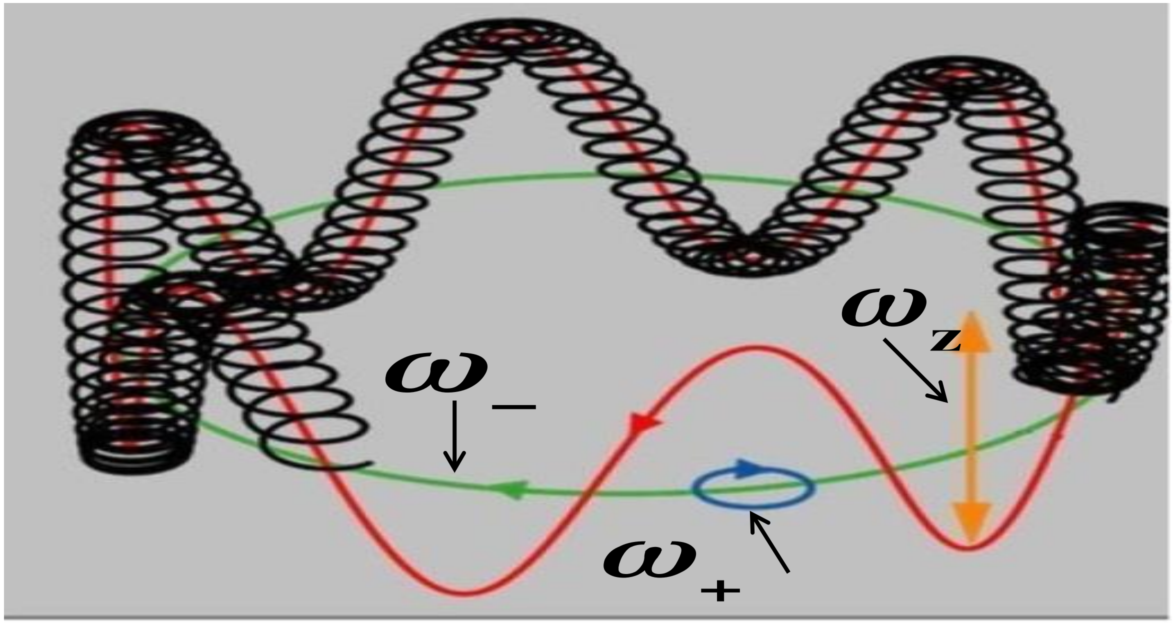
Q-value $\longrightarrow M^{4u}_{\beta} \longrightarrow (T^{0\nu\beta\beta}_{1/2})^{-1} \propto Q^5 \left|M^{0\nu}_{\beta\beta}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$

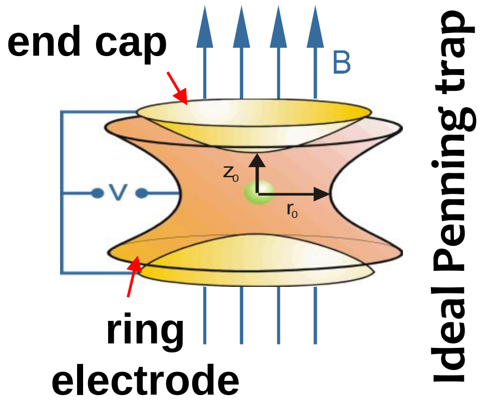
① Wieser, PRC64,2001, ② Barabash, JPG-NPP22, 1996 ③ Heiskanen, JPG3,2007

Ion motion in a Penning trap

Homogeneous magnetic field + static electric field provides 3D confinement results in three eigenmotions:

1. Magnetron motion ω_-
2. Reduced cyclotron motion ω_+
3. Axial motion ω_z





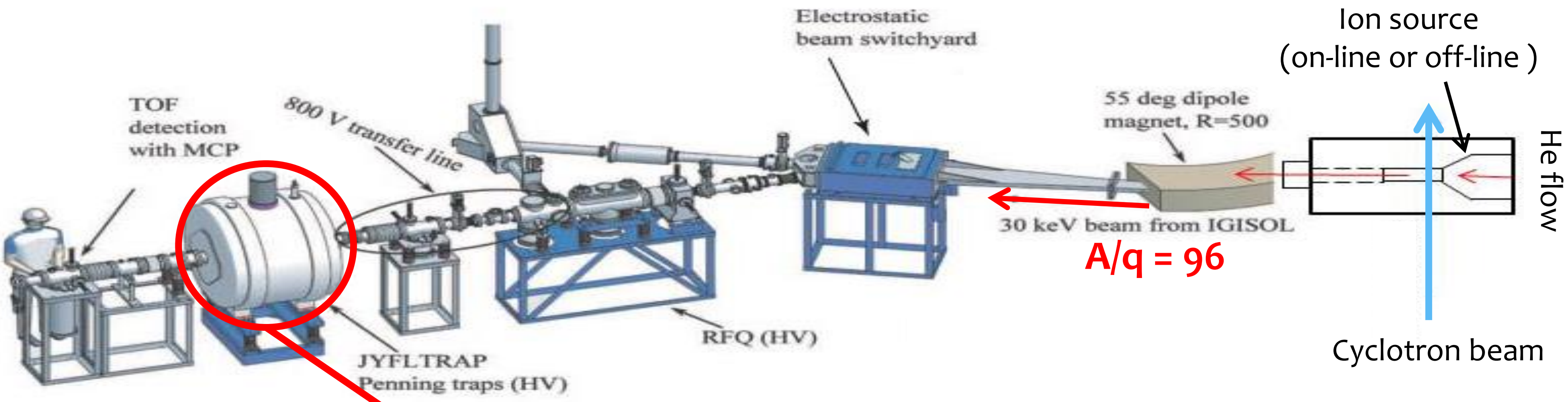
$$\omega_c = \omega_- + \omega_+$$

$\omega_- \approx 1$ kHz,
$\omega_+ \approx 1$ MHz

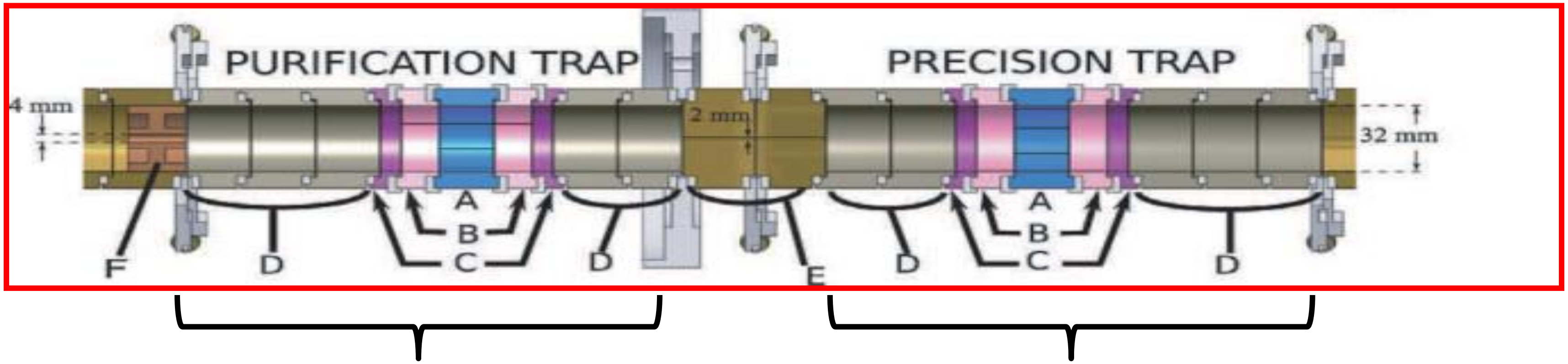
$$\boxed{\omega_c = \frac{q}{m} \cdot B}$$

IGISOL / JYFLTRAP setup

Figures from Eronen EPJA 48-2012



$\Delta B/B = 8.18 \times 10^{-12}$ /min



purification & isobar separation by buffer-gas cooling technique

mass measurement via cyclotron frequency, $p < 10^{-7}$ mbar.

Beam production at IGISOL

Off-line measurements

^{96}Zr and ^{96}Mo

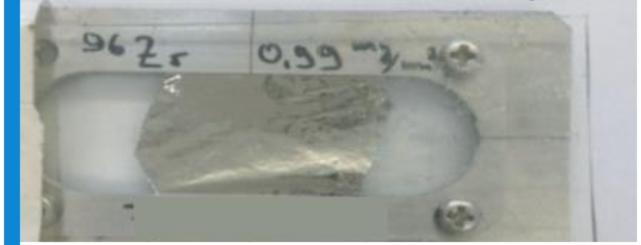
off-line ion source

On-line measurements

^{96}Zr (p, n)^{96}Nb reaction for production of ^{96}Nb

10MeV proton beam

57% enriched ^{96}Zr target



target (on-line) ion source

Note IGISOL produces on-line :

^{96}Zr ----- from target material

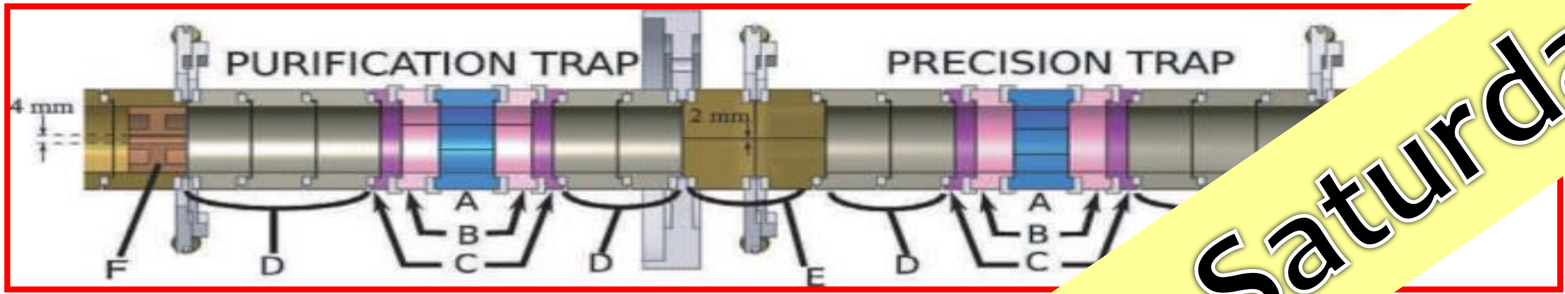
^{96}Nb ----- (p,n) charge-ex reaction

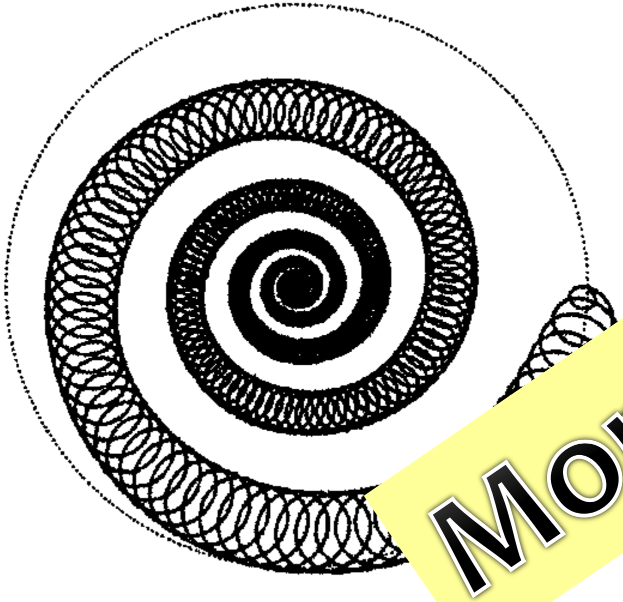
^{96}Mo----- from havar® separator foil

mother & daughter ions are produced at IGISOL at the same time

Principle of isobar separation in purification trap

Excite ion eigenmotion by a dipolar or a quadrupolar electric field with a corresponding frequency (ν_- or ν_c)





excit… …interest with ν_c causes c… …ng of this species in the … the buffer gas …cation trap: R > 500/1)

More T. Eronen, Saturday

Mass measurements in a Penning trap

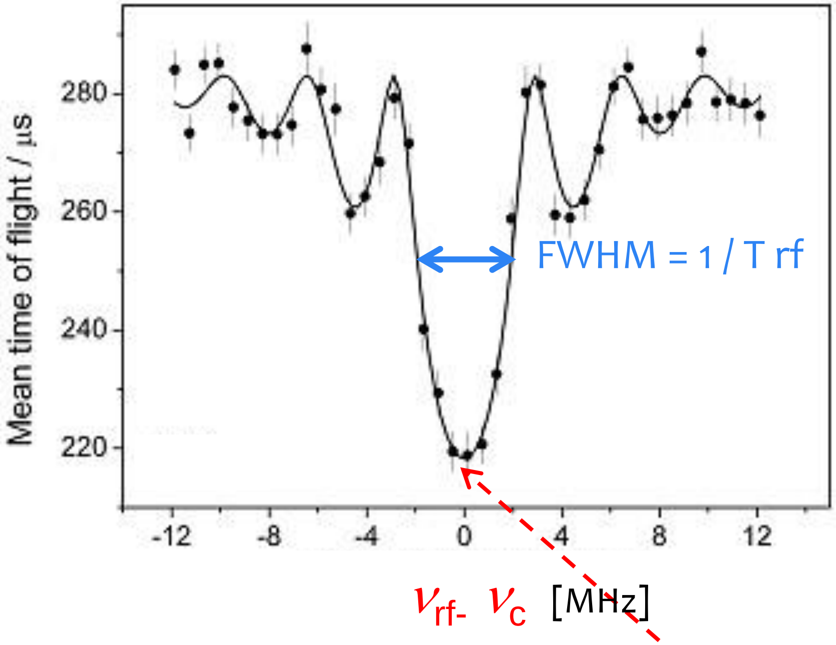
- Performing precision mass determination via **cyclotron frequency** ν_c measurement

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

$\omega_c = 2\pi\,\nu_c$

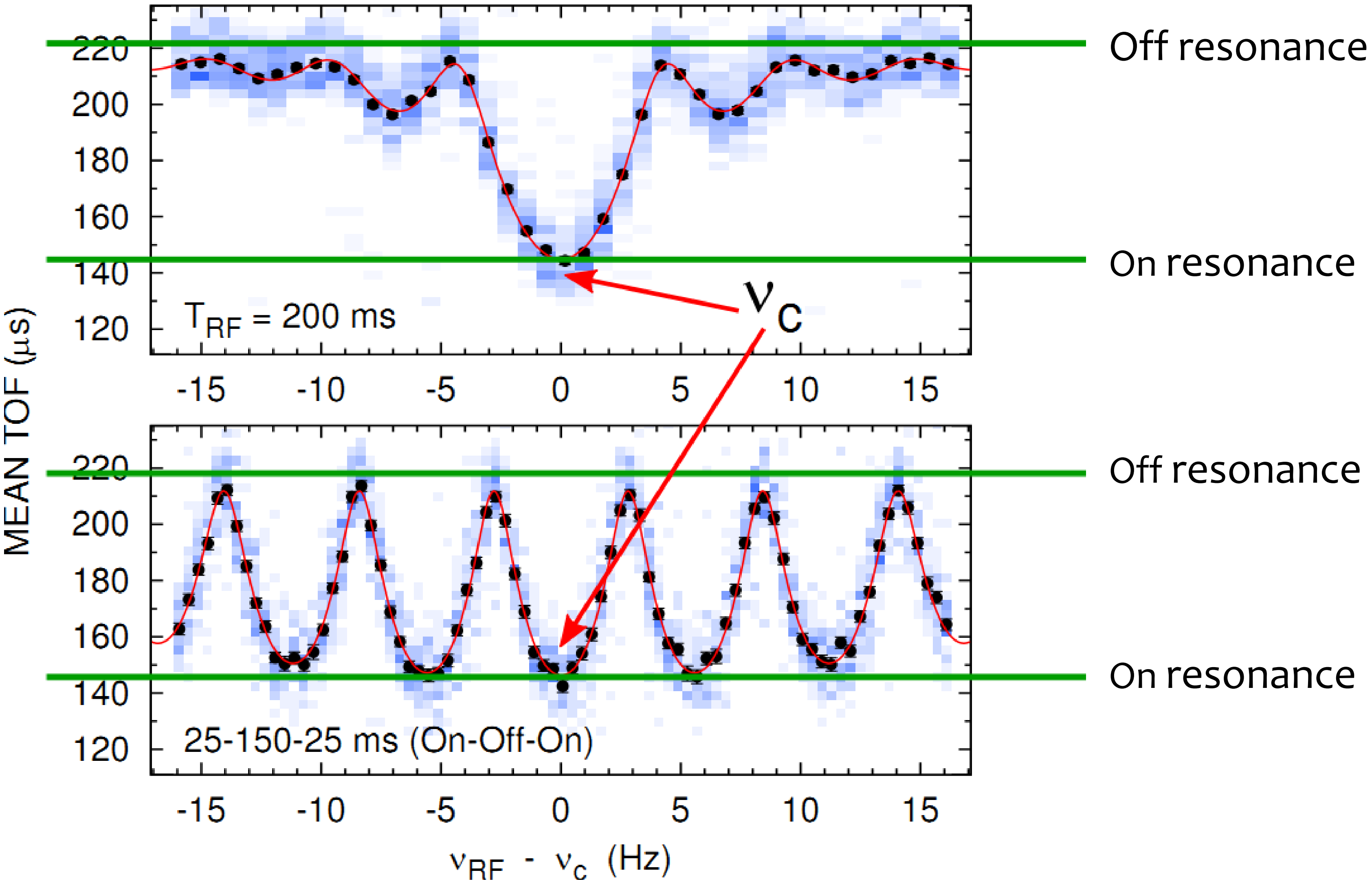
- Cyclotron frequency ν_c determination done by **TOF-ICR** technique

- Frequency ratio $r = \frac{\nu_{c\ daughter}}{\nu_{c\ mother}}$

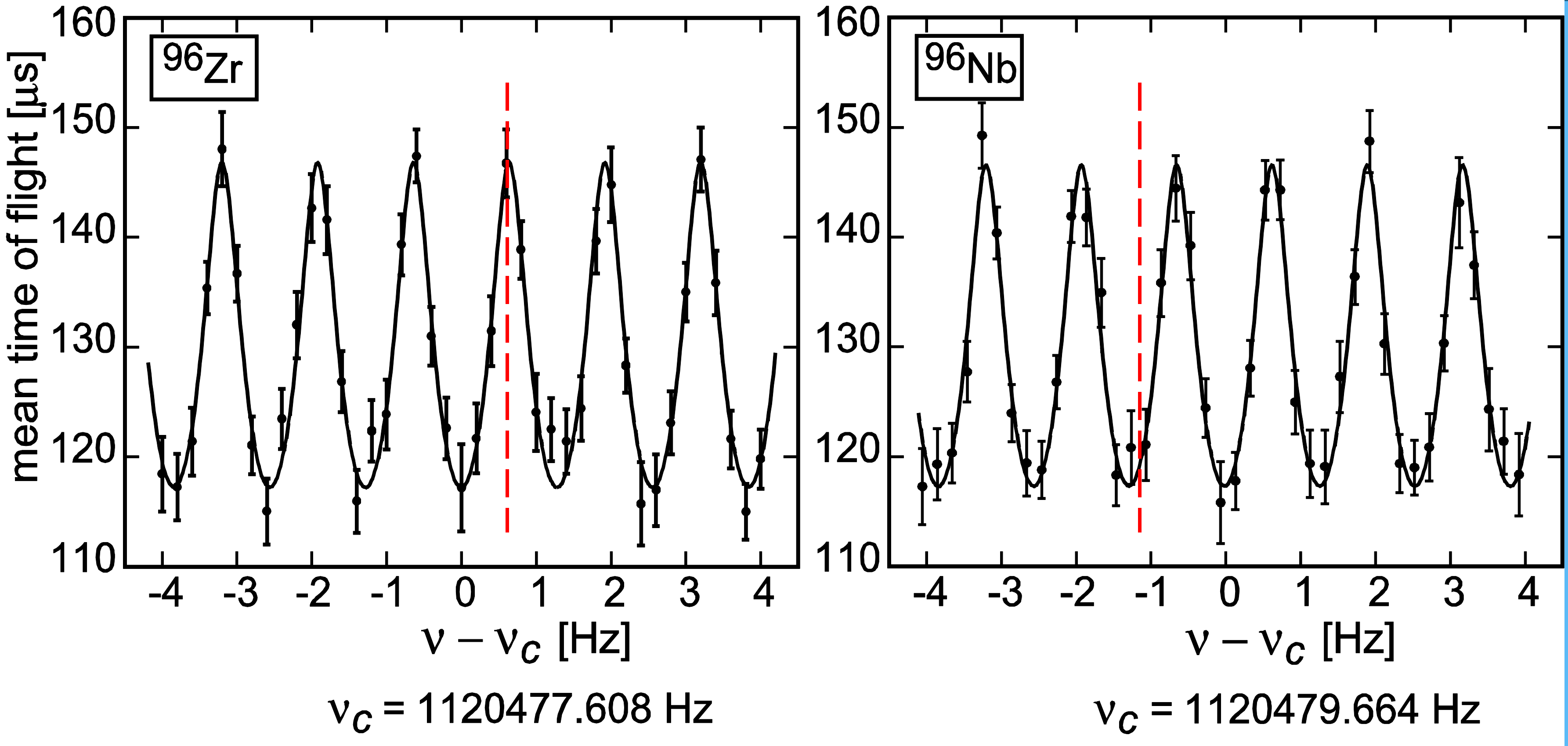


at ν_c ion acquires extra energy
⟶ shorter time of flight

Example resonances



Cyclotron frequency results



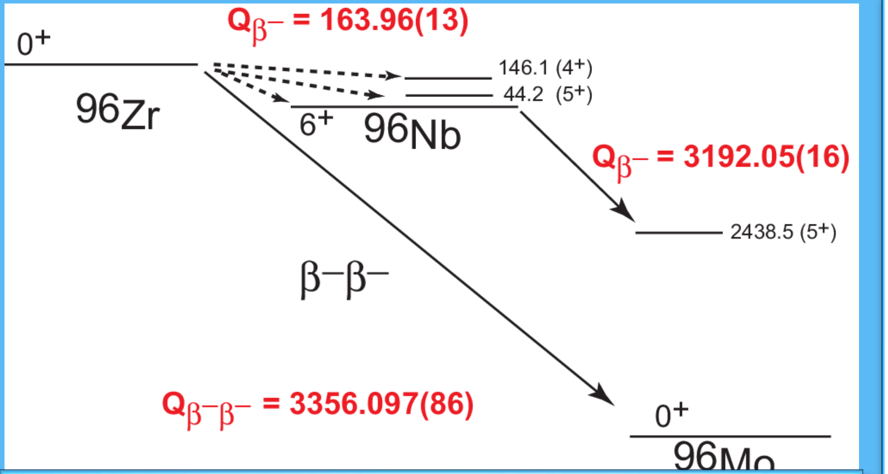
ν_c = 1120477.608 Hz

ν_c = 1120479.664 Hz

The measured cyclotron frequency of ^{96}Zr and ^{96}Nb by

Ramsey excitation pattern 25-750-25 ms (on-off-on)

Q-value results



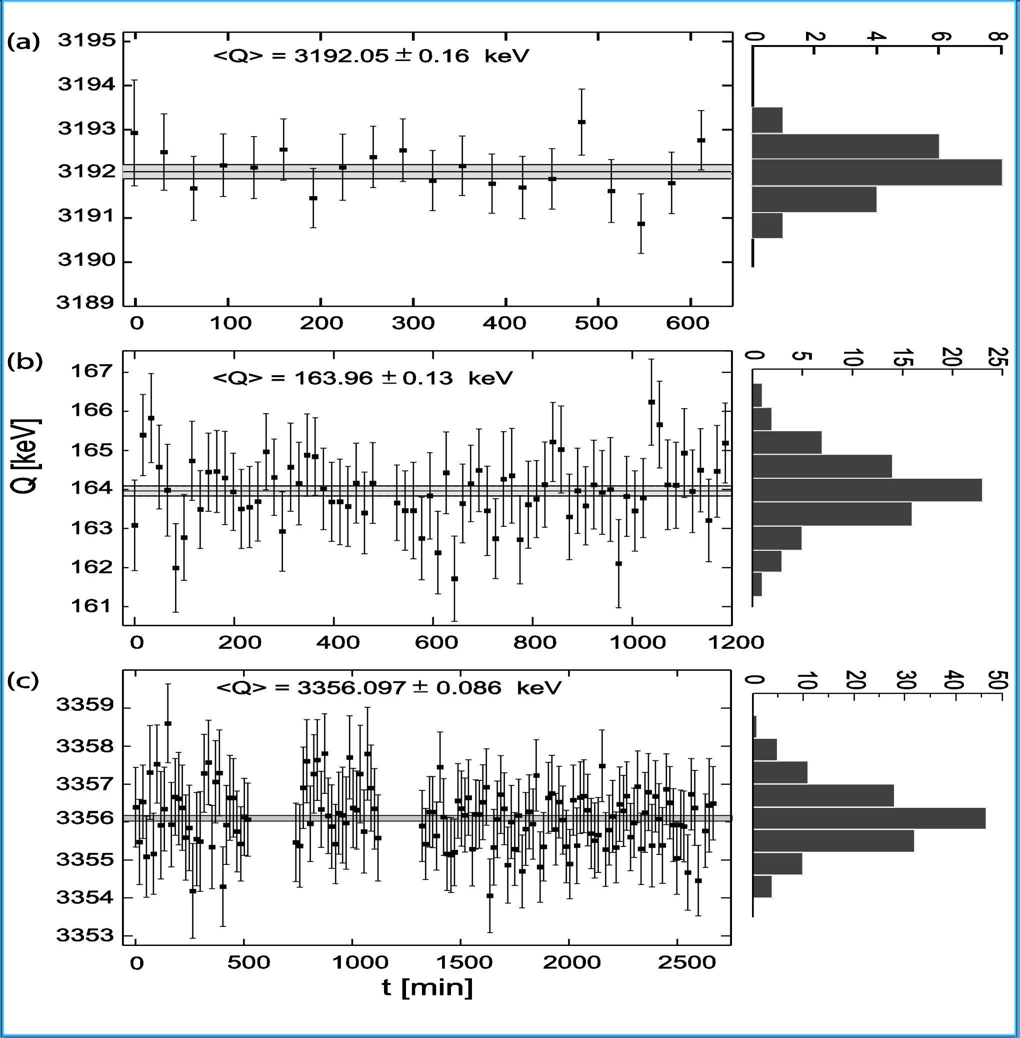
96Zr

$$Q_{\beta\beta} = 3356.097 \pm 0.086\ \text{keV}$$

(7.1 keV higher than AME2012)

$$Q_{\beta} = 163.96 \pm 0.13\ \text{keV}$$

$$Q_{\beta} = 3192.05 \pm 0.16\ \text{keV}$$



The measured single β^- and $\beta^-\beta^-$ decay Q-values of the A=96 triplet

M. Alanssari et al., PRL 116 (2016) 072501

Next: need $T_{1/2}$ of single β decay

$$T_{1/2}(\mathrm{QRPA}) = \frac{24}{g_A^2} \times 10^{19}\ \mathrm{yr}$$

$$T_{1/2}(\mathrm{SM}) = \frac{11}{g_A^2} \times 10^{19}\ \mathrm{yr}$$

$$T_{1/2}(\exp) > 2.3 \times 10^{19}\ \mathrm{yr}$$

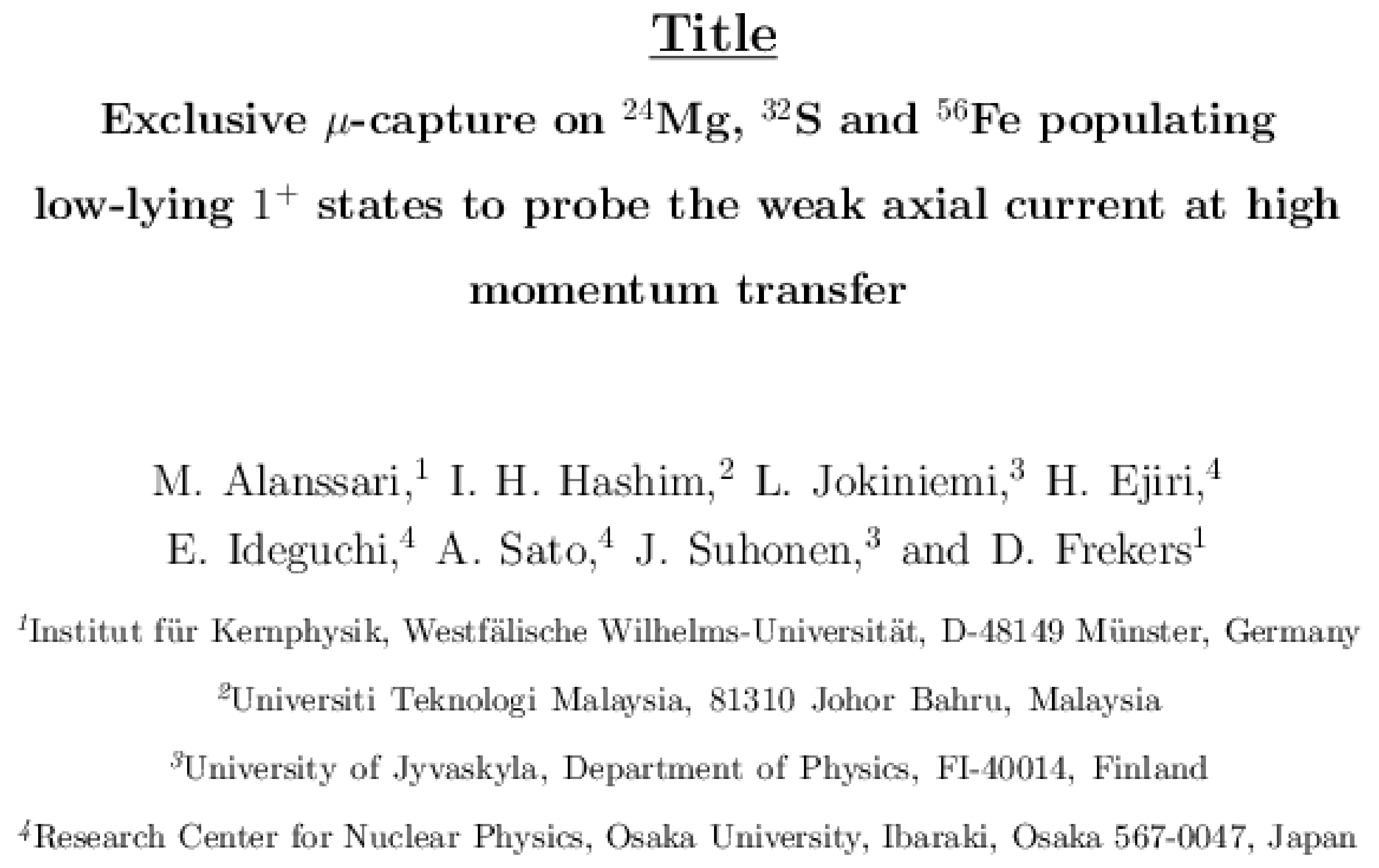
Important side effect:

single β decay depends on g_A^2

$2\nu/0\nu\beta\beta$ decay depends on g_A^4

A measurements of single β decay gives experimental handle on the quenching of g_A

The muon capture and g_A in weak decays



Title

Exclusive μ-capture on ^{24}Mg, ^{32}S and ^{56}Fe populating low-lying 1^+ states to probe the weak axial current at high momentum transfer

M. Alanssari,[1] I. H. Hashim,[2] L. Jokiniemi,[3] H. Ejiri,[4]
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[3]University of Jyvaskyla, Department of Physics, FI-40014, Finland

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The amazing muon

There has not been any other elementary particle so „successful“ in advancing our knowledge in so many different areas of physics.

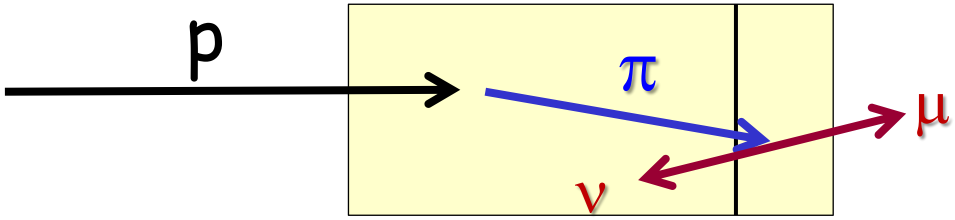
Production: $p + A \rightarrow X + \pi^-$

$(26\mathrm{ns}) \quad \hookrightarrow \mu^- + \bar{\nu}_\mu$

$(2.2\mu\mathrm{s}) \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

$E_{proton} \sim 500$ MeV

Surface muons: produced from stopped (usually negative) pions at end of target



$E_\mu \sim 4.1$ MeV

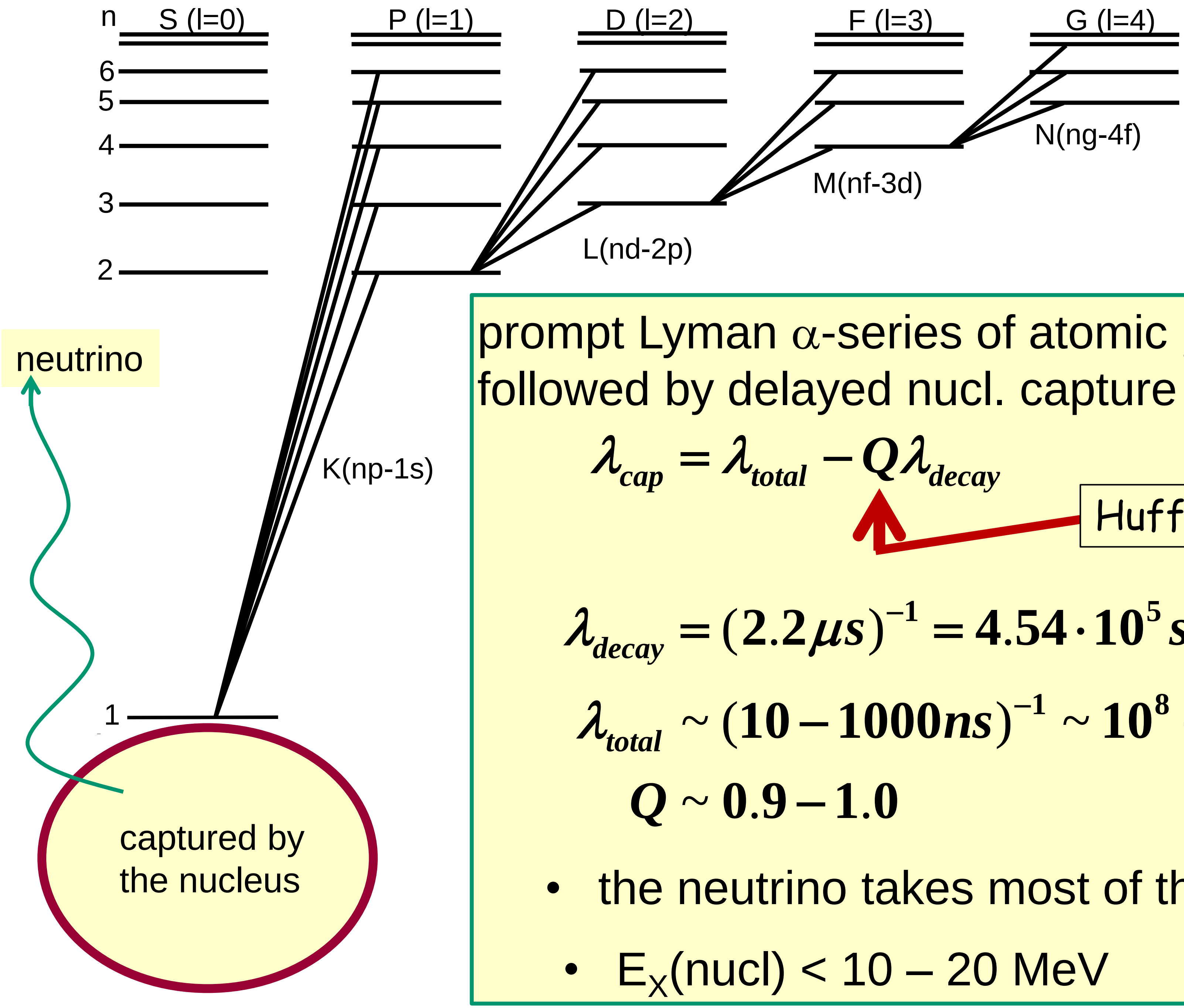
$q_\mu \sim 30$ MeV/c

Life-time:

$$\Gamma_\mu = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1-\varepsilon) = (2{,}196981(2)\ \mu\mathrm{sec})^{-1} \quad (\varepsilon \approx 10^{-3})$$

$$G_F = 1{,}16637(2) \cdot 10^{-5} GeV^{-2} \qquad m_\mu = 105.6583745\left(24\right)\ MeV$$

Muonium: $\mu^+ + e^-$ **an exotic hydrogen** I ~ 13.6 eV



prompt Lyman α-series of atomic μ-capture followed by delayed nucl. capture

$$\lambda_{cap} = \lambda_{total} - Q\lambda_{decay}$$

Huff-factor

$$\lambda_{decay} = (2.2\mu s)^{-1} = 4.54 \cdot 10^{5}\, s^{-1}$$

$$\lambda_{total} \sim (10 - 1000ns)^{-1} \sim 10^{8} - 10^{6}\, s^{-1}$$

$$Q \sim 0.9 - 1.0$$

- the neutrino takes most of the energy
- E_X(nucl) < 10 – 20 MeV

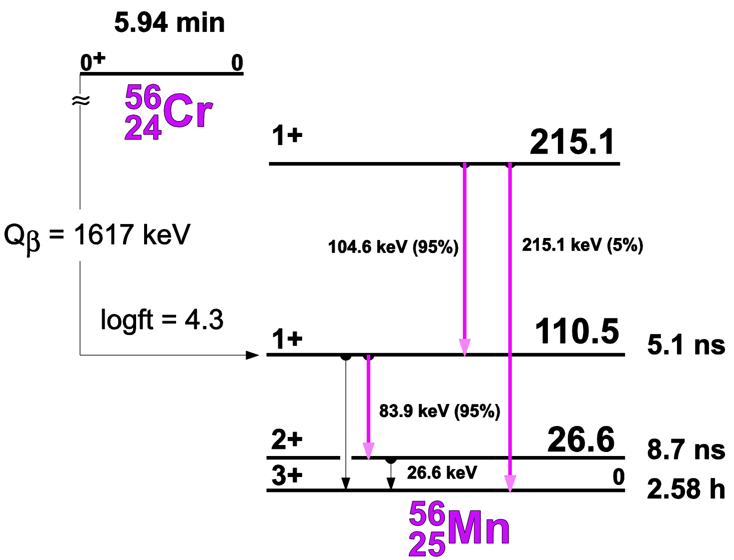
Motivations

- μ-cap features momentum transfers similar to $0\nu\beta\beta$ decay (q_{tr} ~0.5fm^{-1} ~100MeV/c)
- μ-cap processes to 1^+ states in $A(\mu^-,\nu)B$ may be compared with charge-ex reactions of (n,p) type.
- μ-cap may give access to g_A quenching issue

However

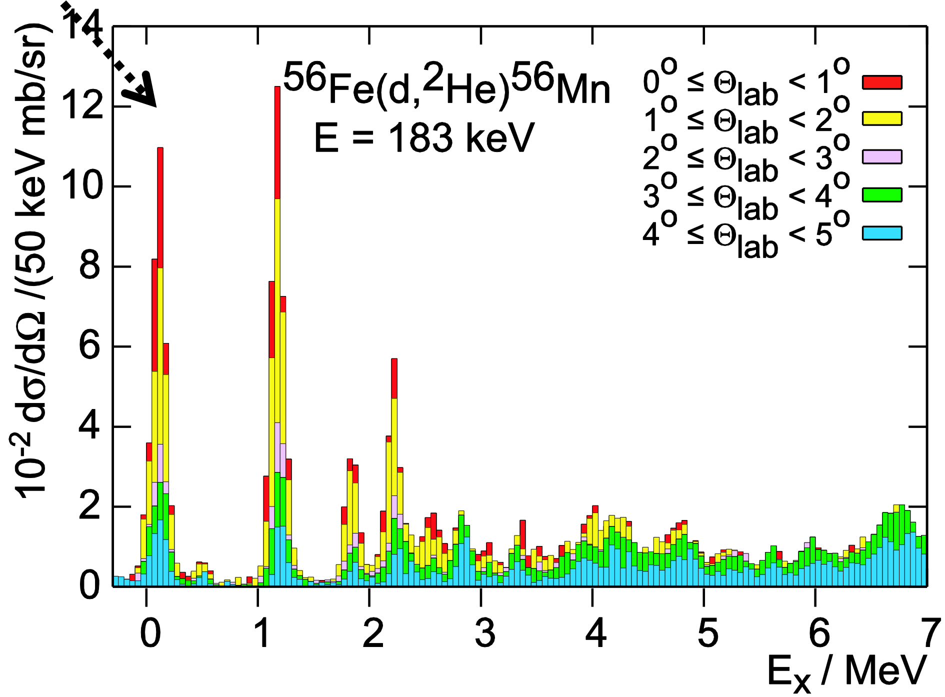
- only the 0n-channel (~5%) is most relevant for $0\nu\beta\beta$ decay
- level scheme of final odd-odd nucleus is extremely!! poorly known

The issue of g_A queching



^{56}Fe(μ,ν_μ)^{56}Mn, (0 n)

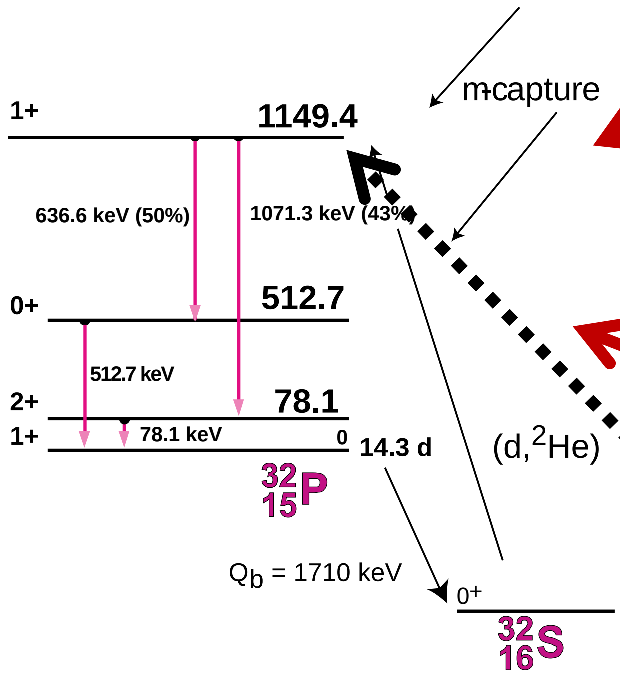
^{56}Fe(d,^{2}He)^{56}Mn



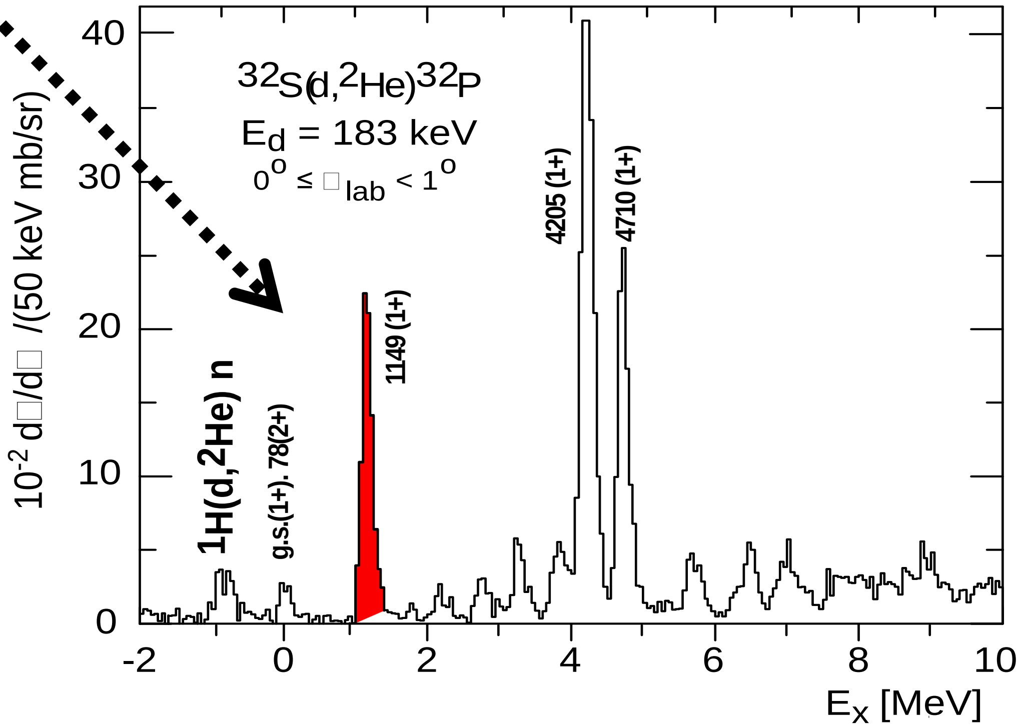
Example:
Compare transition strength in μ-cap and (d,^{2}He) charge-ex

The issue of g_A queching

$^{32}S(\mu,\nu_\mu)^{32}P$, (0 n)



$^{32}S(d,^2He)^{32}P$

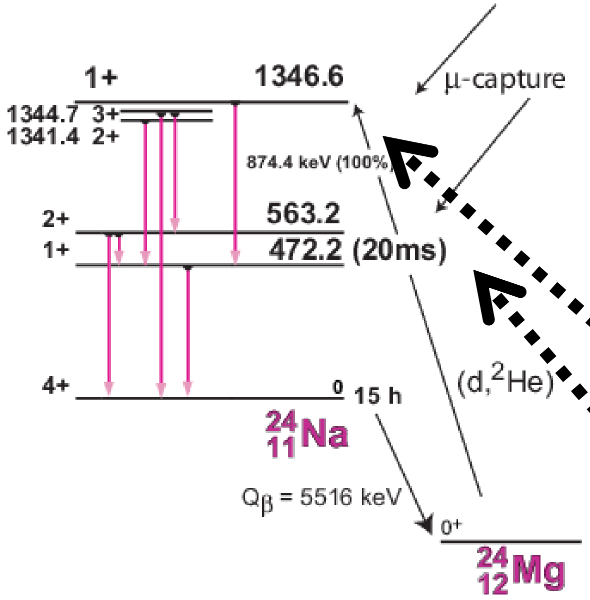


Example:

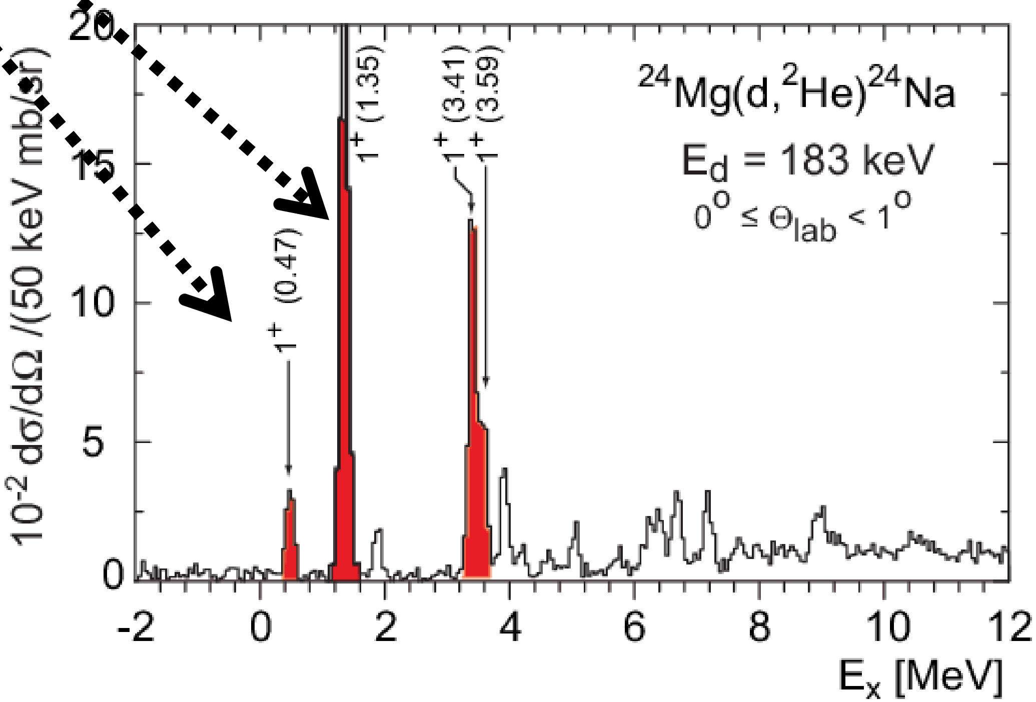
Compare transition strength in μ-cap and (d,^{2}He) charge-ex

The issue of g_A queching

^{24}Mg(μ,ν_μ)^{24}Na, (0 n)

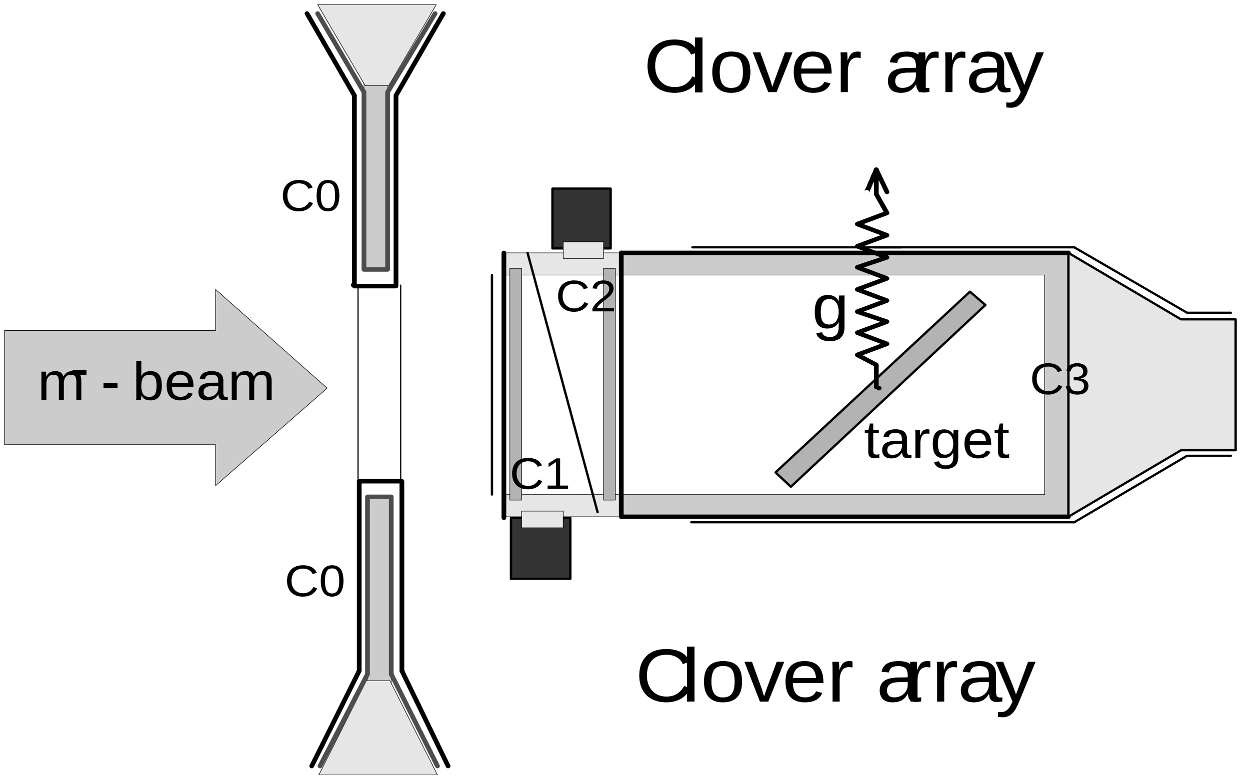


^{24}Mg(d,^{2}He)^{24}Na



Example:
Compare transition strength in μ-cap and (d,^{2}He) charge-ex

Schematics of set-up

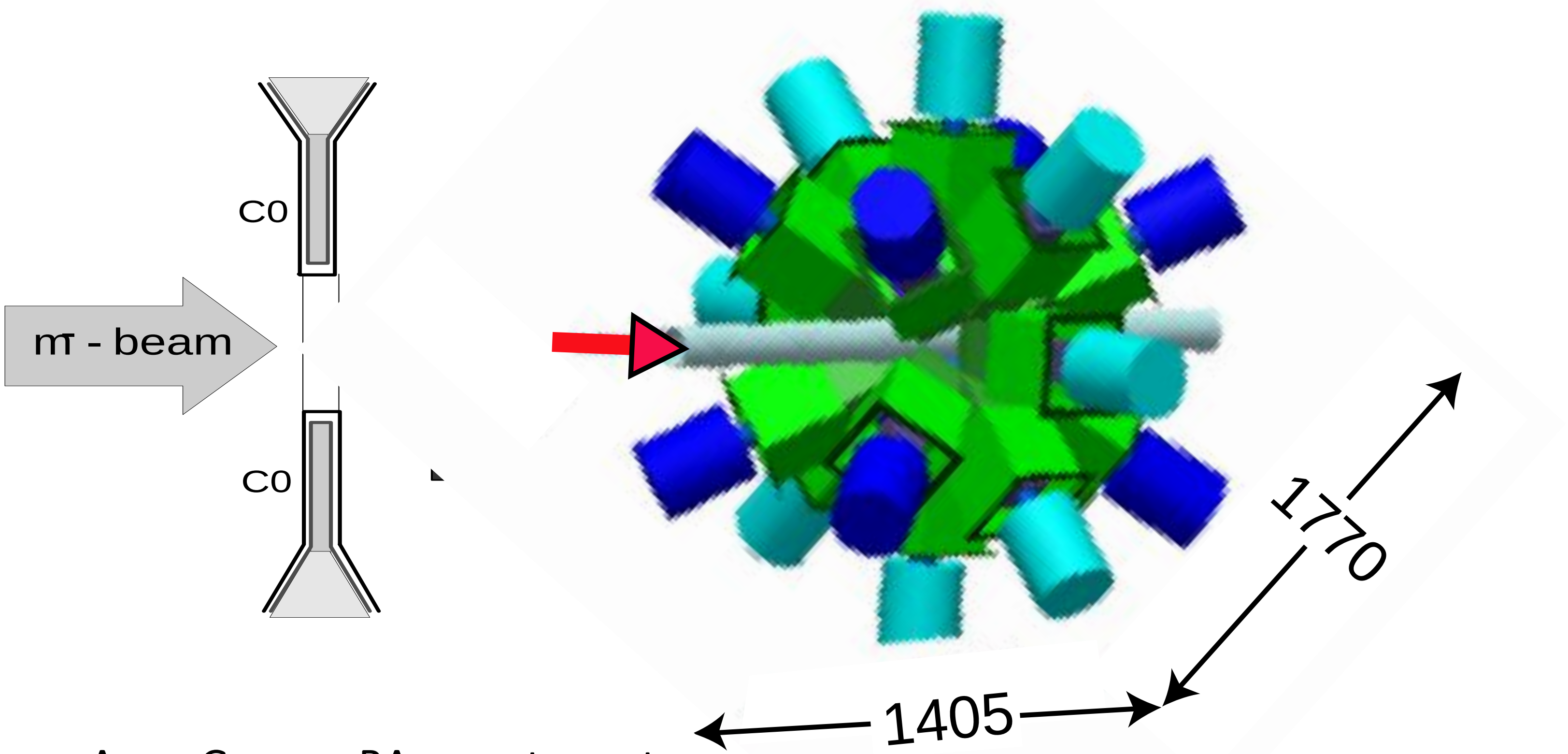


$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3}$$

# of μ–stop = 8 – 25 x 10^3 with 20 – 30 MeV/c

target can be used for solids and gas

Schematics of set-up muon beam line facility "MuSIC" + "CAGRA" at RCNP Osaka



CAGRA = Clover Array Gamma RAy spectrometer
MuSIC = MUon Science Innovative muon beam Channel

The issue of g_A queching

But: things are a bit more complicated

there is a pseudo-scalar coupling effective in μ-capture with a constant g_P (also badly known !!)

What is this ????

Inside the nucleus the muon can decay back into a virtual pion (lots of energy available!!), and the pion generates a final state imprinting it with the parity of the pion. $(P(\pi) = -1)$

The effect depends on how many protons there are.

^{24}Mg → 12 protons

^{32}S → 16 protons

^{56}Fe → 26 protons

Conclusion

- **Precision mass measurement:**

^{96}Zr →golden case for testing NME's of $0\nu\beta\beta$ decay gives handle on g_A for a unique forbidden decay

- **μ-capture**

maybe the only viable tool to study weak response at high momentum transfer ($0\nu\beta\beta$ decay) and to fix the g_A problem by comparing with (d,^{2}He)

Thank you

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