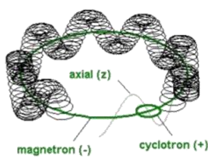
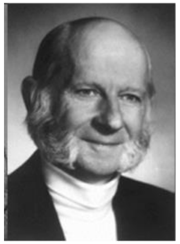
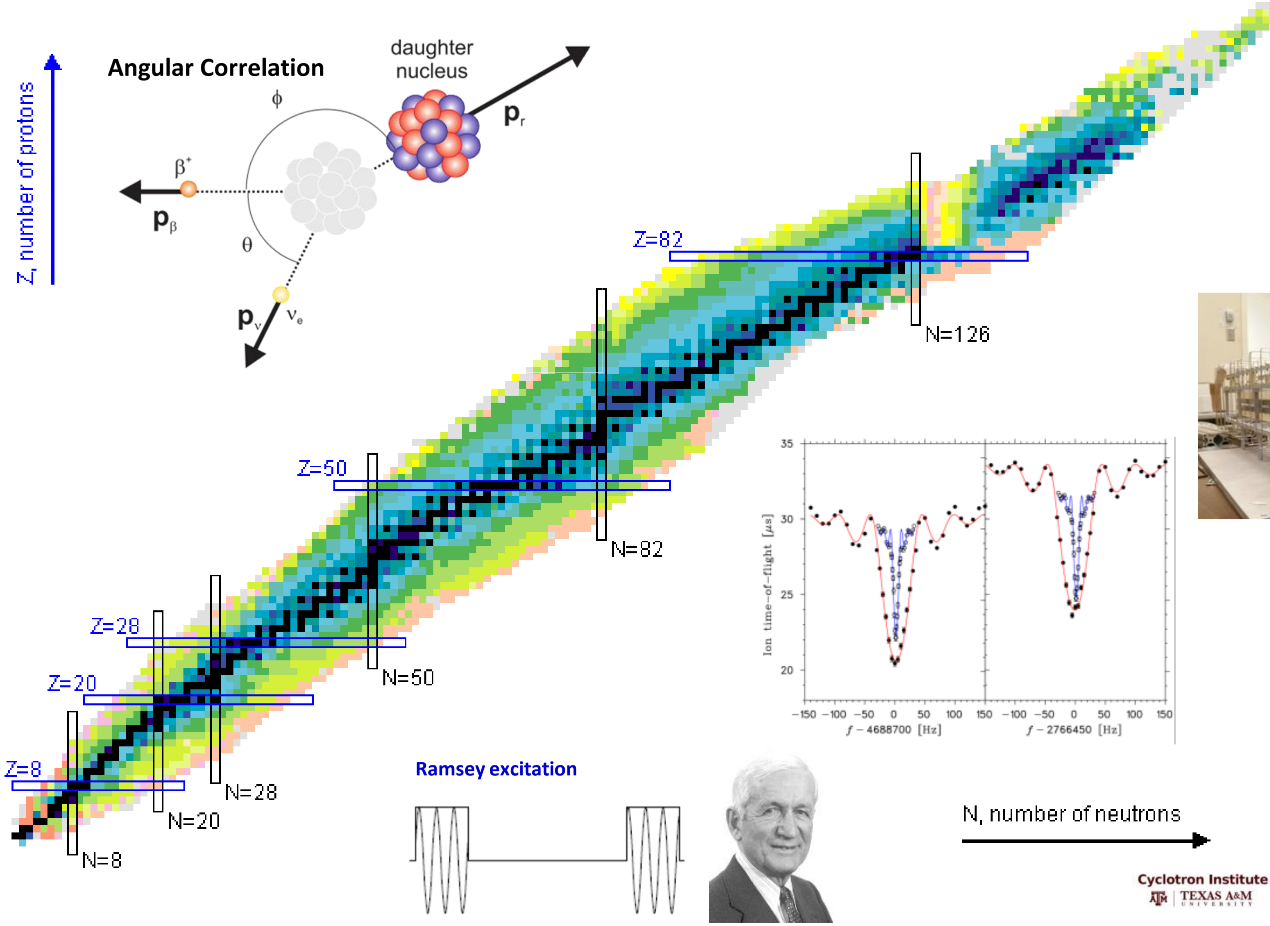
Ion Trap Application:
Fundamental weak interaction studies using ion traps

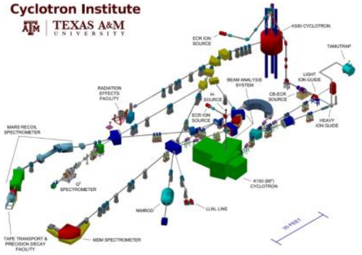



H. G. Dehmelt



N. F. Ramsey


W. Paul



Cyclotron Institute
TEXAS A&M UNIVERSITY

P.D. Shidling

Outline

- Ion traps in Nuclear Physics
  - Mass Measurement
  - Angular correlation measurements
  - Results
  - Ion trap facilities

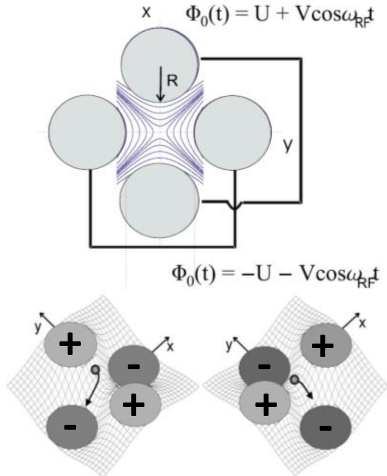
- Research Program at Cyclotron Institute Texas A&M University (TAMU) using Ion trap
  - Physics Program

Types of Ion Traps used in Nuclear Physics

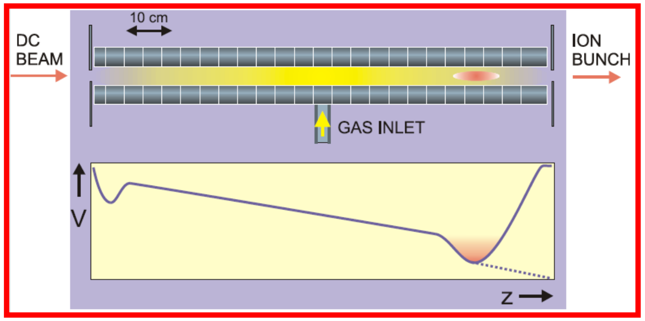
Paul Trap: Electrodynamic Field

Hyperbolic Paul Trap

RF field yields pseudopotential



Linear Paul Trap

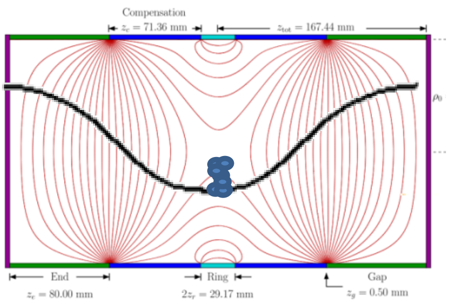


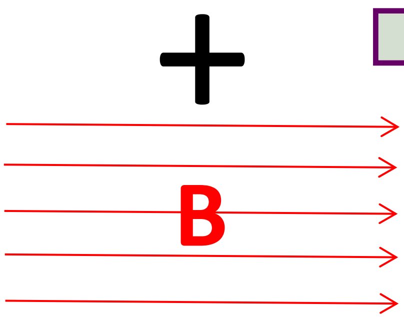
Suited for Ion manipulation : Cooling and Bunching, retardation, ion optical properties

Penning Trap

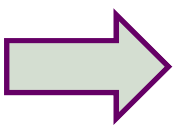
Penning Trap: **Static Electrostatic quadrupole field + Magnetic Field**

$$\sum \vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

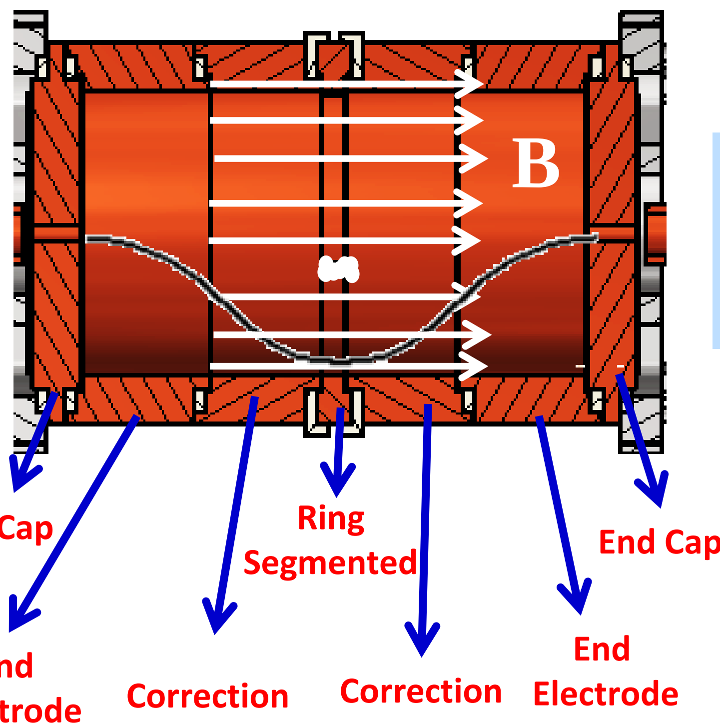




Homogenous uniform magnetic field ~ 3ppm



Cylindrical Penning Trap



Cyclotron frequency:

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

Precision

$$\frac{\delta m}{m} \propto \frac{m}{qBT_{\mathrm{rf}}\sqrt{N_{ion}}}$$

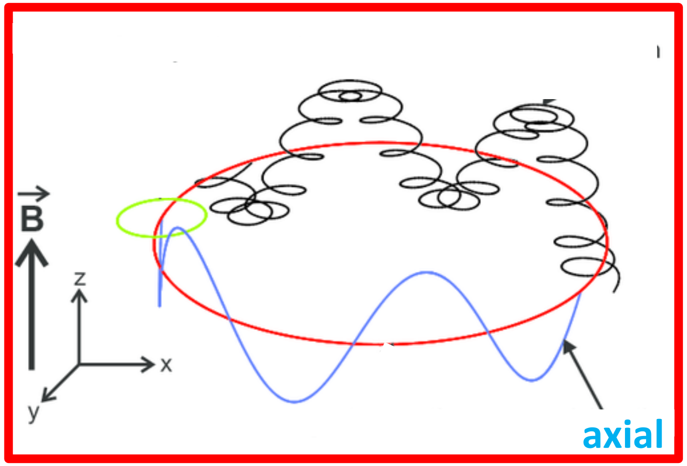
Ion motion in Penning trap

Three characteristic harmonic motions:

Ion motion in Penning trap

Three characteristic harmonic motions:

(a) axial motion (f_z)



Axial motion

$$f_z = \sqrt{\frac{eU}{4\pi^2 m d^2}}$$

Ion motion in Penning trap

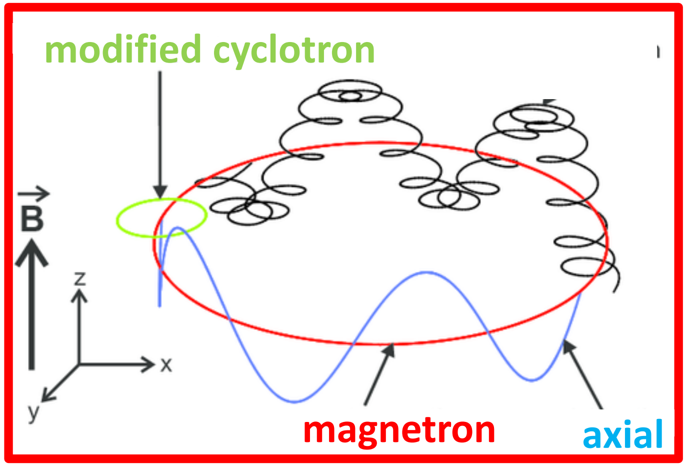
Three characteristic harmonic motions:

(a) axial motion (f_z)

(b) magnetron motion (f_-)

(c) modified cyclotron motion (f_+)

} Radial motion



Axial motion

$$f_z = \sqrt{\frac{eU}{4\pi^2 md^2}}$$

Radial motion

$$f_- = \frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} - \frac{f_z^2}{2}}$$

$$f_+ = \frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} - \frac{f_z^2}{2}}$$

Ion motion in Penning trap

Three characteristic harmonic motions:

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(b) magnetron motion (f_-)

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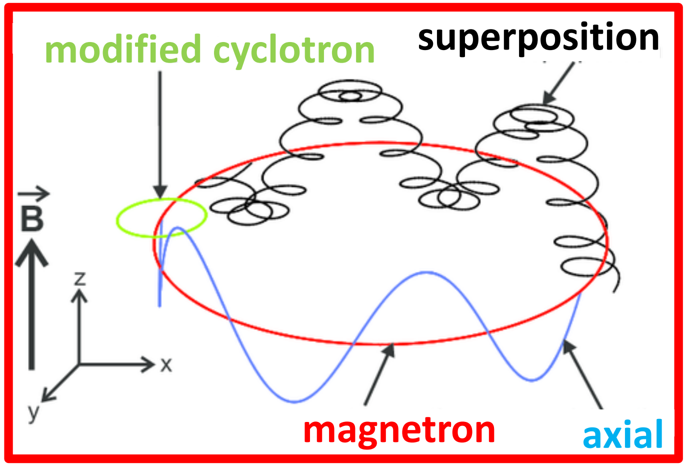


Axial motion

$$f_z = \sqrt{\frac{eU}{4\pi^2 m d^2}}$$

Radial motion

$$f_- = \frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} - \frac{f_z^2}{2}}$$

$$f_+ = \frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} - \frac{f_z^2}{2}}$$

Sideband excitation:

$$f_- + f_+ = f_c$$

Cyclotron frequency:

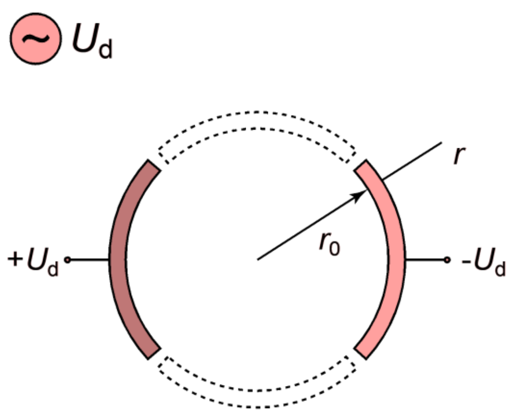
$$f_c = \frac{1}{2\pi}\frac{q}{m}B$$

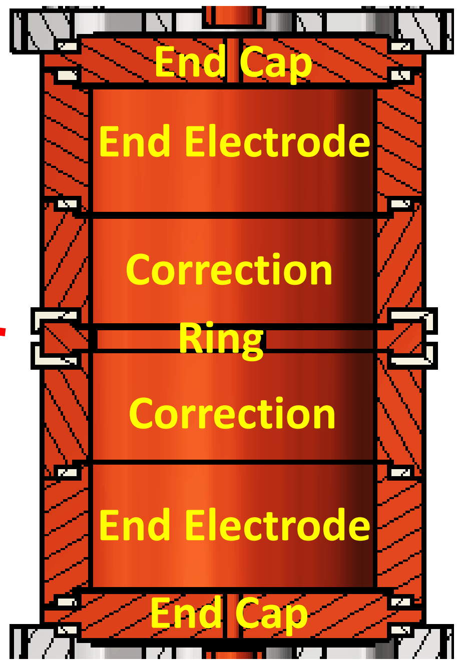
Mass measurement

Coupling Radial motions

Dipolar radial excitation at f_-

$\Rightarrow$ increase of r_-





Mass measurement

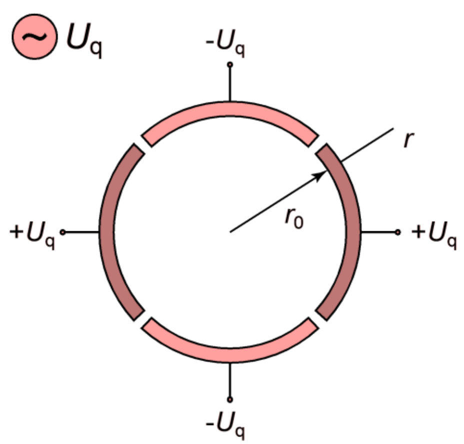
Coupling Radial motions

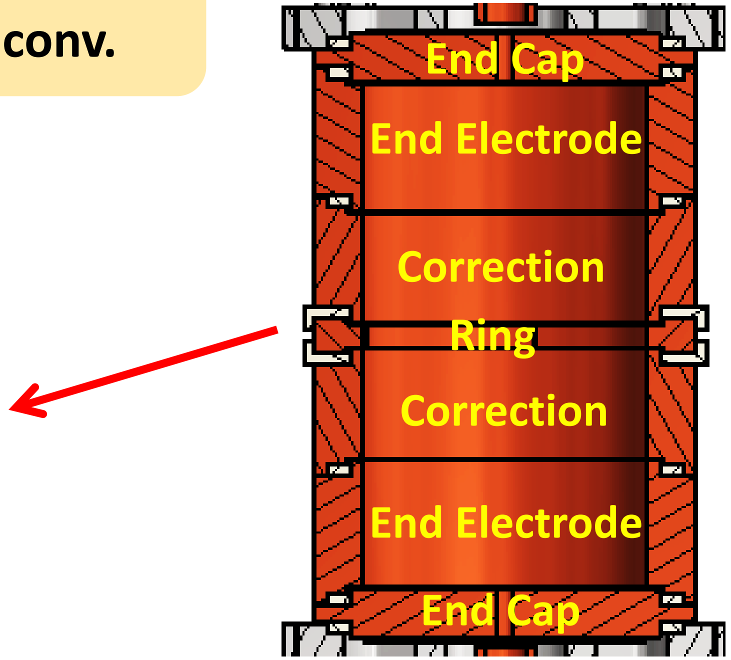
Dipolar radial excitation at f_-

$\Rightarrow$ increase of r_-

Quadrupolar radial excitation near f_c

$\Rightarrow$ coupling of radial motions, conv.





Mass measurement

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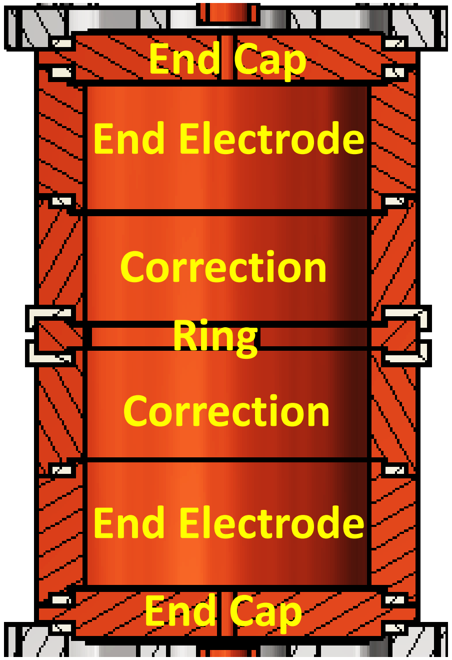
Quadrupolar radial excitation near f_c

$\Rightarrow$ coupling of radial motions, conv.

Ejection along the magnetic field lines

$\Rightarrow$ radial energy converted to axial energy



Mass measurement

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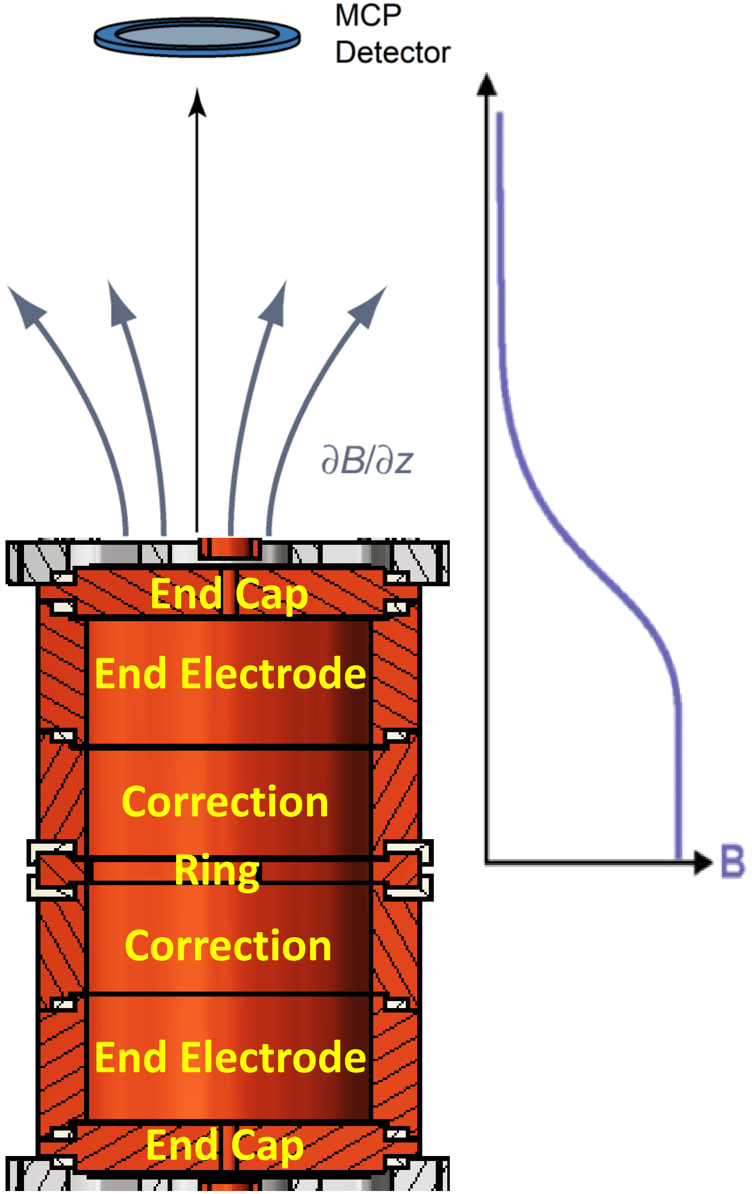
TOF Resonance Technique



Mass measurement

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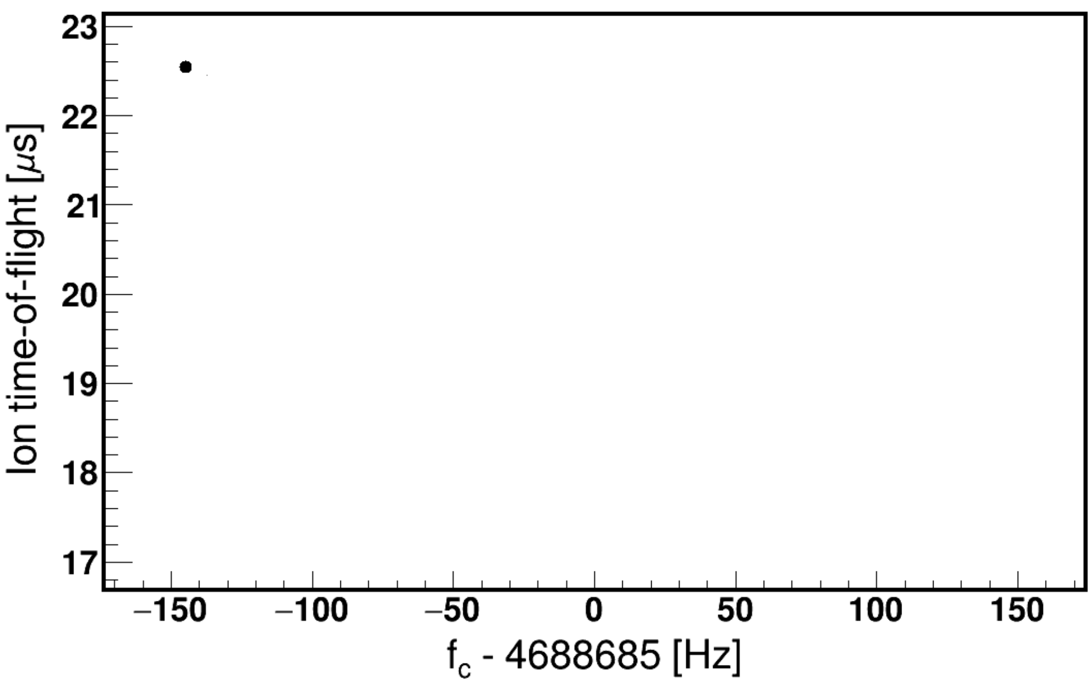

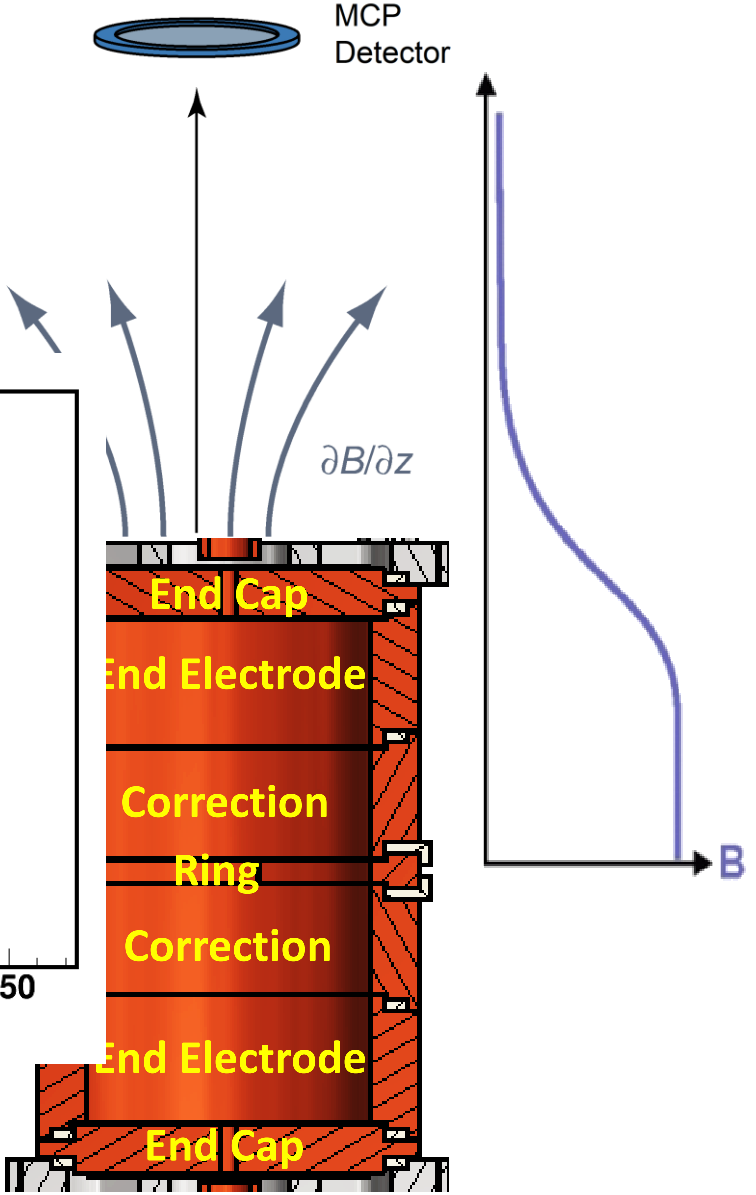

TOF Resonance Technique

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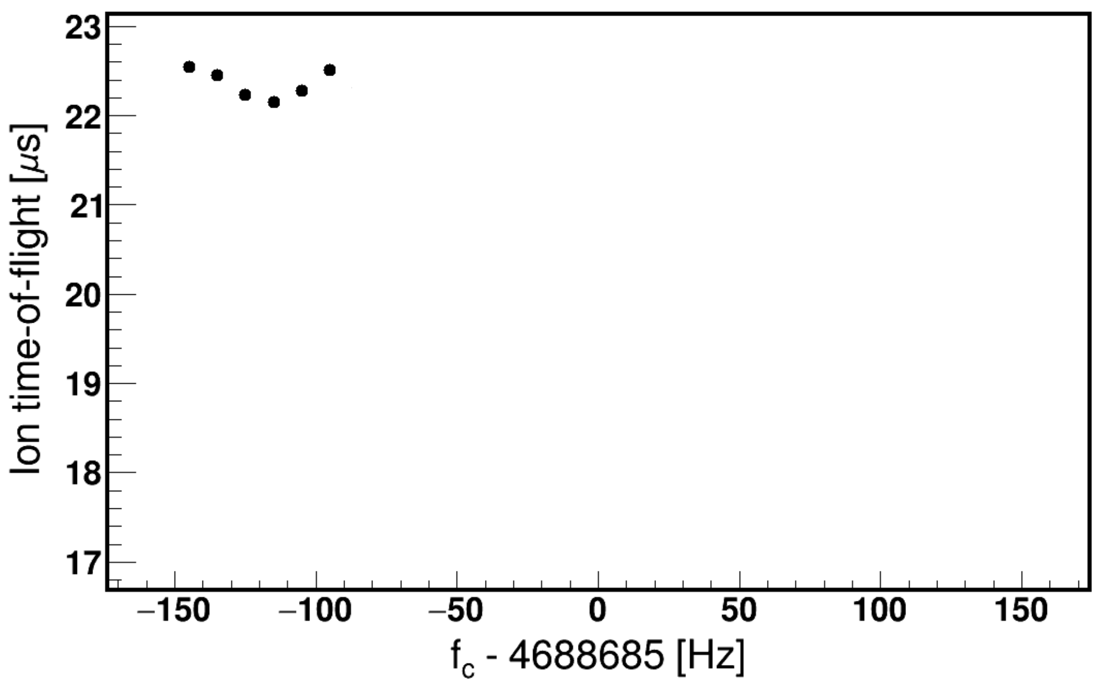

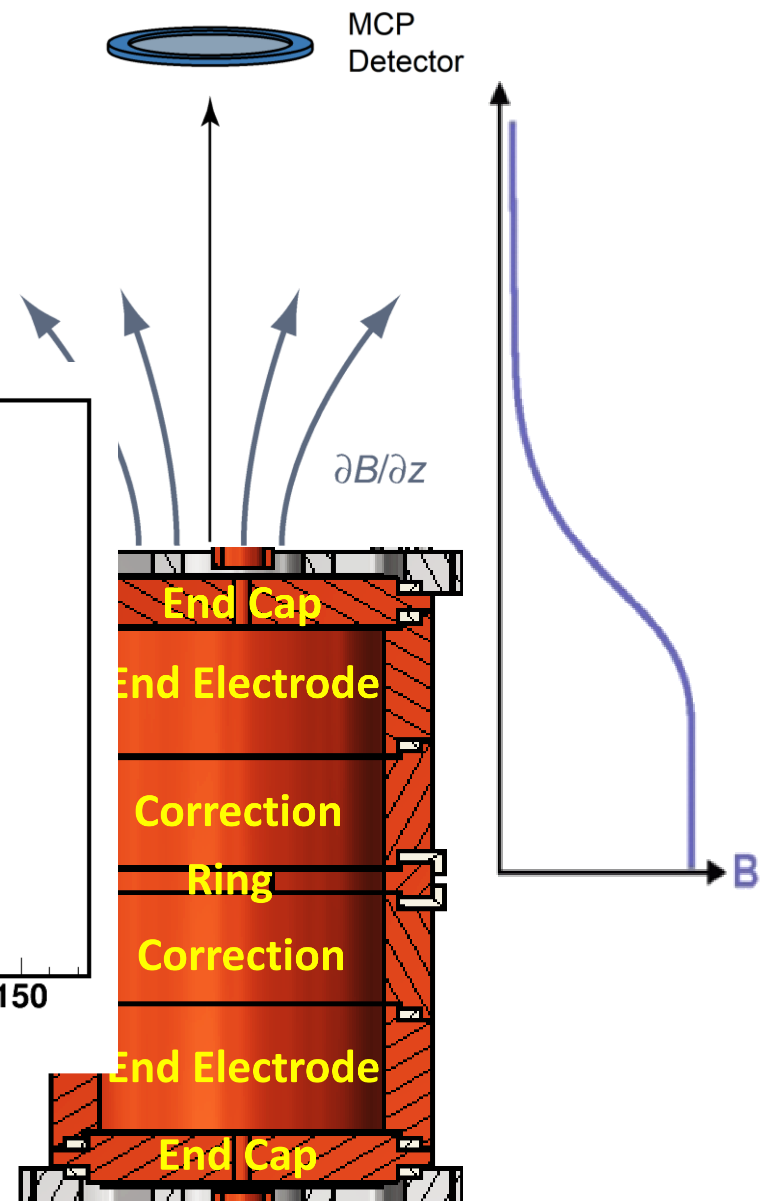

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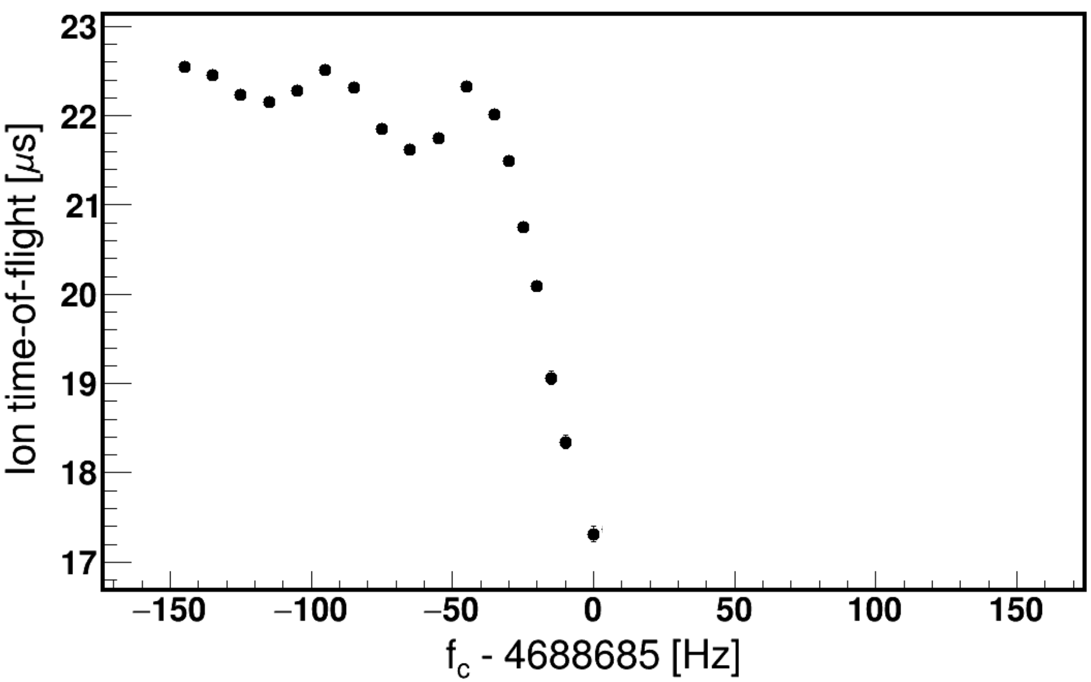

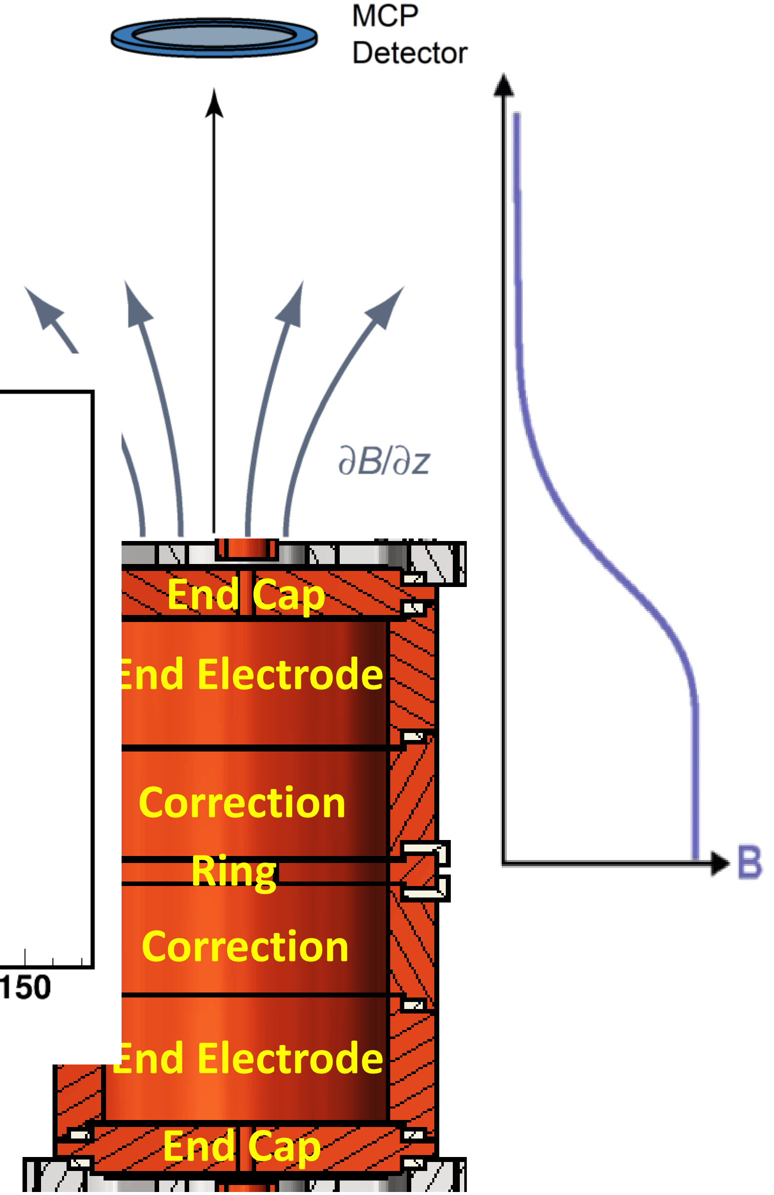

TOF Resonance Technique

Mass measurement

Coupling Radial motions

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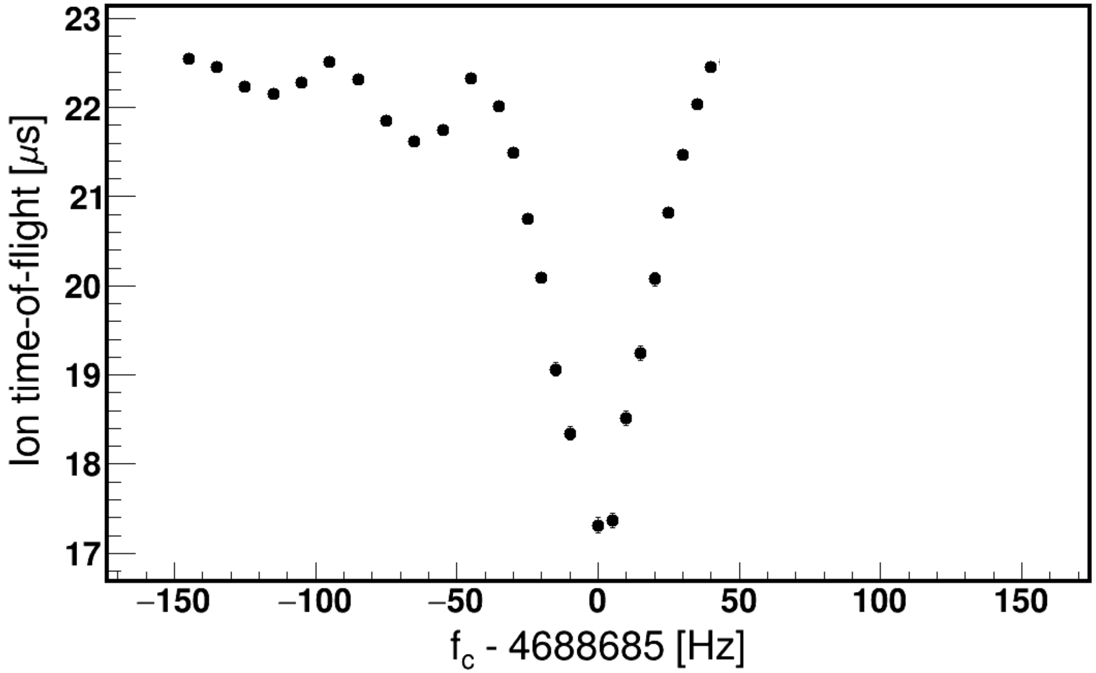
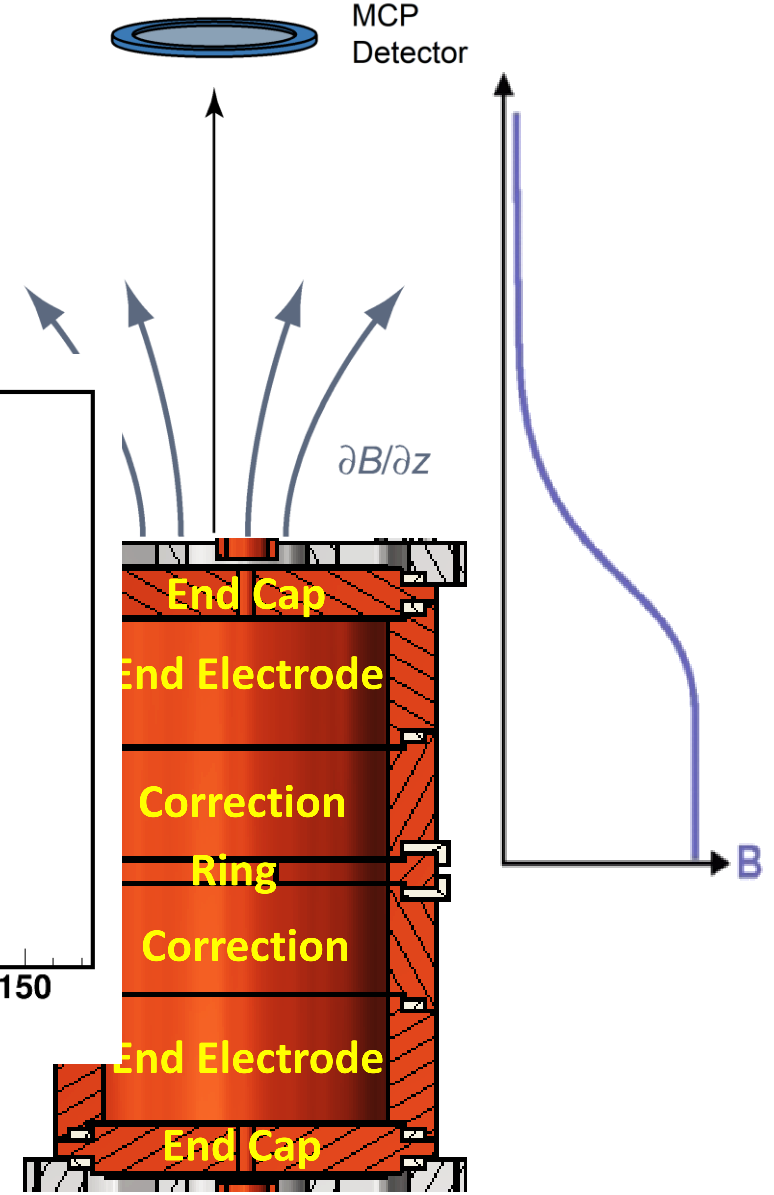


TOF Resonance Technique



Mass measurement

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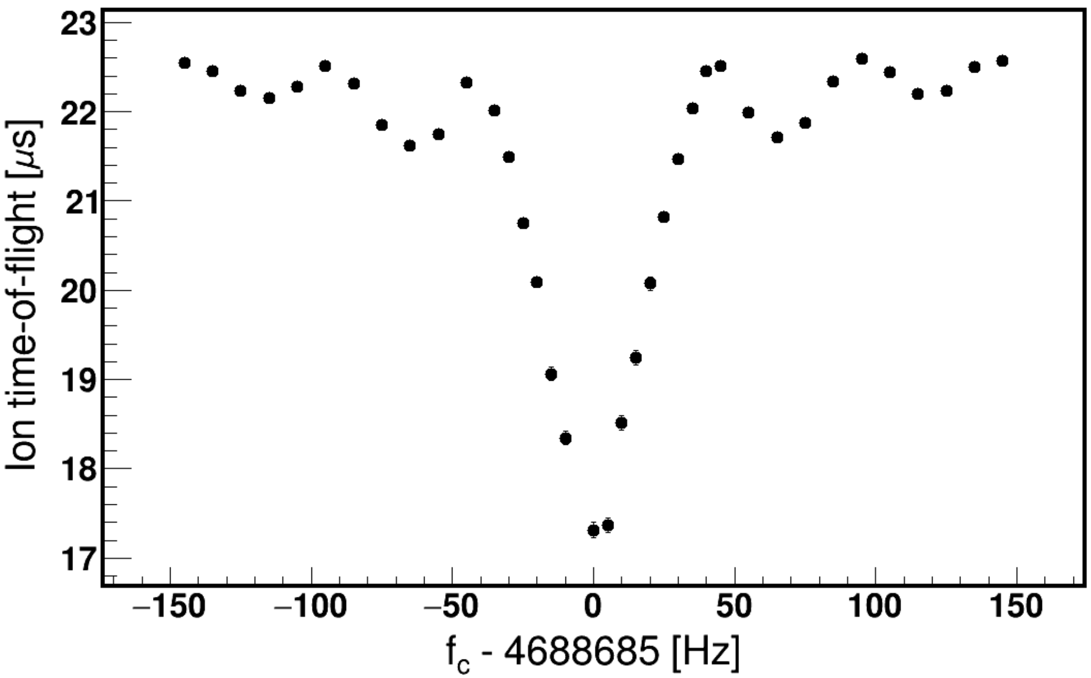
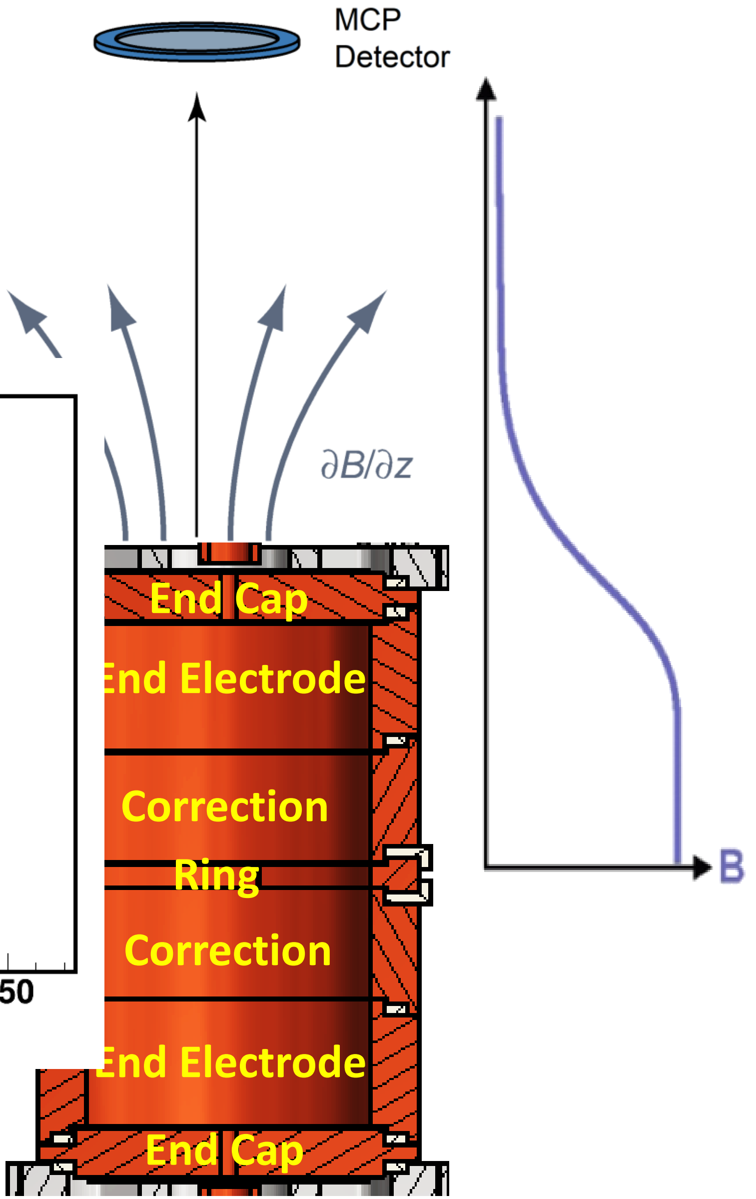
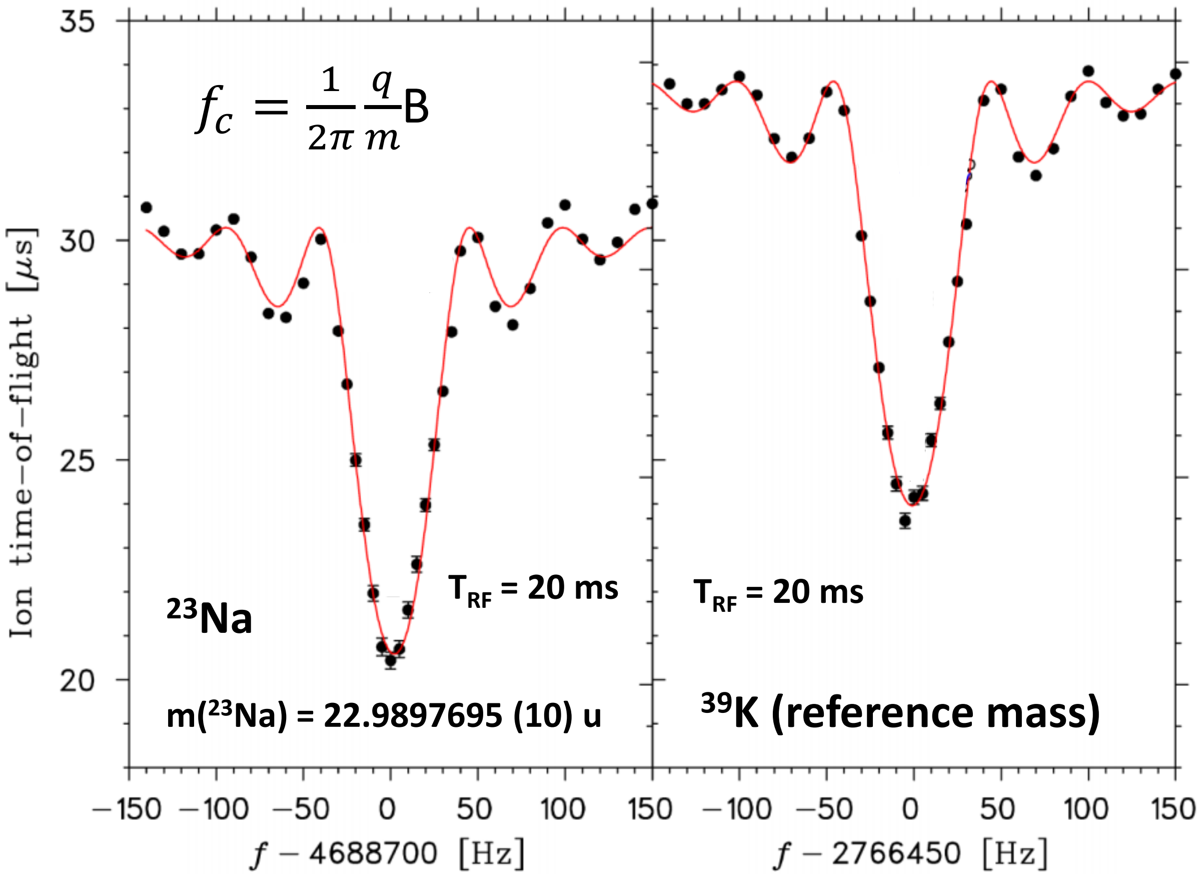


TOF Resonance Technique



TOF as a function of the excitation frequency

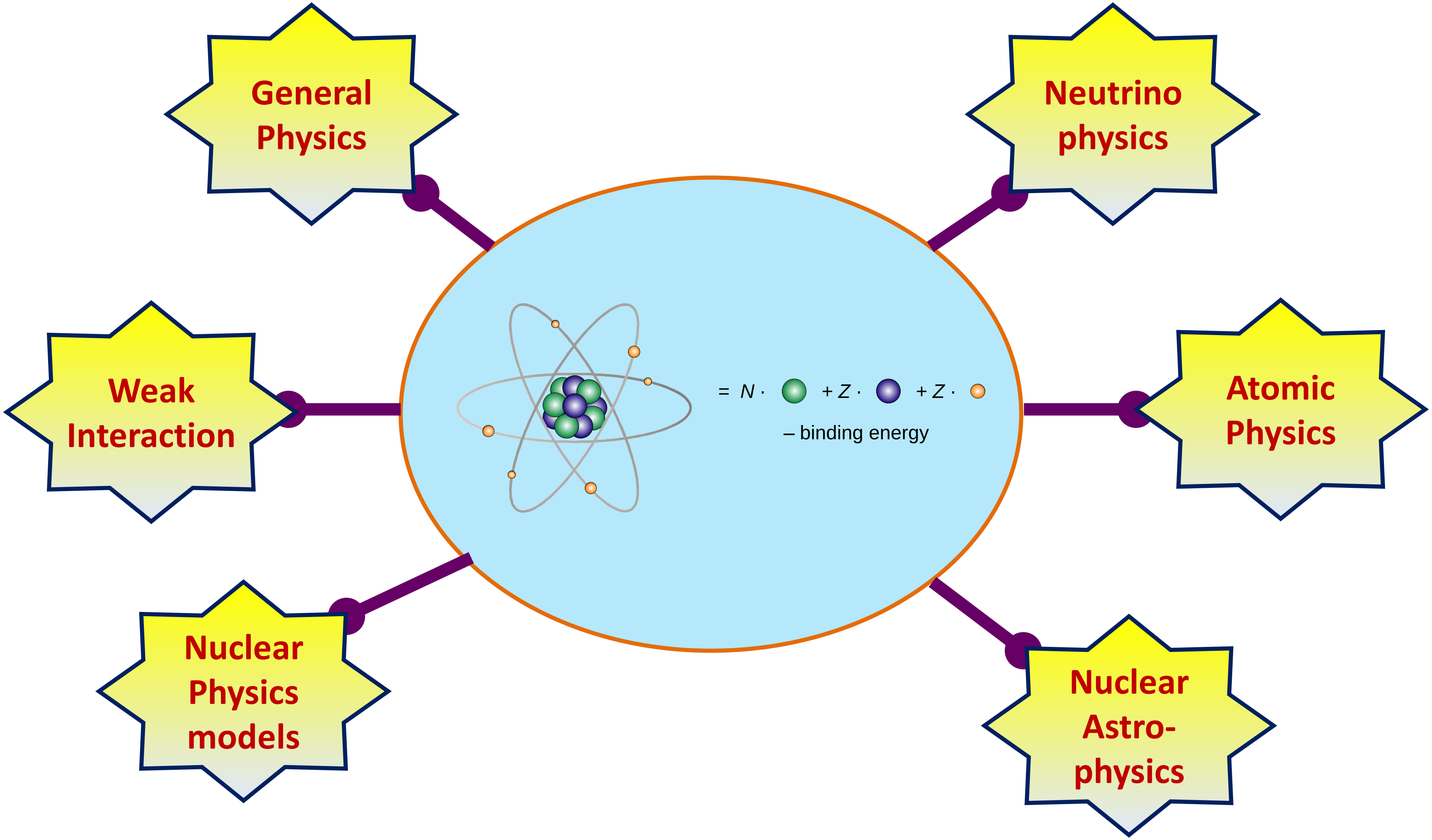


Atomic mass from frequency ratio:

$$m = (m_{ref})\left(\frac{f_c^{ref}}{f_c}(m_{ref} - m_e)\right) + m_e$$

Ion trap worldwide for Nuclear Physics studies

Importance of Atomic mass



Importance of Atomic mass

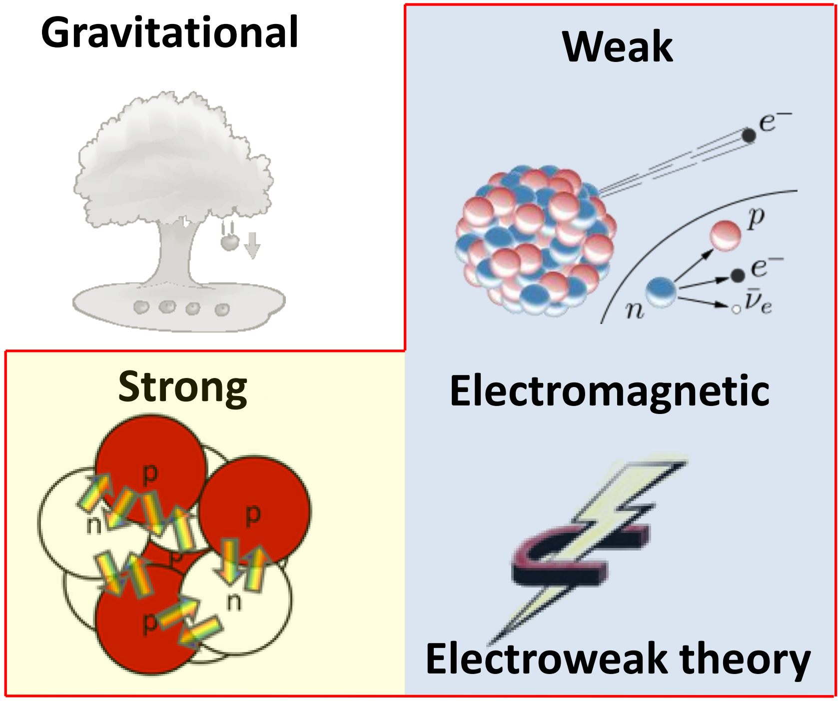
Fields	Precision
Astrophysics: r-process, rp-process, waiting points	10^{-7}
Nuclear models and formulas, Nuclear fine structure: deformation , halo nuclei	$10^{-7} – 10^{-8}$
Weak Interaction studies: CVC Theory, CKM Unitarity	10^{-8}
Neutrino physics: Q-value	10^{-9}
Fundamental constants, CPT	$\leq 10^{-10}$
Atomic physics: binding energies, QED	$10^{-9} – 10^{-11}$

Weak

Atomic Physics

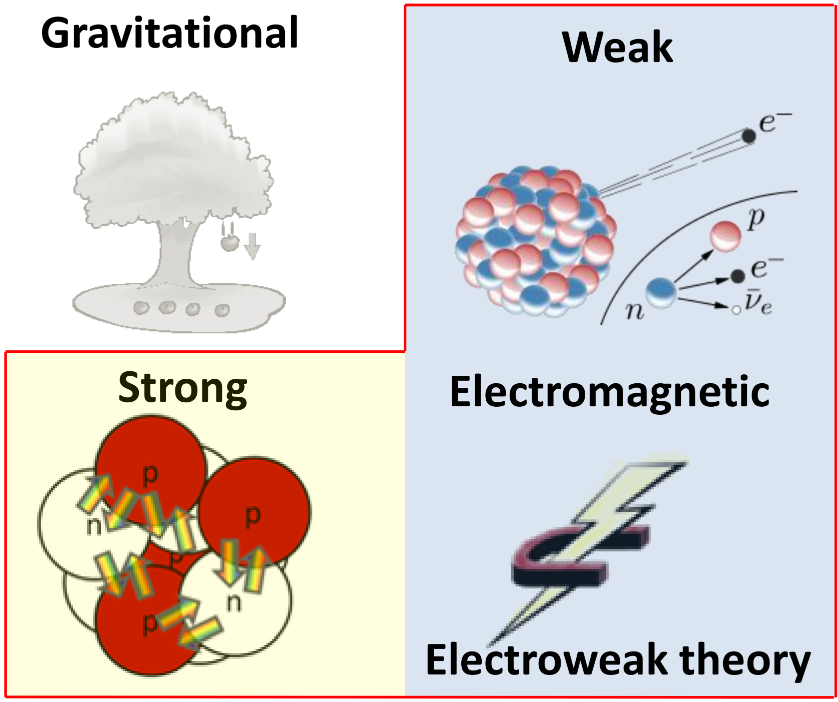
physics

Standard Model



- 3 Fundamental forces
  Electromagnetic, Weak, Strong
- 12 Fundamental Fermions
  Quarks (u, d, c, s, t, b)
  Leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$
- Force carriers (Gauge Bosons)
  (g, γ, Z, W)
- Scalar Bosons (Higgs)
  $(H, \ldots)$

Standard Model



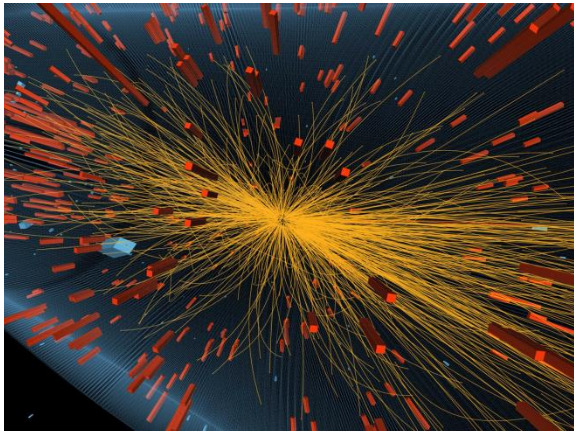
- **3 Fundamental forces**
  Electromagnetic, Weak, Strong
- **12 Fundamental Fermions**
  Quarks (u, d, c, s, t, b)
  Leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$
- **Force carriers (Gauge Bosons)**
  (g, γ, Z, W)
- **Scalar Bosons (Higgs)**
  $(H, \ldots)$

Standard Model
may require extension

- why three families of Fermions
- Origin of parity violation
- Dark matters
- Number of parameters of theory
- . . . .

Test of Standard Model

High energy collider experiment



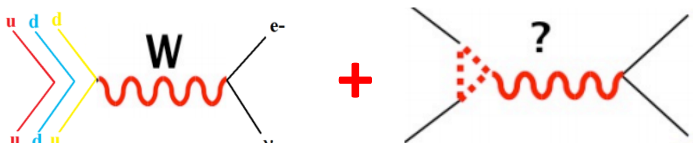
Direct observation of New particles

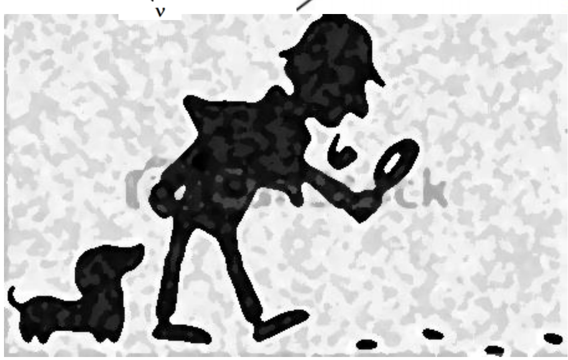
Test of Standard Model

Search for “deviations/traces”

Nuclear β-decay = Governed by Weak Interaction

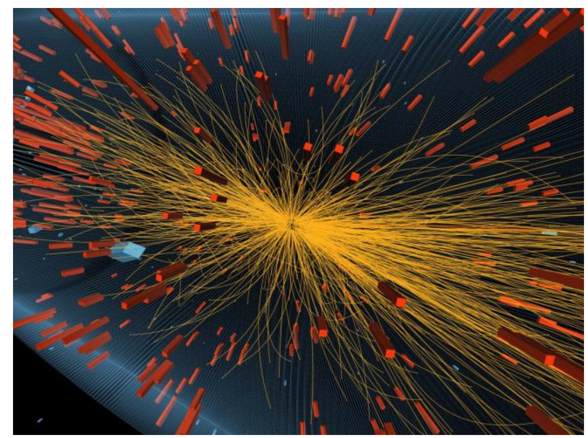
Standard Model Beyond Standard Model





Low energy precision experiments

High energy collider experiment



Direct observation of New particles

Low energy precision experiments in nuclear beta decay ⟹ **Tests of the under lying Fundamental Symmetries**

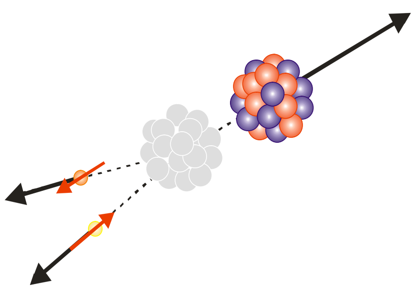
Nuclear Beta decay test of SM

- **Test of Conservation of Vector Current (CVC)**

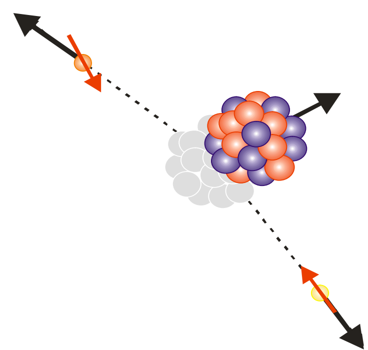
- **Test of unitarity of CKM Matrix**

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

- **Correlation experiments:**



Standard Model

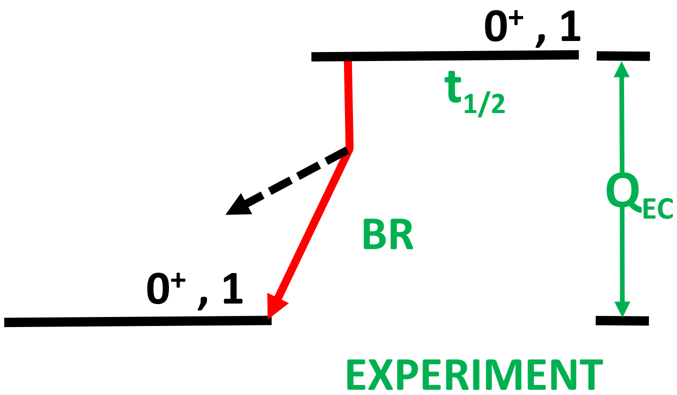


Physics beyond Standard Model

Test of Conserved Vector Current

Basic Weak Decay Equation

$$ft = \frac{K}{G_V^2 |M|^2}$$



f = statistical rate function : f(Z, Q_{EC})
t = partial half-life
G_V = vector coupling constant
|M|^2= Fermi matrix element

$$t = \ln 2\, \tau \left(\frac{1 + P_{EC}}{BR} \right)$$

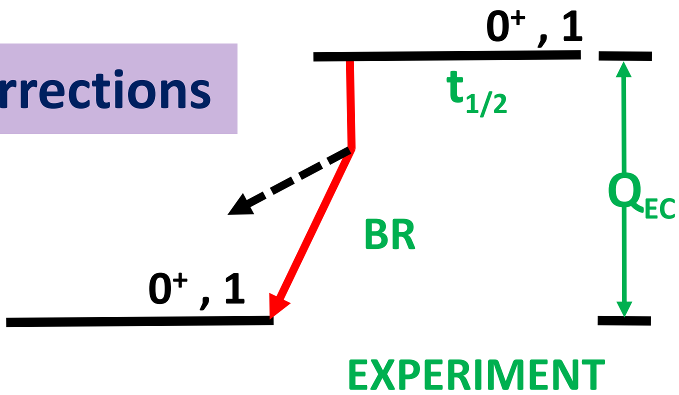
Q_{EC} - Decay Energy ⟺ mass m (Q^5 dependence;
goes into statistical rate calculation (f_V))

Test of Conserved Vector Current

Pure Fermi transitions

Theory corrections

$$\mathcal{F}t^{0^+\to 0^+} \equiv ft^{0^+\to 0^+}(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C) = \frac{K}{2\,G_F^2 V_{ud}^2 C_V^2 (1+\Delta^V_R)}$$



$$t = \ln 2\,\tau\left(\frac{1+\ P_{EC}}{BR}\right)$$

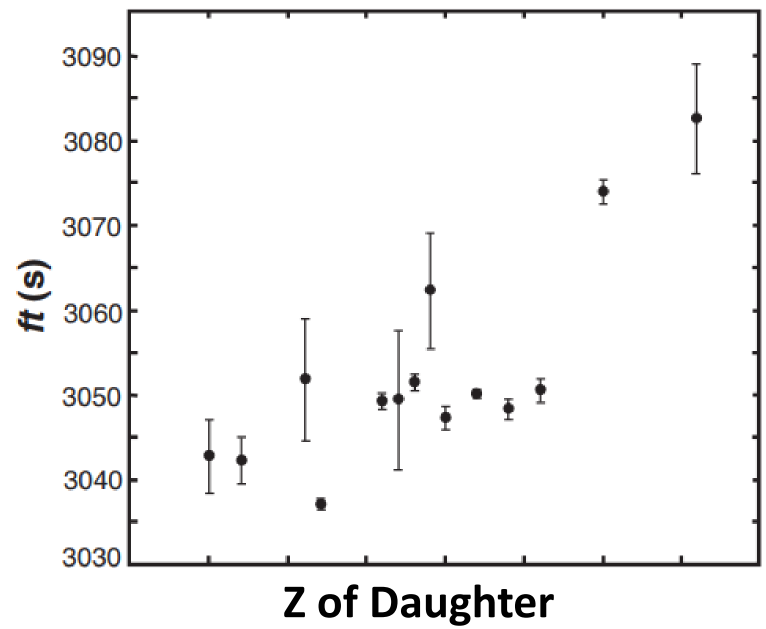
Q_{EC} - Decay Energy ⟺ mass m (Q^5 dependence; goes into statistical rate calculation (f_V))

δ'_R, δ^V_{NS}, Δ^V_R ⟹ Radiative Corrections

δ^V_C ⟹ Isospin symmetry breaking correction

Test of Conserved Vector Current

Measure ft **value for several nuclear β-decay with similar decay mode**
(Fermi transition)



Hardy & Towner, Phys. Rev. C **91** (2015) 025501

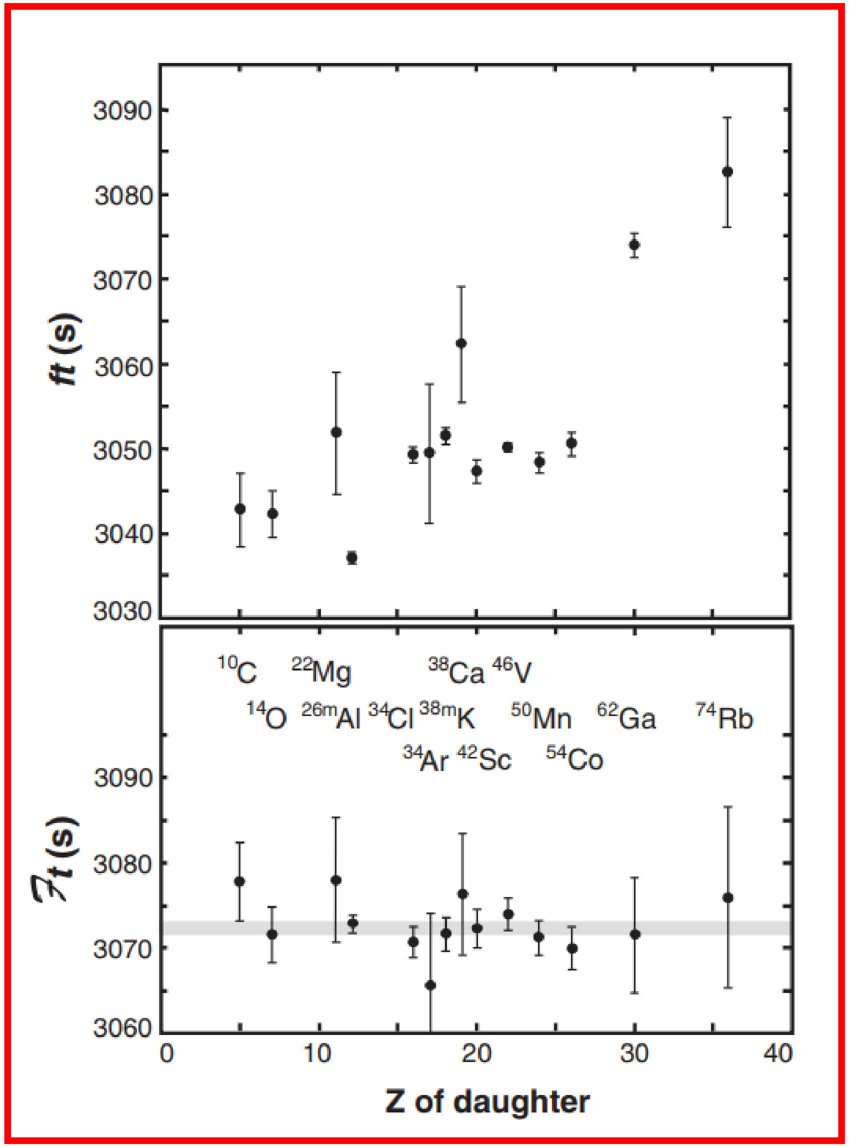
Test of Conserved Vector Current

Measure ft **value for several nuclear β-decay with similar decay mode**

(Fermi transition)

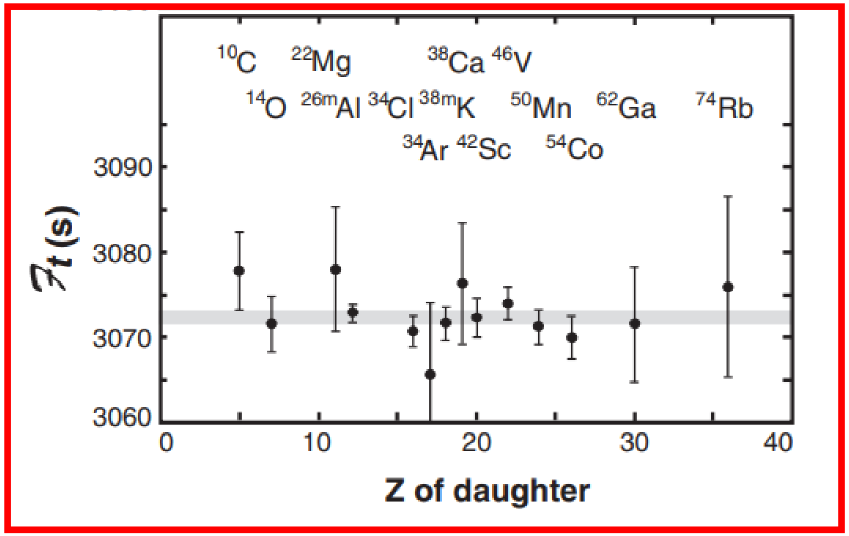
ft **value constant after theory corrections**

CVC Verified



Hardy & Towner, Phys. Rev. C **91** (2015) 025501

Test of Conserved Vector Current



Hardy & Towner, Phys. Rev. C **91** (2015) 025501

Studied for more than 30 years
Close to 300 measurements
Limited by theoretical corrections

$\mathcal{F}t$ = **3072.27 ± 0.72 s**

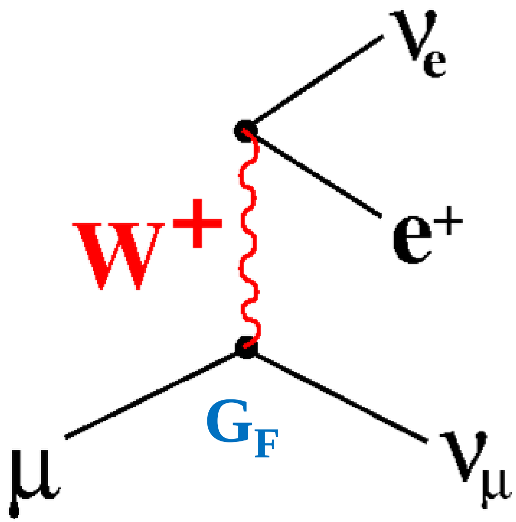
CVC Theory verified @ 0.023%

$\mathcal{F}t$ **values constant** →

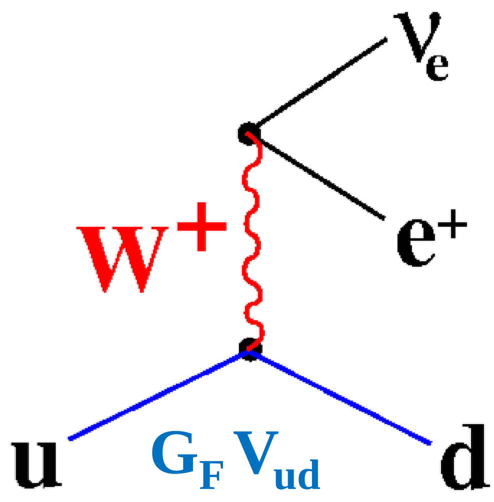
$$|V_{ud}| = \frac{G_V}{G_F}$$

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

Unitarity of CKM Matrix



Leptonic



Semi Leptonic

Cabbibo

Mass Eigen states $\neq$ Weak Eigen states
(u,d,c,s,t,b) (u′,d′,c′,s′,t′,b′)

Kobayashi and Maskawa: Generalized to 3 quark families

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

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

Unitarity of CKM Matrix

The 2008 Nobel Prize in Physics was awarded to Makoto Kobayashi and Toshihide Maskawa:

... for "the discovery of the origin of broken symmetry, which predicts the existence of at least three families of quarks in nature."

Kobayashi and Maskawa: Generalized to 3 quark families

β-decay | K decay | B meson

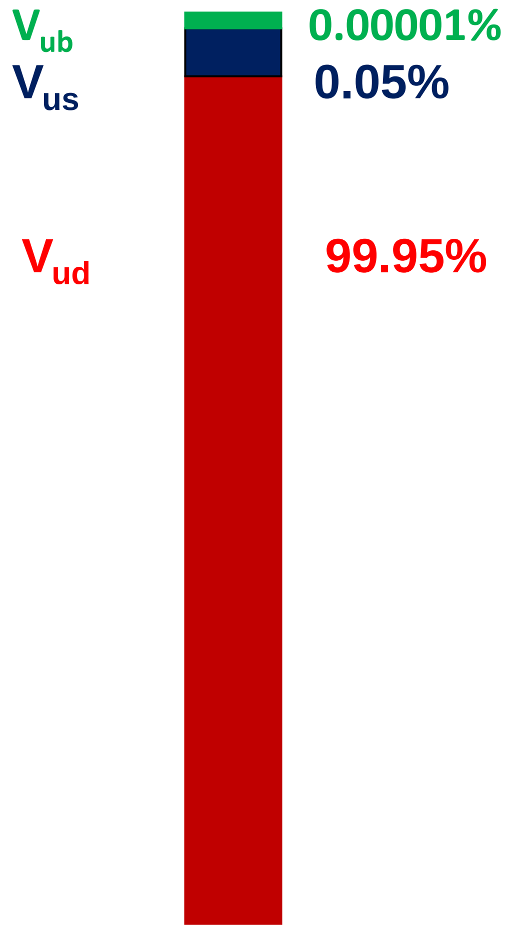
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

Unitarity of CKM Matrix

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

Contribution to the unitarity



V_{ud} (nuclear β-decay) = 0.97417(21) Hardy2015

V_{us} (kaon-decay) = 0.2253(14) PDG 2014

V_{ub} (B meson decay) = 0.00415(49) PDG 2014

$$|V_u|^2 = 0.99978 \pm 0.00055$$

CKM unitarily satisfied to within an uncertainty of 0.05%.

ACFI-T18-12
MITP/18-070

Reduced hadronic uncertainty in the determination of V_{ud}

Chien-Yeah Seng[a], Mikhail Gorchtein[b], Hiren H. Patel[c], and Michael J. Ramsey-Musolf[c,d]
[a] *INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, MOE Key Laboratory for Particle Physics, Astrophysics and Cosmology, School of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China*
[b] *Institut für Kernphysik, PRISMA Cluster of Excellence Johannes Gutenberg-Universität, Mainz, Germany*
[c] *Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA 01003 and*
[d] *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125 USA*

(Dated: July 2018)

We analyze the universal radiative correction Δ_R^V to neutron and superallowed nuclear β decay by expressing the hadronic γW-box contribution in terms of a dispersion relation, which we identify as an integral over the first Nachtmann moment of the γW interference structure function $F_3^{(0)}$. By connecting the needed input to existing data on neutrino and antineutrino scattering, we obtain an updated value of $\Delta_R^V = 0.02467(22)$, wherein the hadronic uncertainty is reduced. Assuming other Standard Model theoretical calculations and experimental measurements remain unchanged, we obtain an updated value of $|V_{ud}| = 0.97366(15)$, raising tension with the first row CKM unitarity constraint. We comment on ways current and future experiments can provide input to our dispersive analysis.

$$V_{ud} = 0.97366\,(15)\ (2018)$$

$$V_{ud} = 0.97417\,(21)(2015)$$

arity

V_{ud}

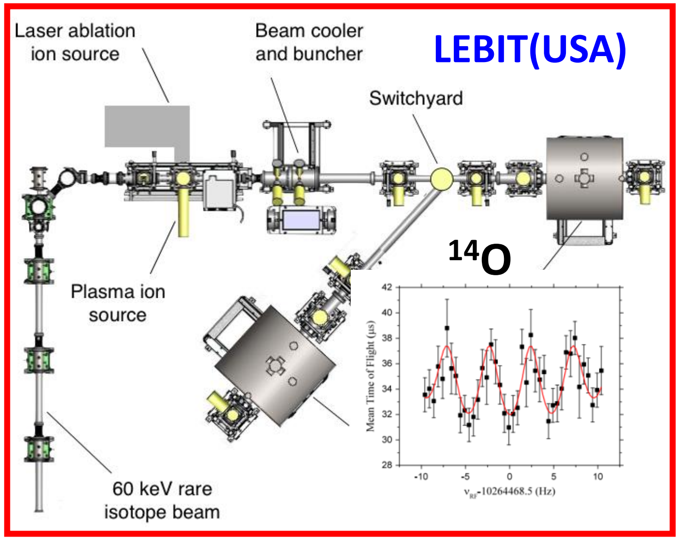
V_{us}

V_{ub} (B meson decay) = 0.00415(49) PDG 2014

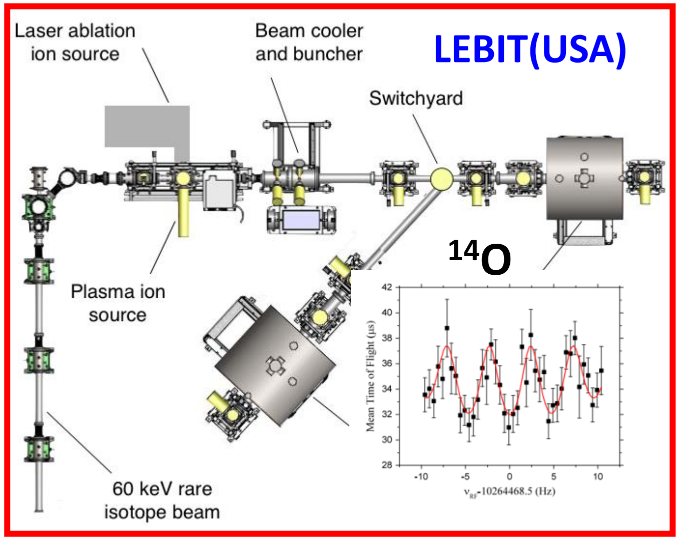
$$|V_u|^2 = 0.99978 \pm 0.00055$$

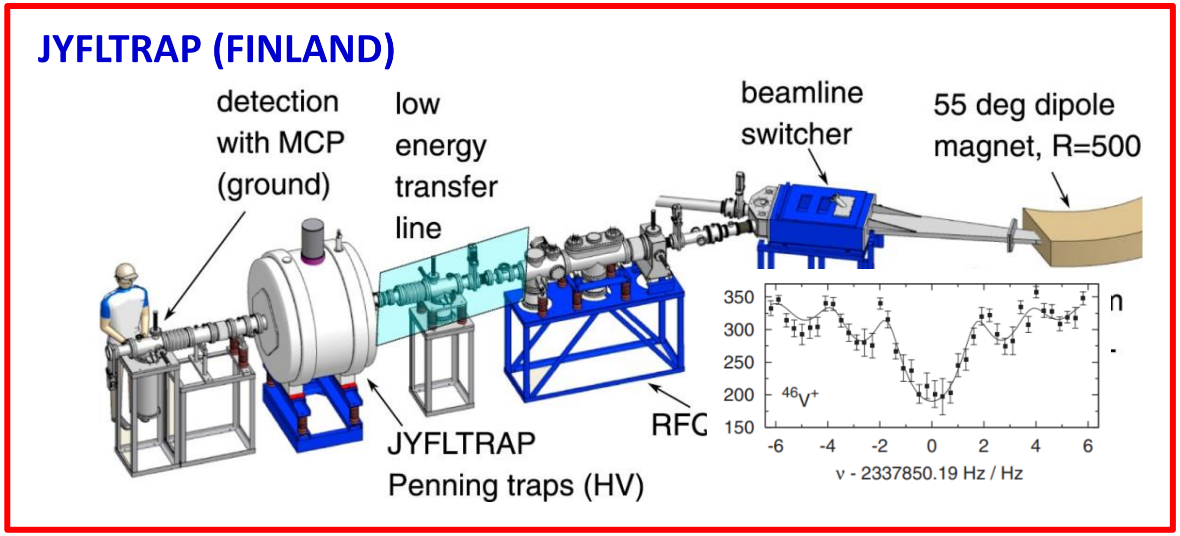
Ion trap facilities for mass measurements

Ion trap facilities for mass measurements



Ion trap facilities for mass measurements





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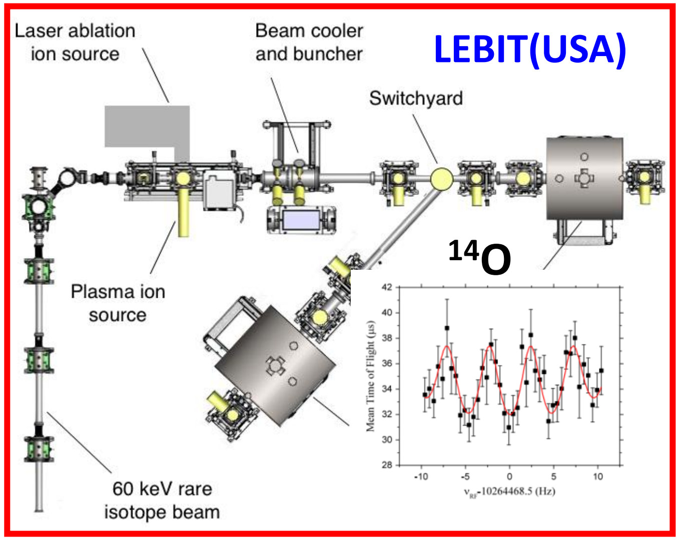

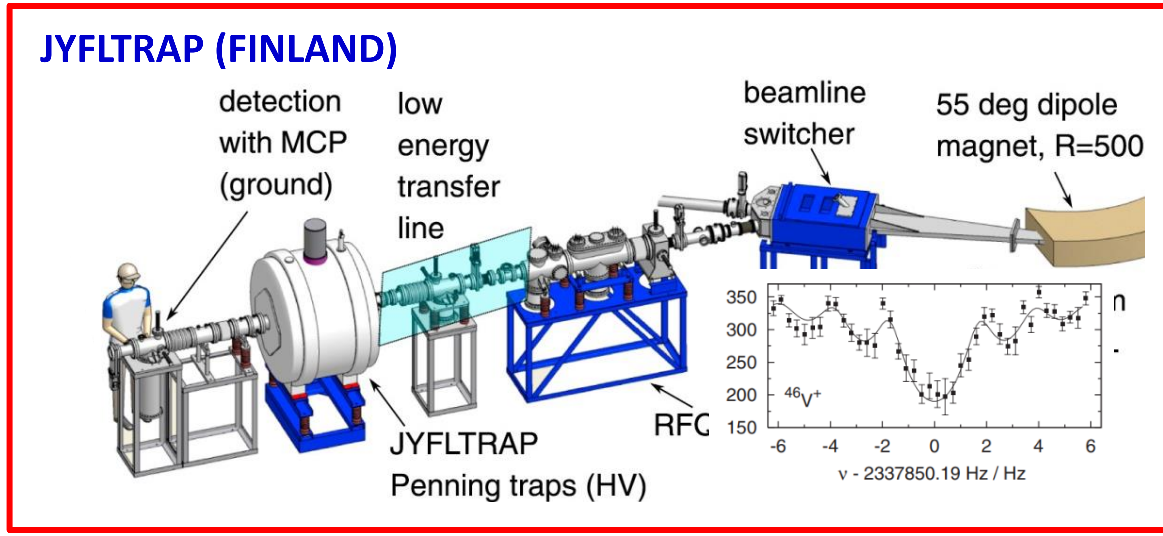

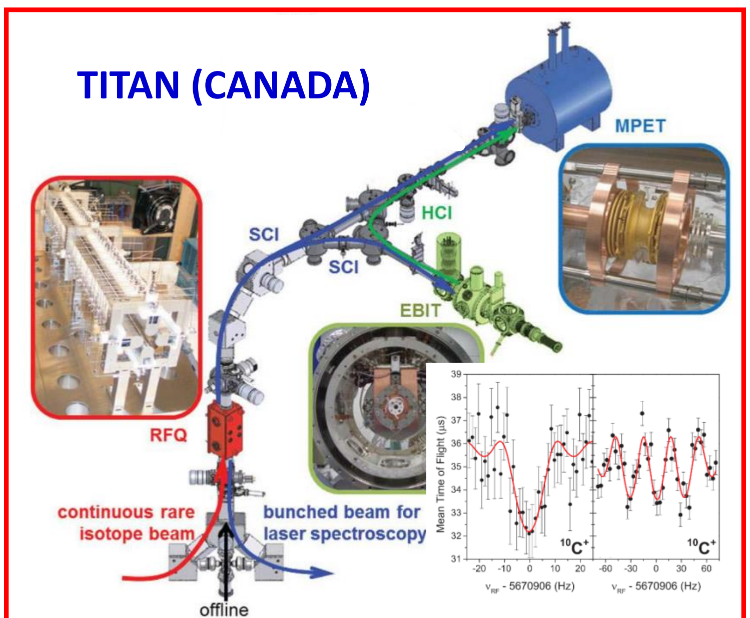

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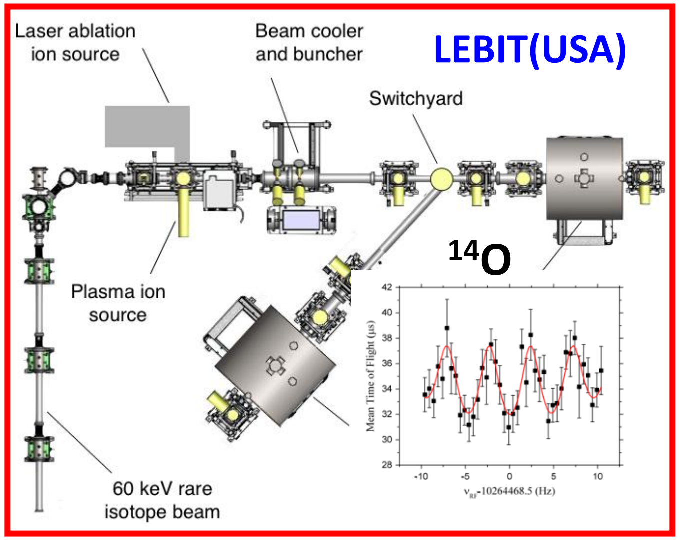

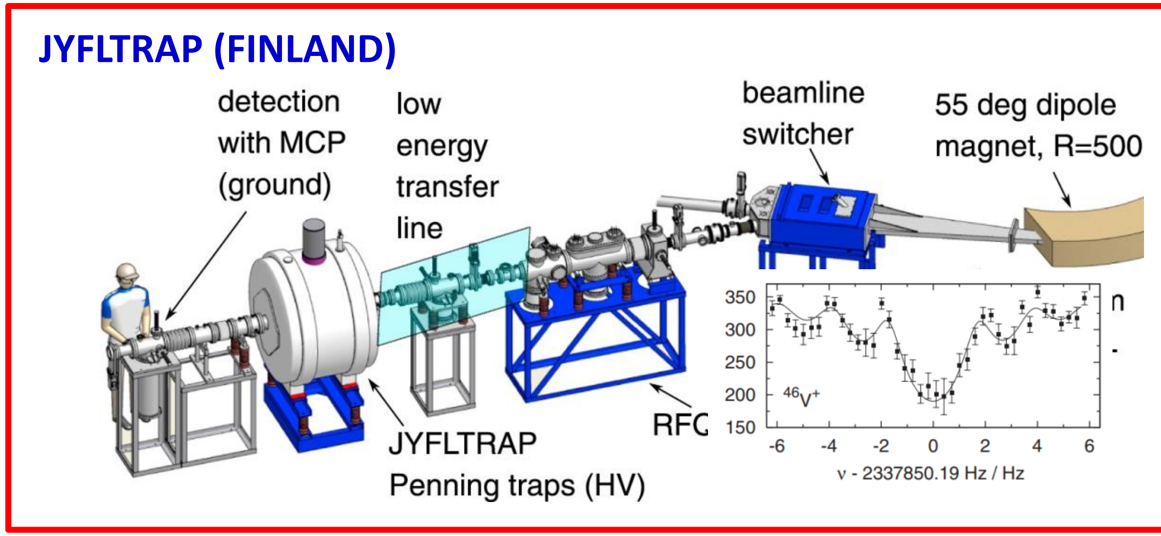

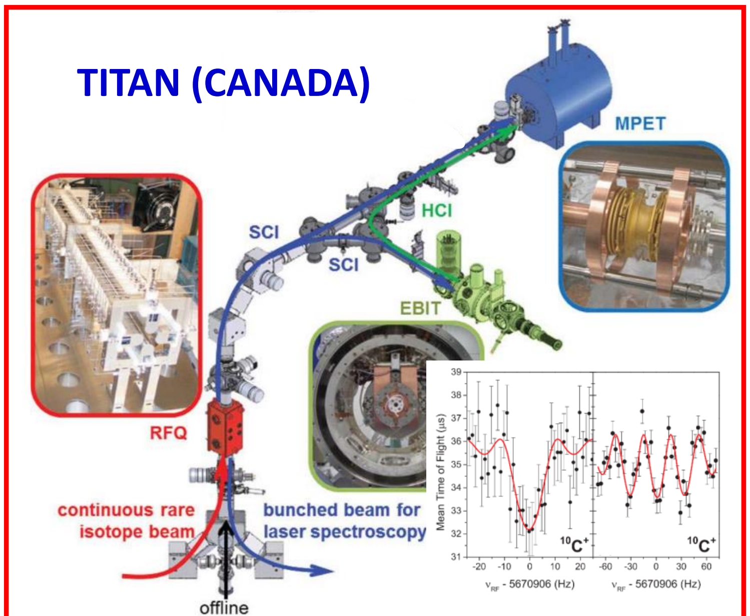

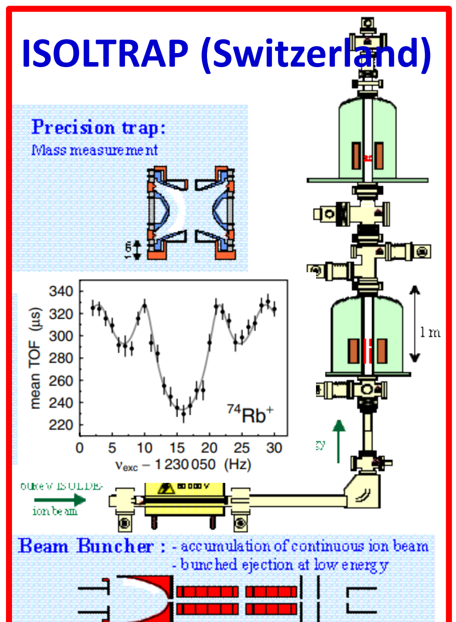

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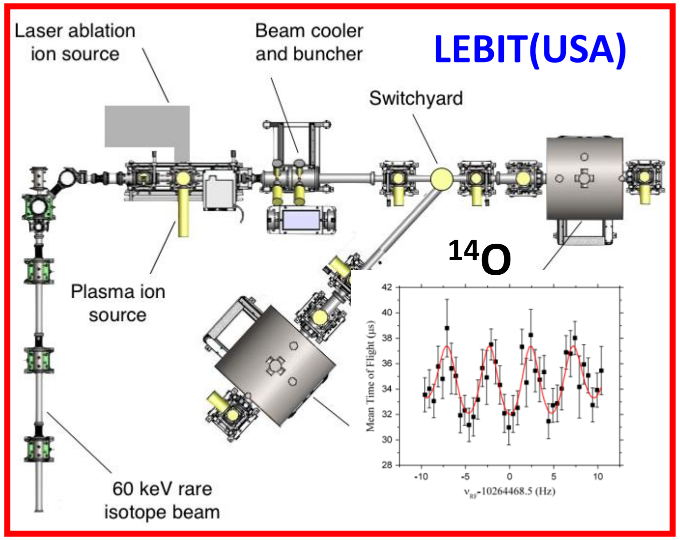
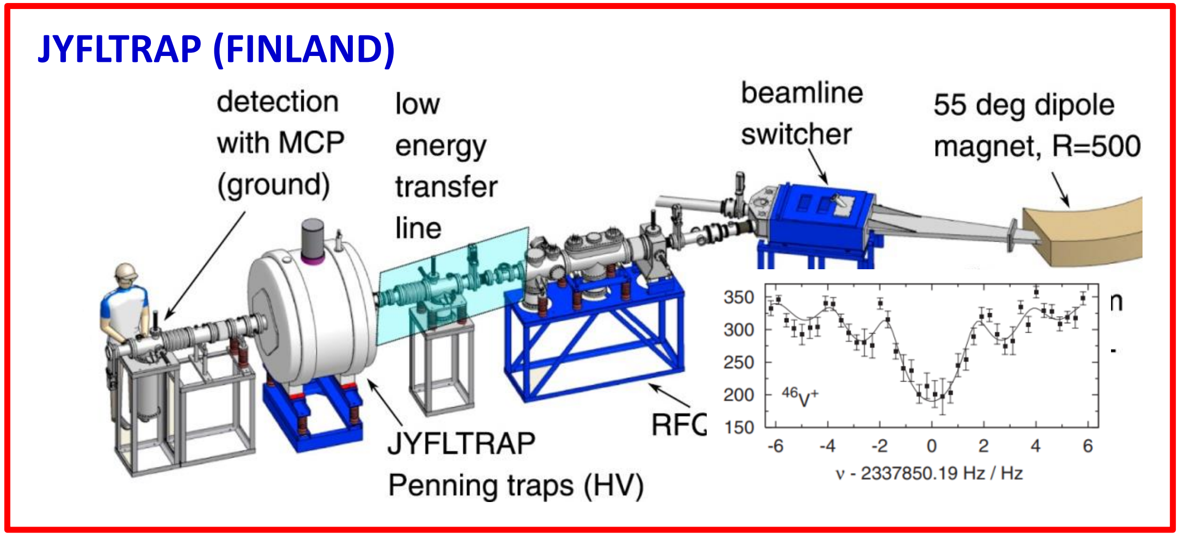
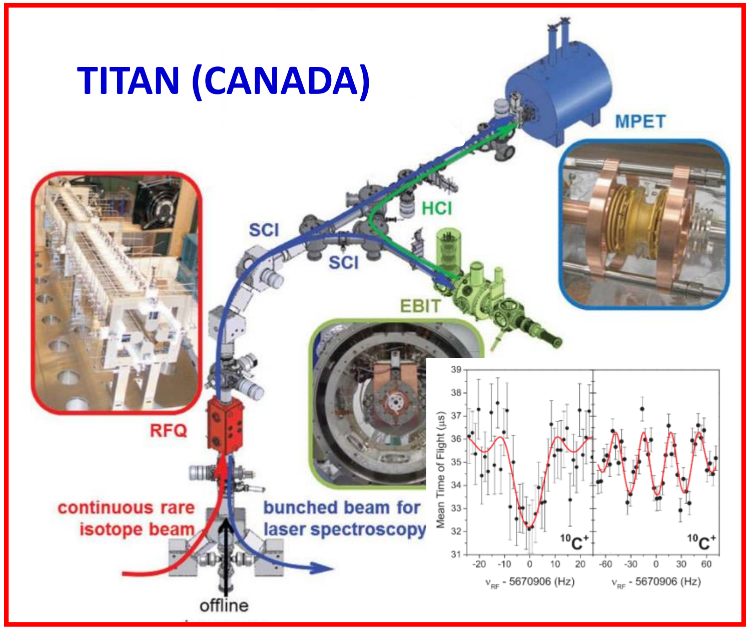
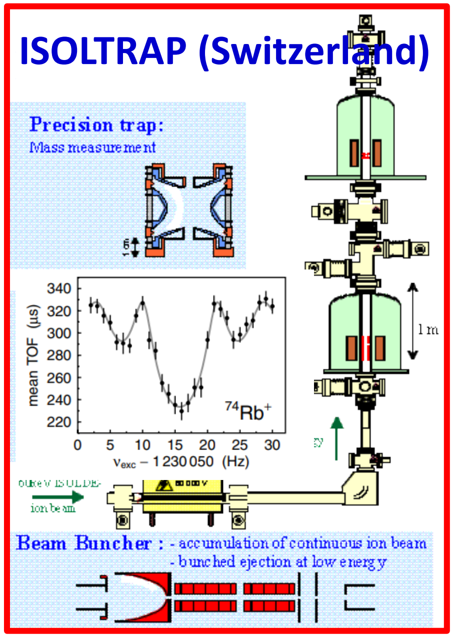
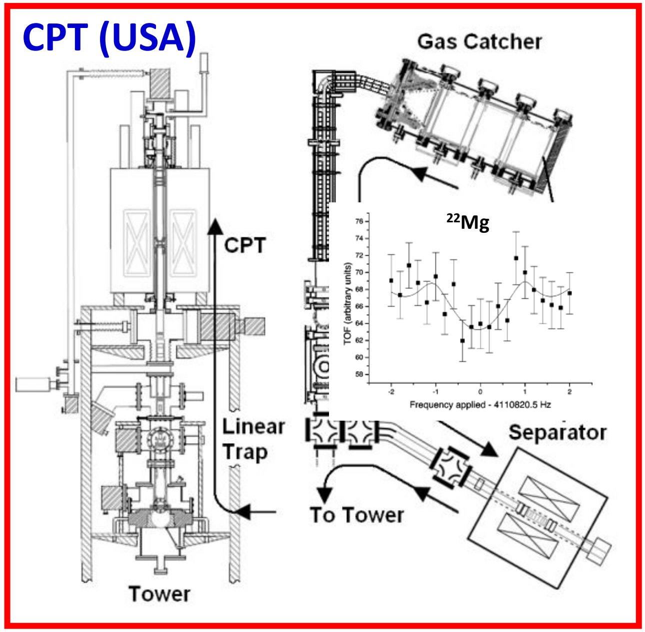




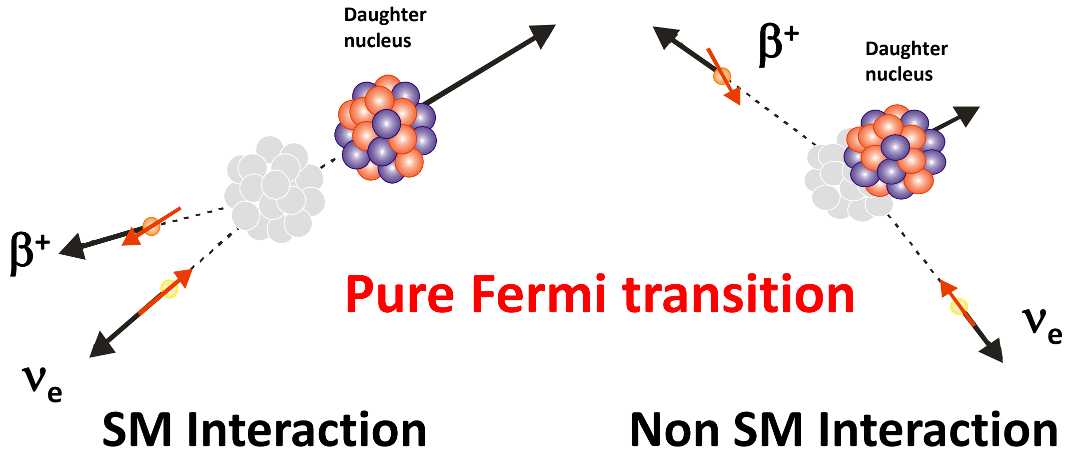






Measurement of *Correlation* parameter

In Standard Model (SM)
weak interaction is
V-A
In general β decay can also be
Scalar, Tensor, V+A interaction



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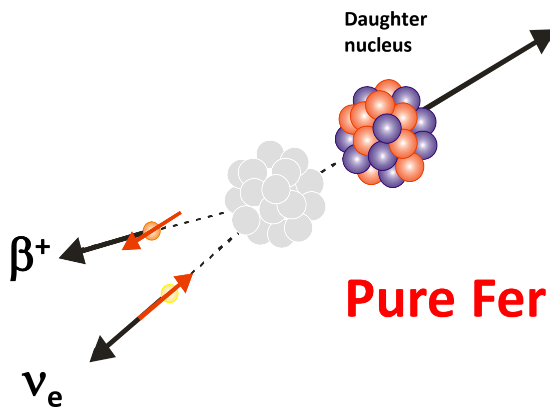
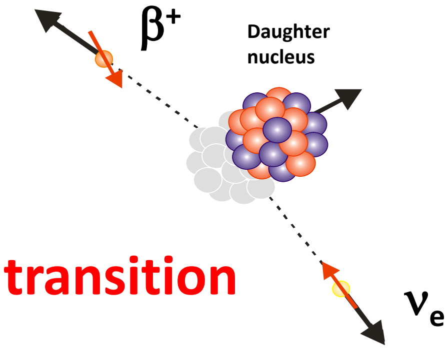


SM Interaction

Pure Fermi transition

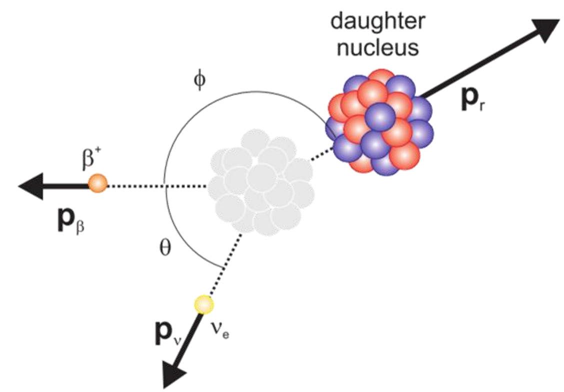


Non SM Interaction

Correlation parameter

$$dW(\theta) \cong \left(1 + a_{\beta\nu}\frac{p_e p_\nu}{E_e E_\nu} cos\theta_{e\nu} + \ \dots\right)$$

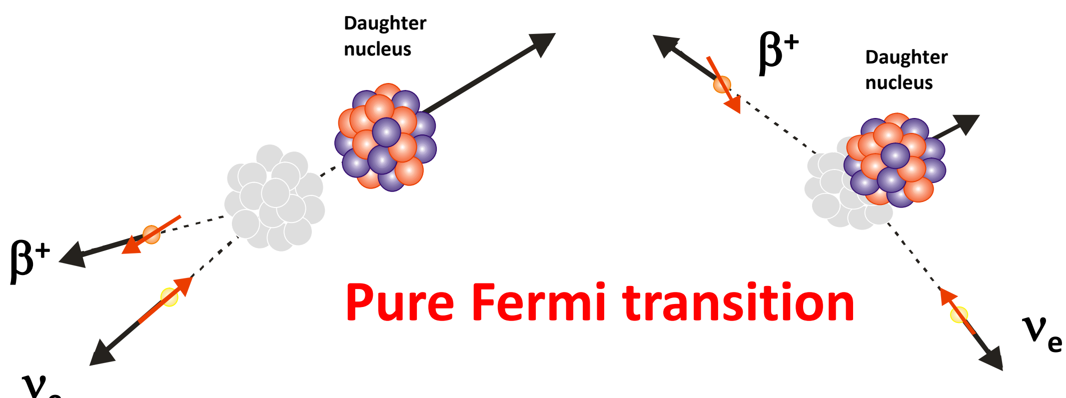
β-ν correlation parameter



*Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957):*

Measurement of *Correlation* parameter

In Standard Model (SM)
weak interaction is
V-A
In general β decay can also be
Scalar, Tensor, V+A interaction



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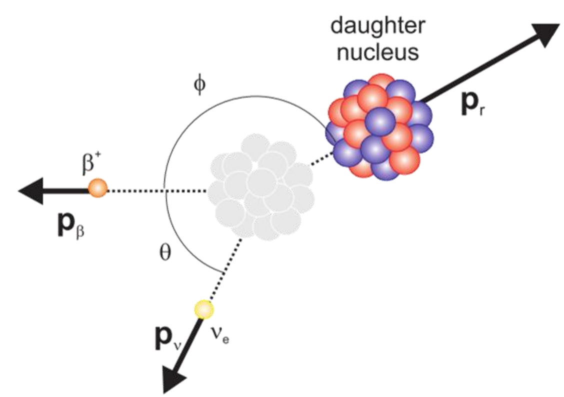
β-ν correlation parameter



Pure Fermi Transition:

$$a_{\beta\nu} \overset{?}{=} 1$$

Test of Standard Model

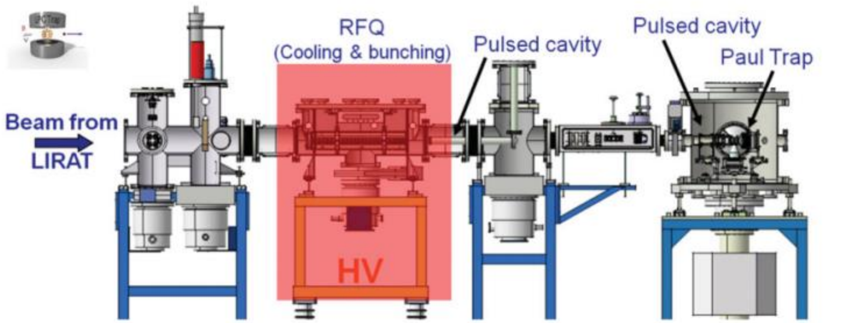
*Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957):*

Ion trap facilities for angular correlation measurements

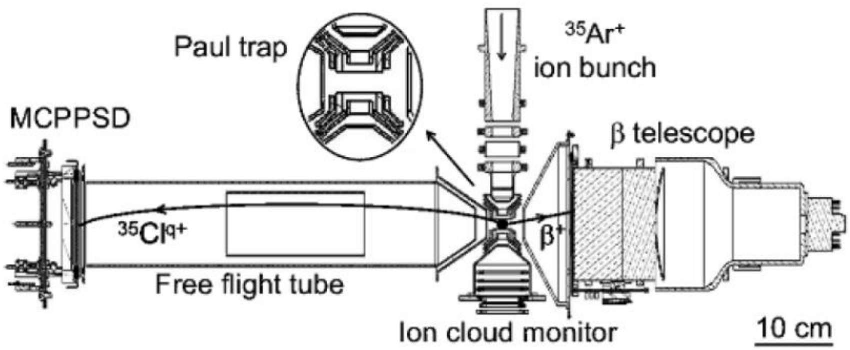
Ion trap facilities for angular correlation measurements

LPC TRAP, FRANCE

$a_{\beta\nu}$ correlation parameter in ^{35}Ar, ^{6}He



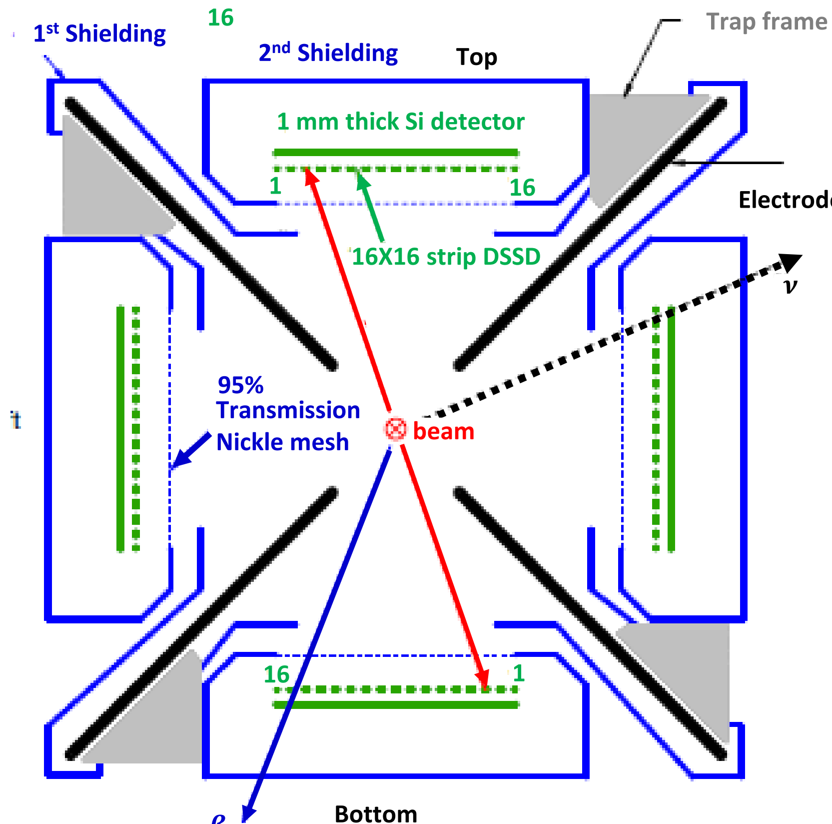
Detector Setup:



Ann. Phys. (Berlin) 525, (2013) 576-587

Beta-decay Paul Trap @ ANL, USA

$$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}^{*} + \bar{\nu} + \beta$$
$$^{8}\mathrm{Be}^{*} \rightarrow \alpha + \alpha$$

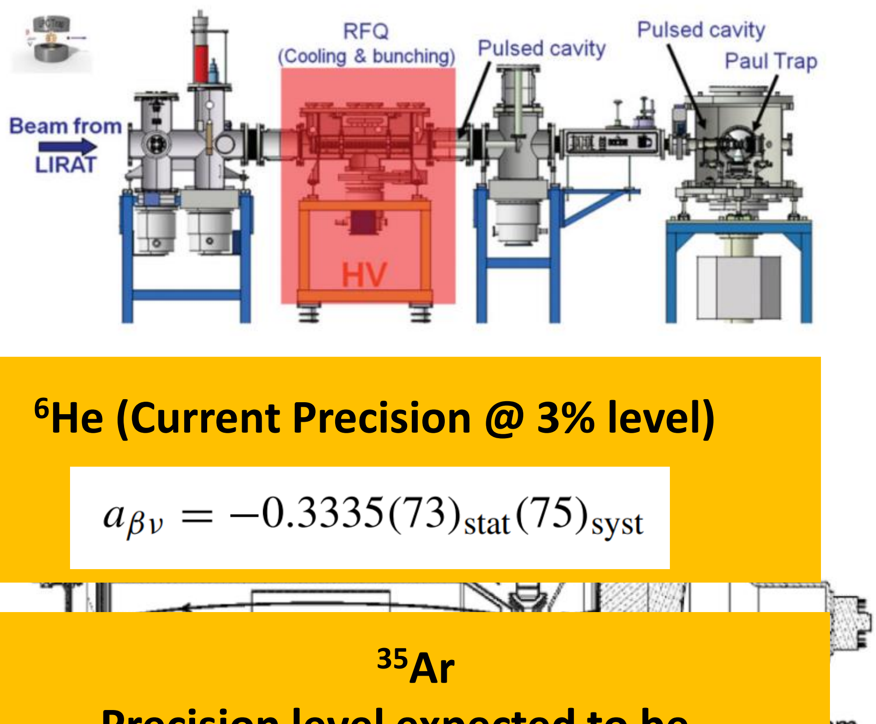


Phys. Rev. Lett., ***110*** *(2013) 092502*

Ion trap facilities for angular correlation measurements

LPC TRAP, FRANCE

$a_{\beta\nu}$ correlation parameter in ^{35}Ar, ^{6}He



^{6}He (Current Precision @ 3% level)

$$a_{\beta\nu} = -0.3335(73)_{stat}(75)_{syst}$$

^{35}Ar

Precision level expected to be at 0.5% level

Ann. Phys. (Berlin) 525, (2013) 576-587

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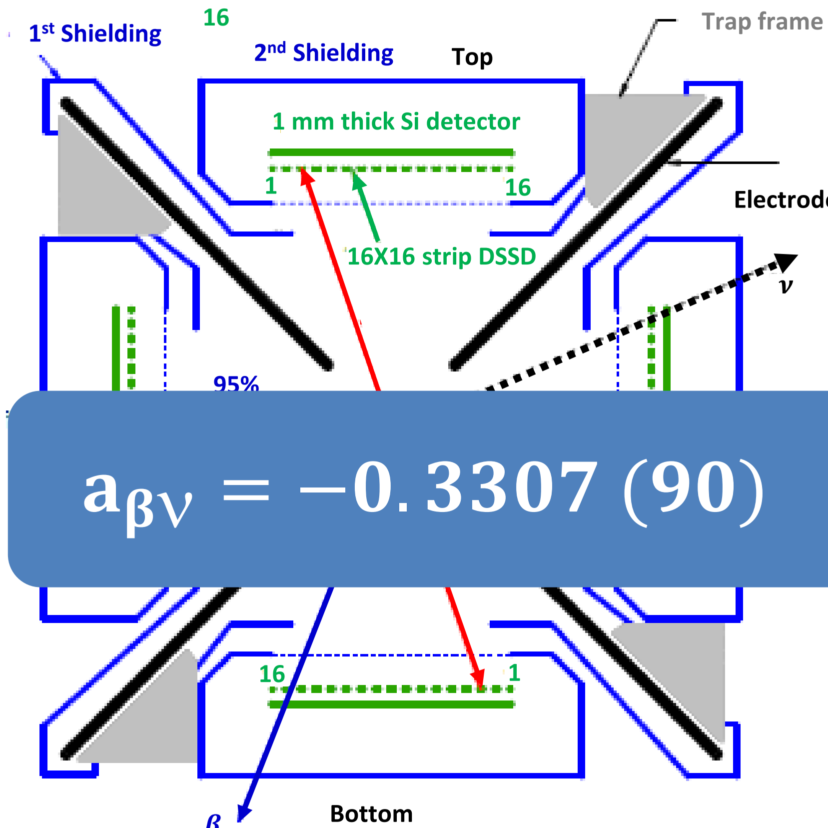
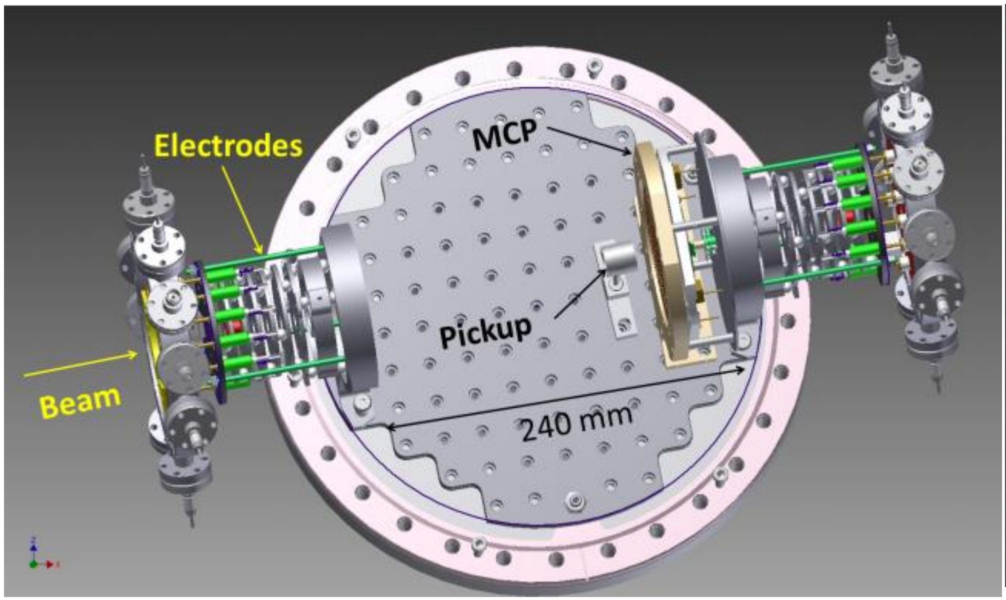


$$a_{\beta\nu} = -0.3307\,(90)$$

Phys. Rev. Lett., ***110*** *(2013) 092502*

Ion trap facilities for angular correlation measurements

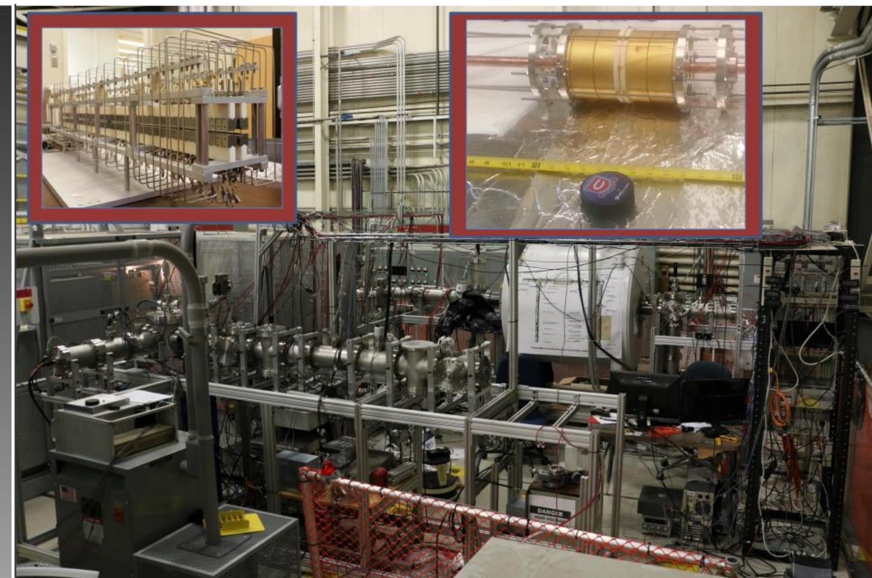
Weizmann Institute, Israel (Commissioning stage)



$a_{\beta\nu}$ correlation parameter in ^{6}He

Journal of Phys. Conf. Proc. ***267*** *(2011)012013*

TAMUTRAP, Cyclotron Institute, USA (Commissioning stage)



TAMUTRAP Facility aiming to perform $a_{\beta\nu}$ & *ft*-value measurements.

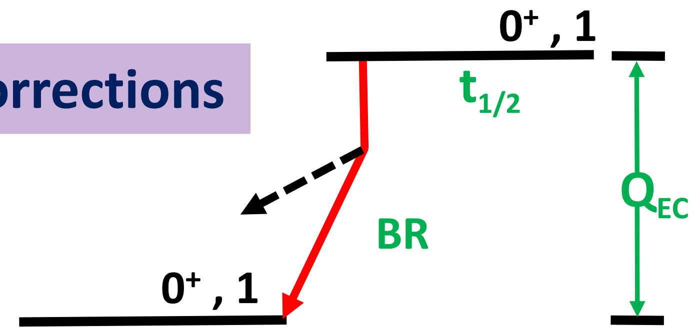
M. Mehlman et al. NIMA ***712*** *(2013) 9*

Research program at TAMUTRAP facility

Pure Fermi transitions

Theory corrections

$$\mathcal{F}t^{0^+\to 0^+} \equiv ft^{0^+\to 0^+}(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C) = \frac{K}{2\,G_F^2 V_{ud}^2 C_V^2 (1+\Delta^V_R)}$$



EXPERIMENT

$$t = \ln 2\,\tau\left(\frac{1+\ P_{EC}}{BR}\right)$$

Isospin symmetry breaking correction (δ^V_C)

- Mixing of states of same spin
- Difference in *n* and *p* radial wave functions

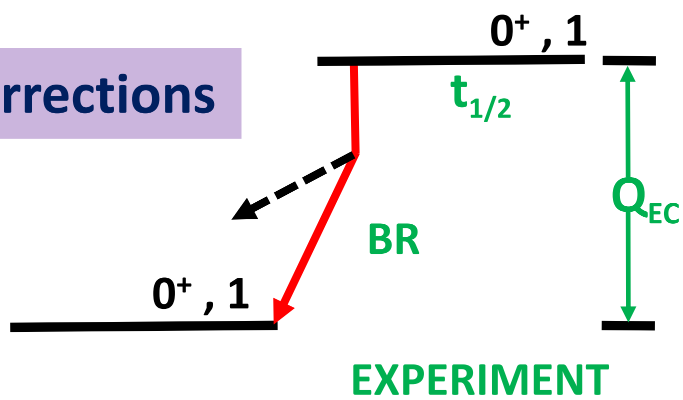
$$\delta_C = \delta_{c1} + \ \delta_{c2}$$

- Model dependence

Research program at TAMUTRAP facility

Pure Fermi transitions

Theory corrections



$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv ft^{0^+\rightarrow 0^+}(1+\delta_R')(1+\delta_{NS}^V-\delta_C^V) = \frac{K}{2\,G_F^2 V_{ud}^2 C_V^2 (1+\Delta_R^V)}$$

$$t = \ln 2\,\tau\left(\frac{1+\ P_{EC}}{BR}\right)$$

Isospin symmetry breaking correction (δ_C^V)

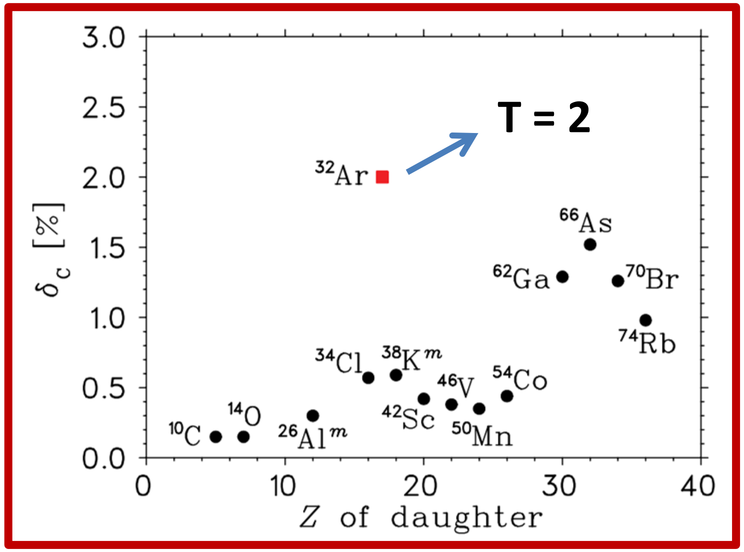
- Mixing of states of same spin
- Difference in *n* and *p* radial wave functions

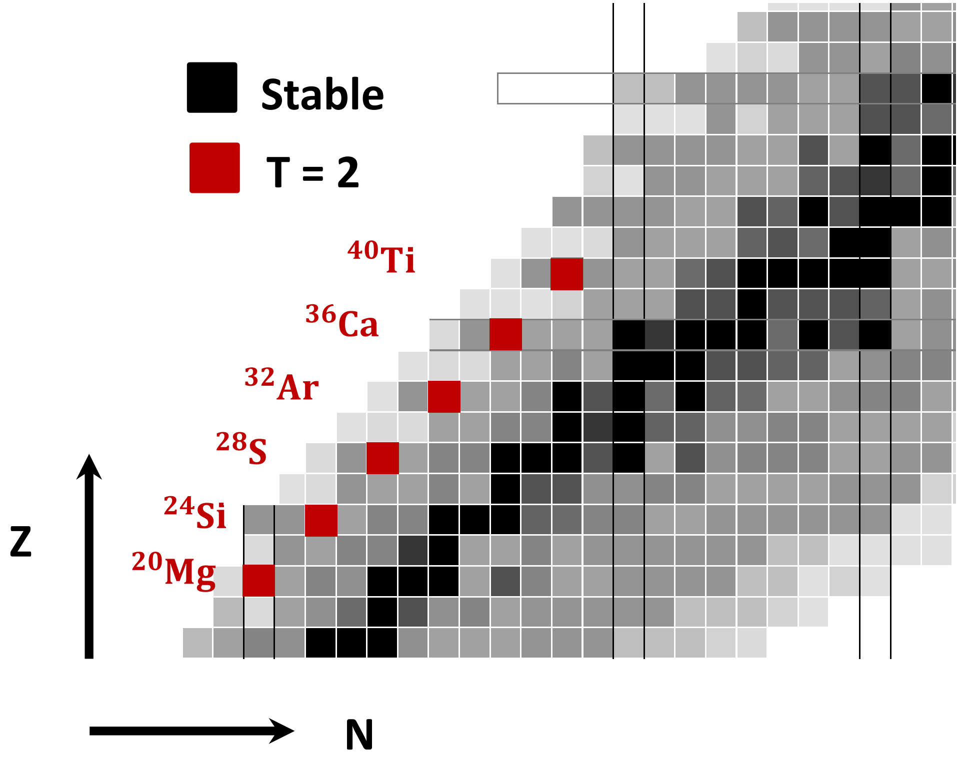
$$\delta_C = \delta_{c1} + \ \delta_{c2}$$

- Model dependence

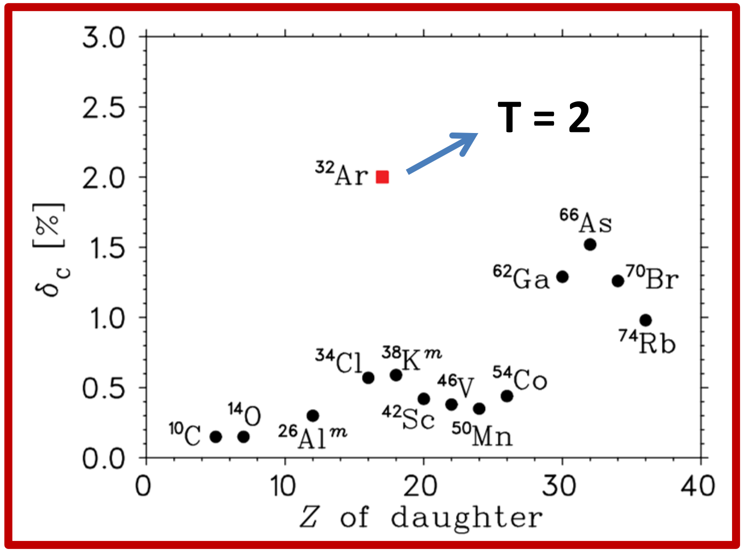
Needs experimental verification for large corrections

Superallowed Transitions



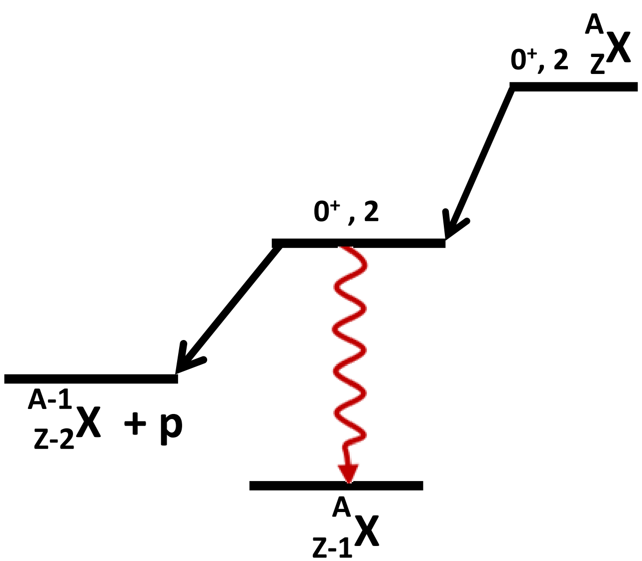


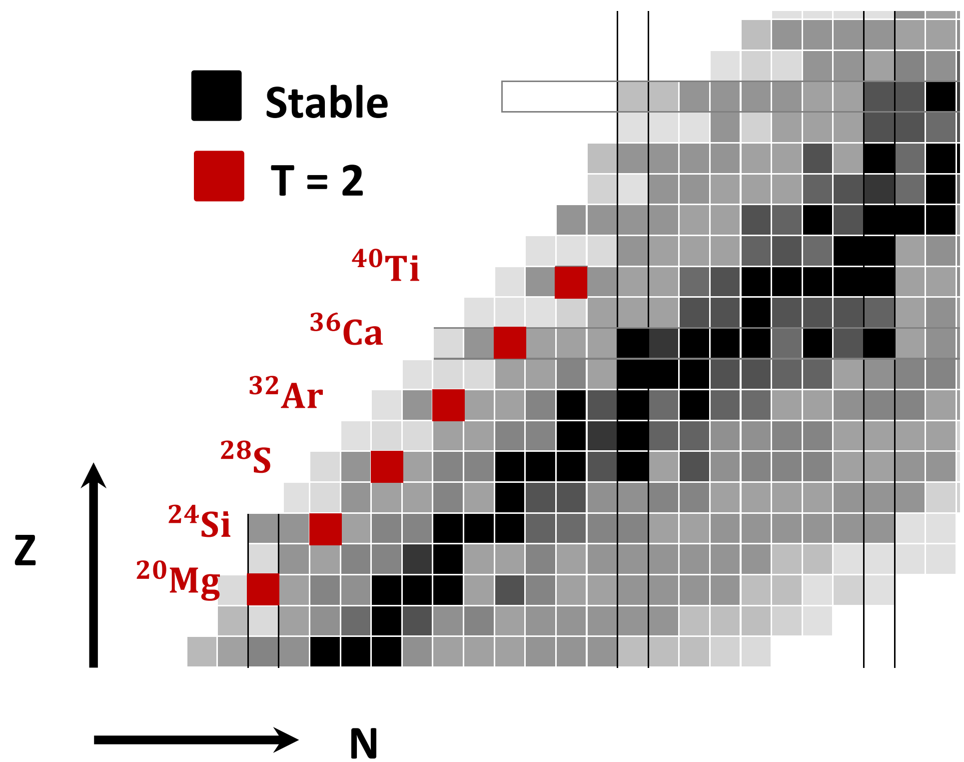
Superallowed Transitions



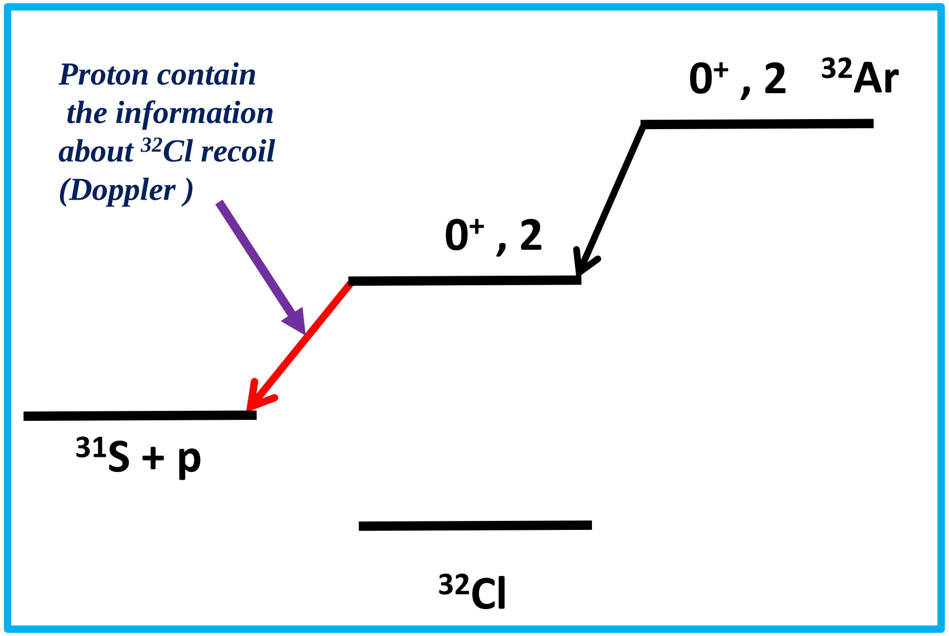
- Large correction is predicted for T = 2 transition.
- Measurements will allow to test and verify these corrections.
- New cases to test the CVC Theory.
- New cases for V_{ud}.

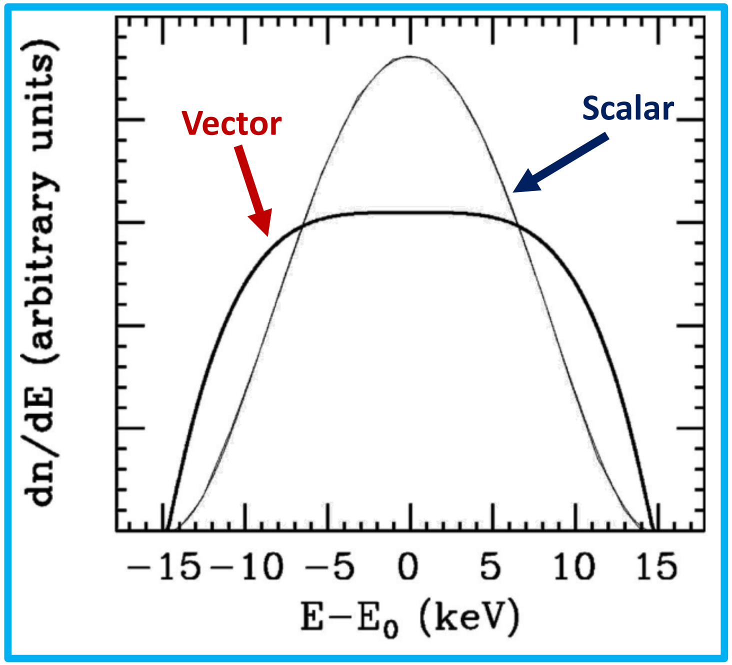
Beta delayed proton decay



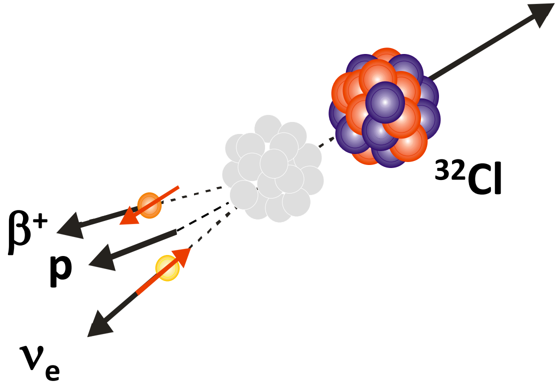


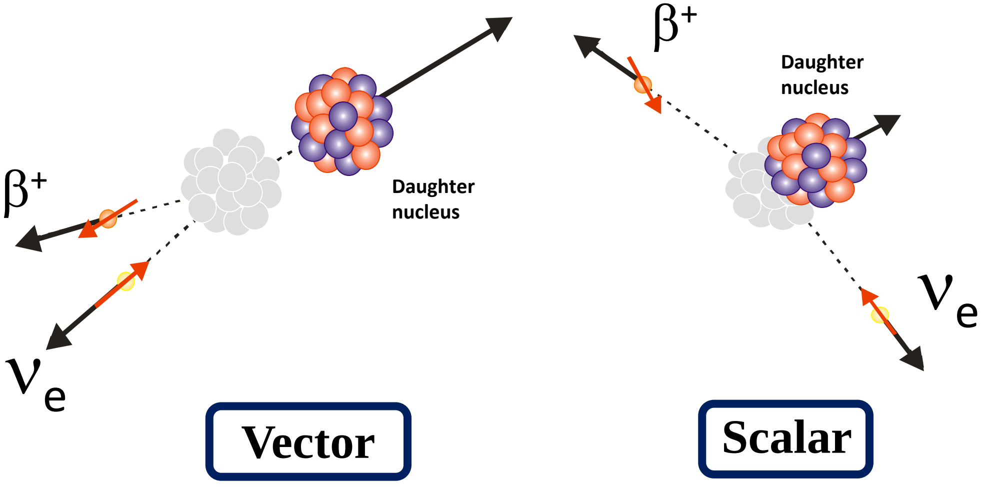
$\beta - \nu$ correlation parameter



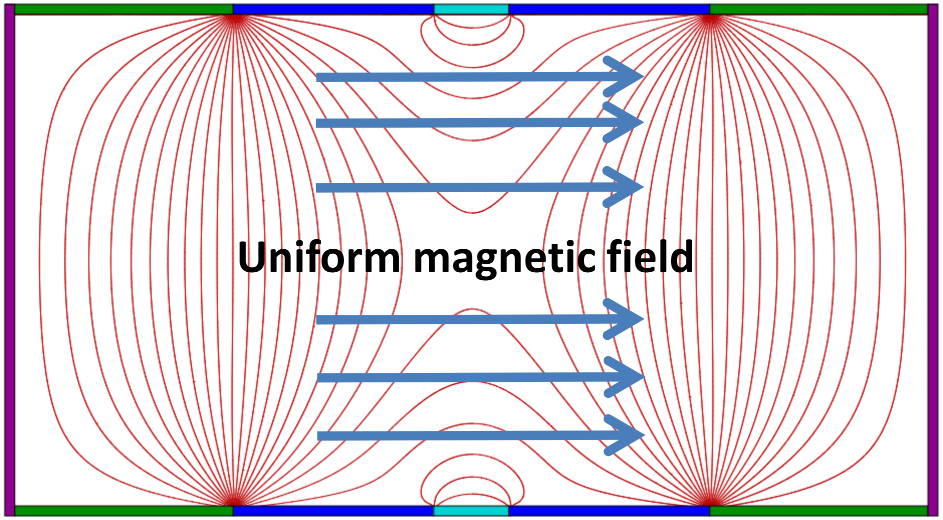


Adelberger E.G. et al. Phys. Rev. Lett. 1299 **83** (1999)





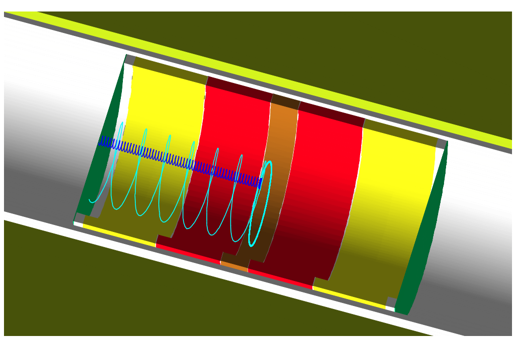
Penning trap $\beta - \nu$ correlation parameter



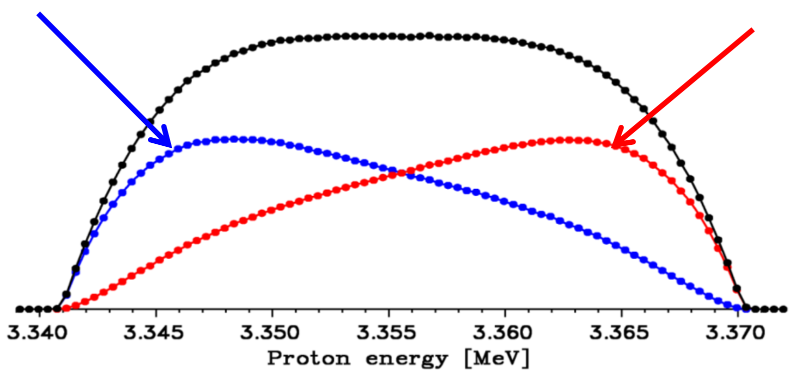
Penning traps

- Increase solid angle.
- Increase sensitivity.
- Allows to detect e along with p

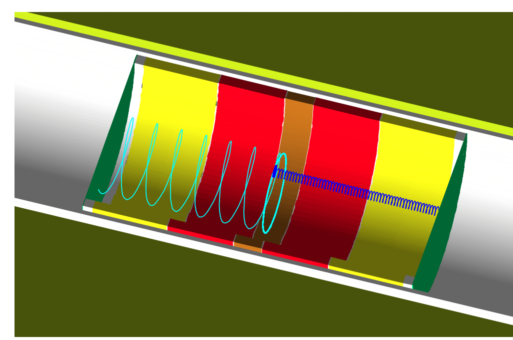
Beta & Proton in same hemisphere



Total

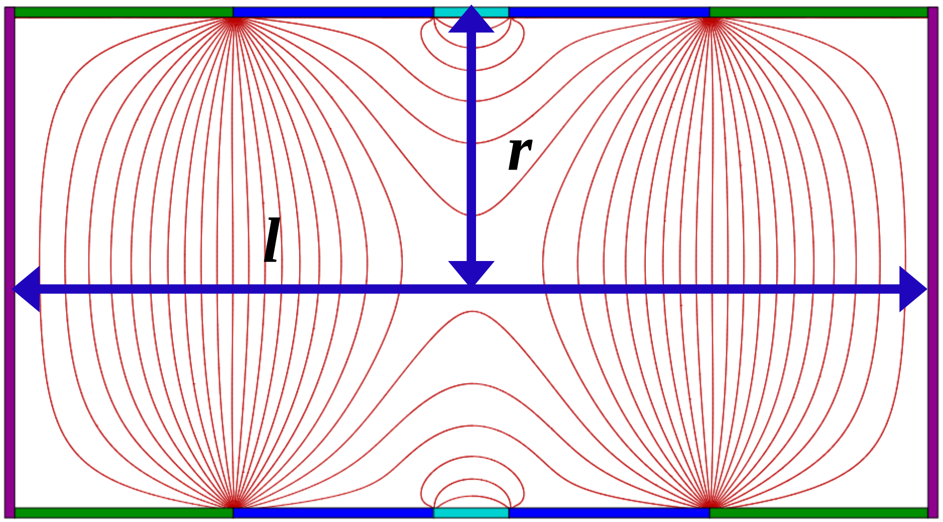


Beta & Proton in different hemisphere



TAMU – Penning Trap

Cylindrical Penning Trap



Nuclide	Lifetime (ms)	Proton Energy (MeV)	Larmour radii (mm)
^{20}Mg	137.05	4.28	42.7
^{24}Si	147.15	3.91	40.8
^{28}S	180.33	3.70	39.7
^{32}Ar	141.38	3.36	37.8
^{36}Ca	141.15	2.55	33.0
^{40}Ti	72.13	3.73	39.9
^{48}Fe	63.48	1.23	22.9

Other existing Cylindrical Penning Trap

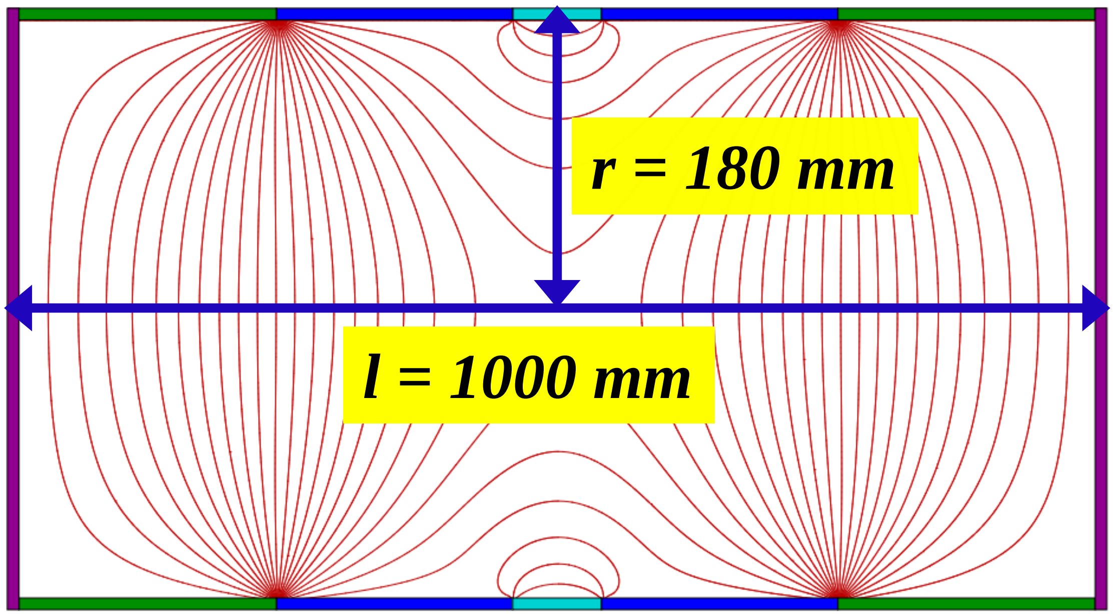
l/r = 11.75

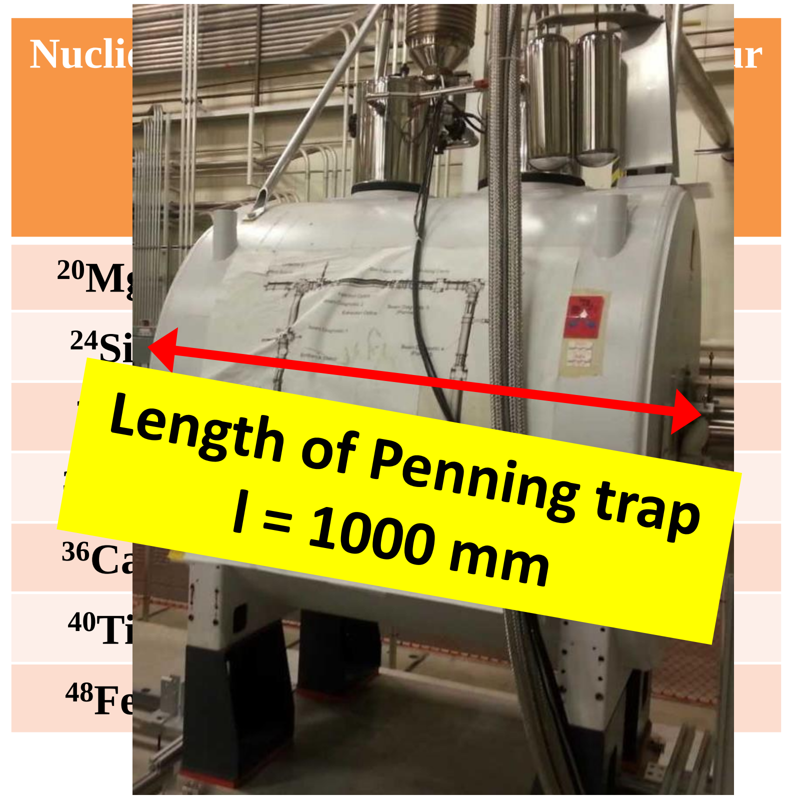
Inner diameter of the trap to contain decay products (protons, electrons): at least:

diameter = 170 mm

TAMU – Penning Trap

Cylindrical Penning Trap





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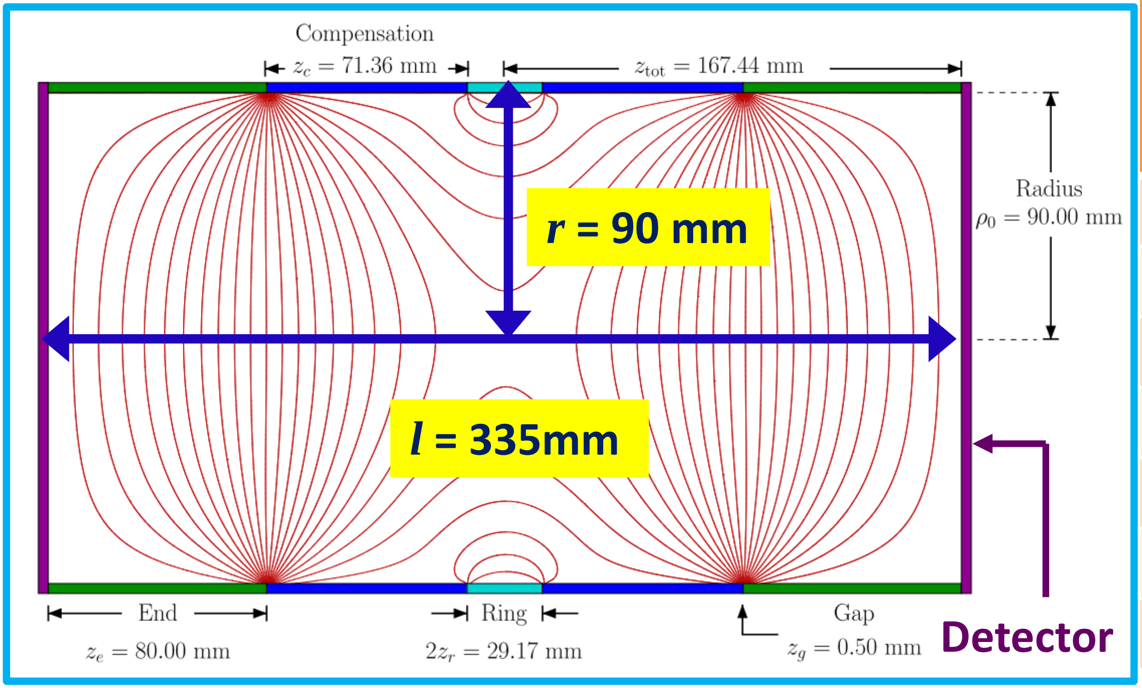
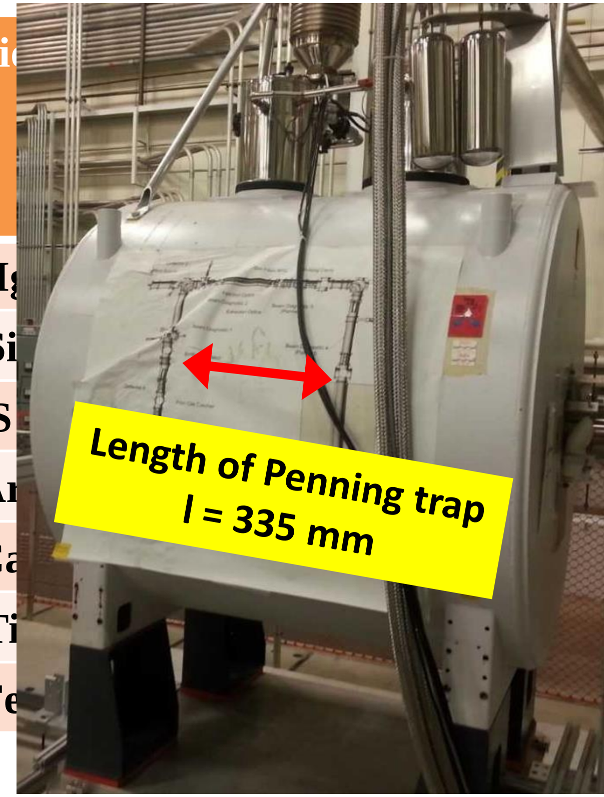


M. Mehlman et al. NIMA ***712*** *(2013) 9*

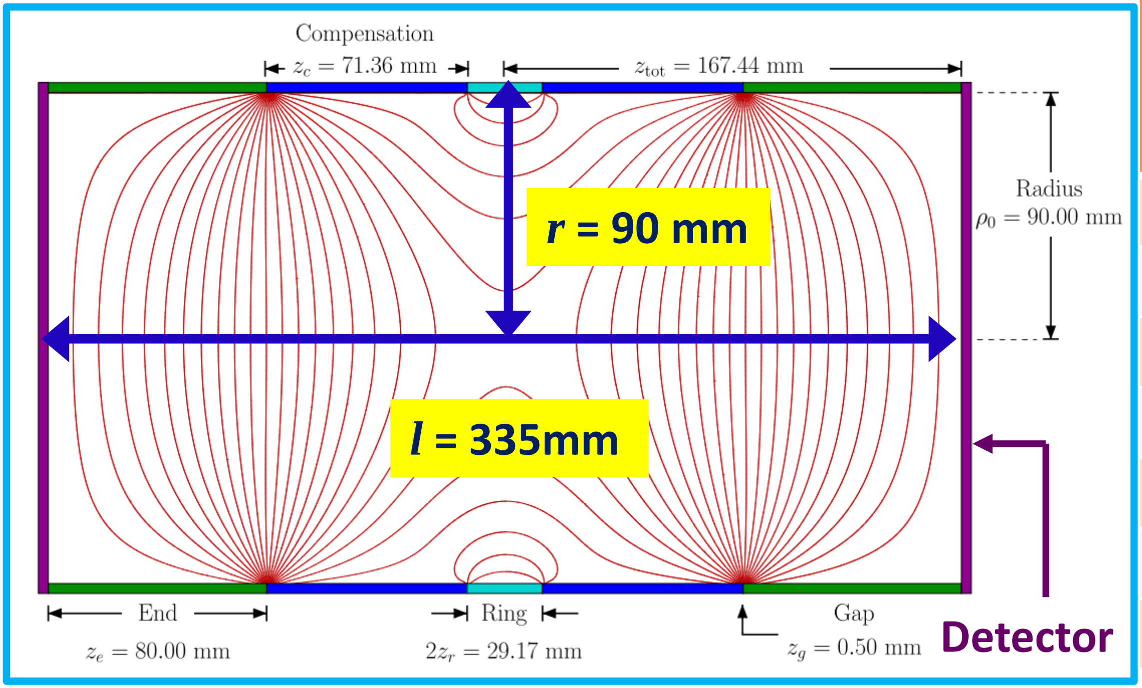
Nucli	ur
^{20}Mg	
^{24}Si	
^{28}S	
^{32}Ar	
^{36}Ca	
^{40}Ti	
^{48}Fe	



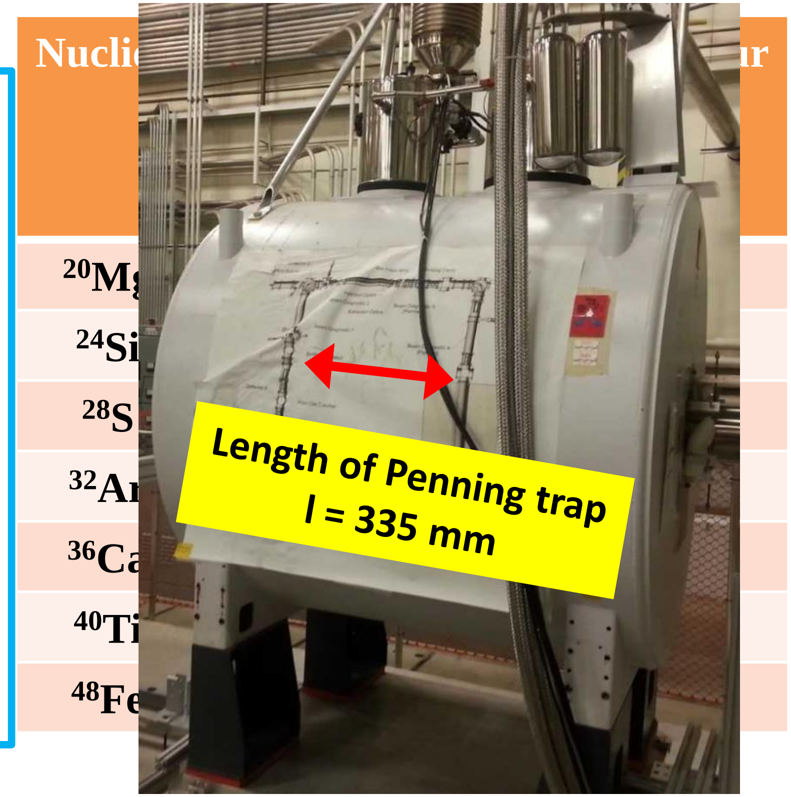
Radius : 90 mm
l/r = 3.72

TAMU – Penning Trap

Cylindrical Penning Trap



M. Mehlman et al. NIMA ***712*** *(2013) 9*

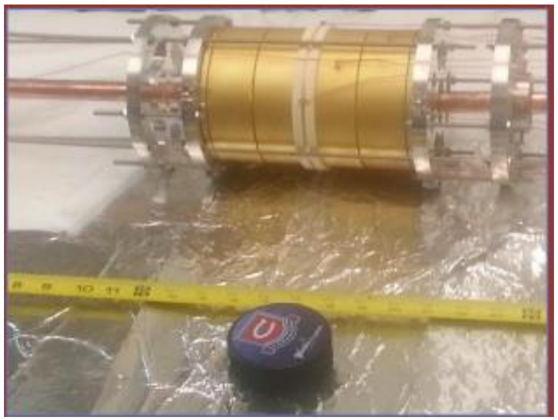


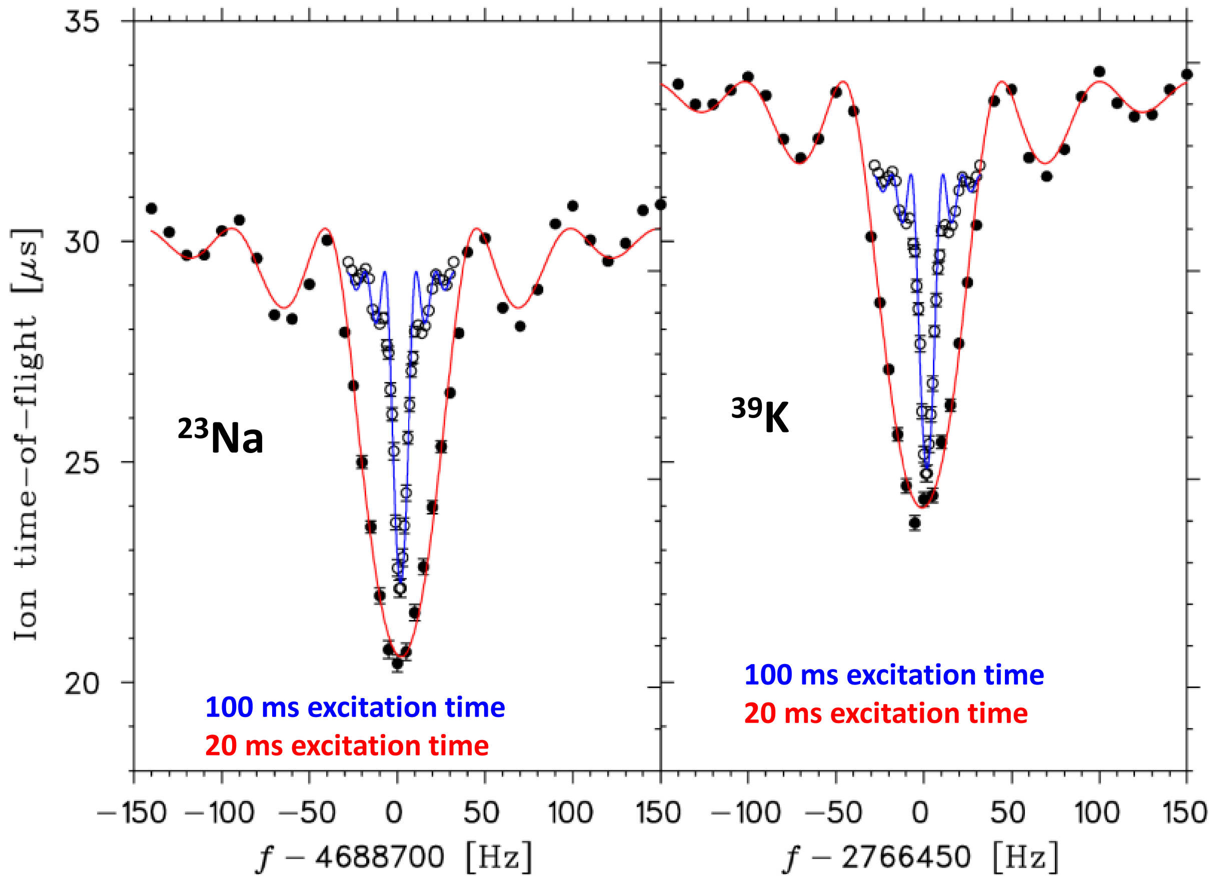
Radius : 90 mm
l/r = 3.72

Trap dimensions are also optimized to perform high precision mass measurement.

TAMU – Prototype Penning Trap

Penning Trap: *l/r* = 3.72



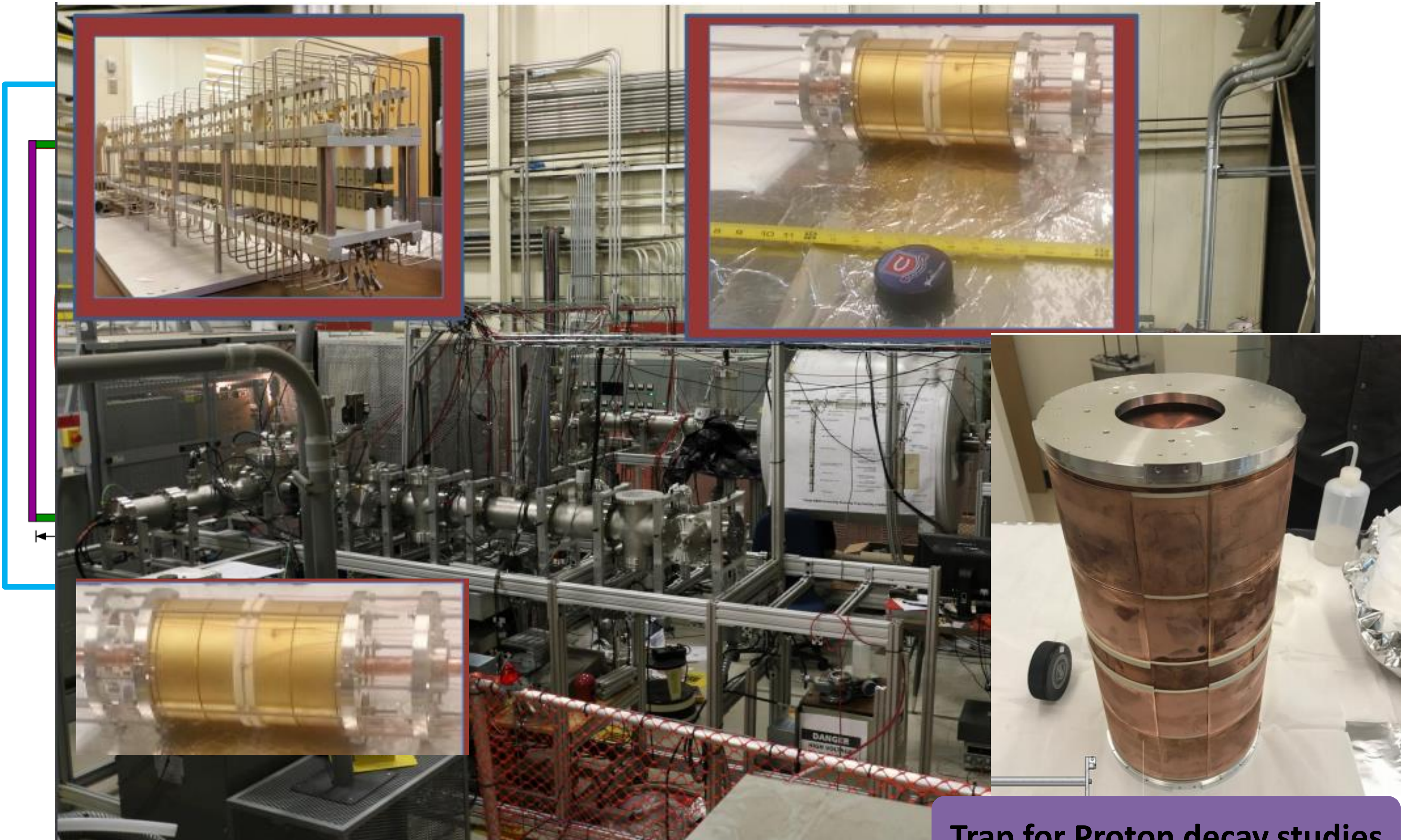


Mass measurement of ^{23}Na:

$$M_{diff} = calc - AME$$
$$= -0.3 \pm 1.3 \text{ keV}$$

(a 0.06 ppm measurement)

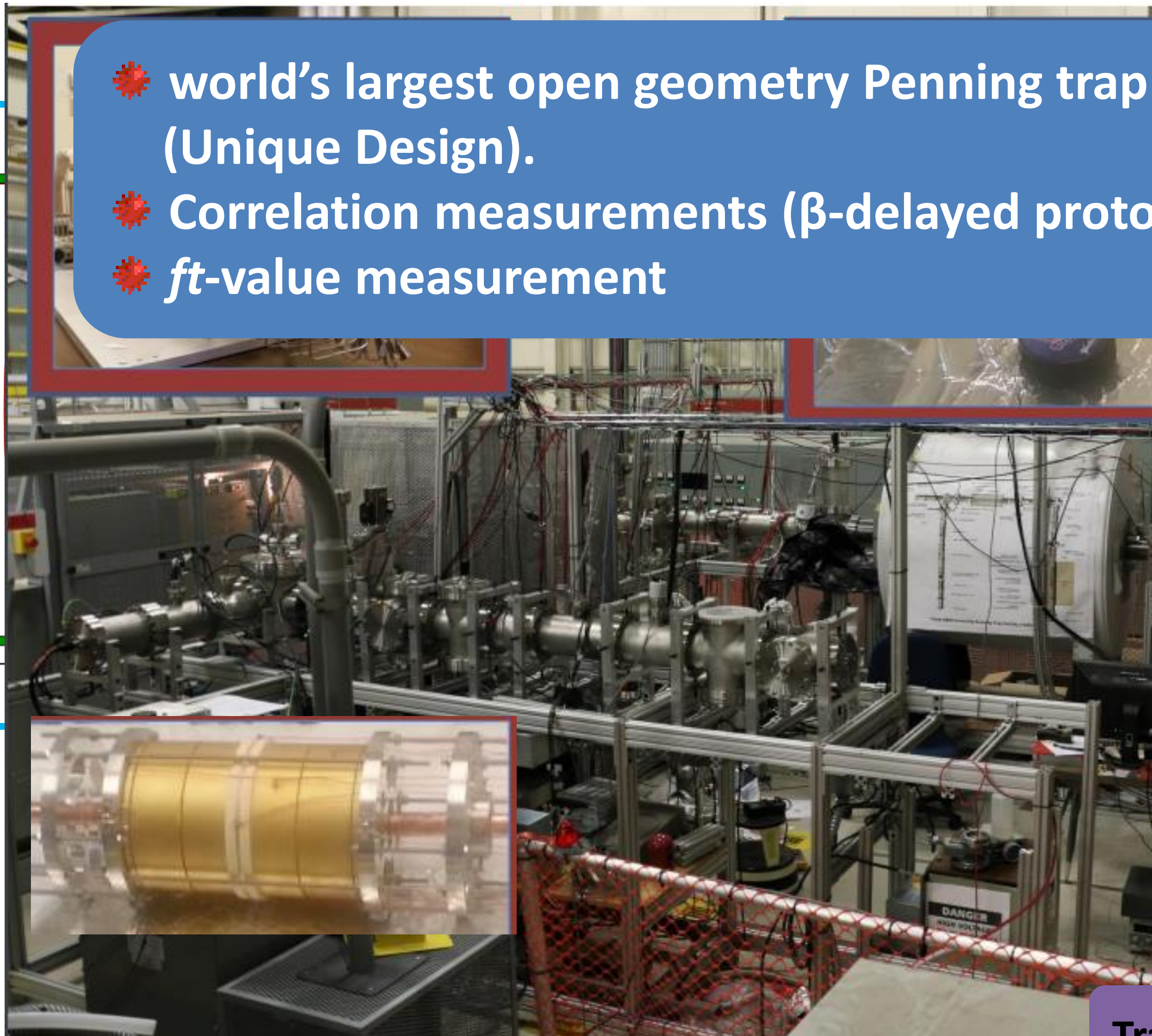
TAMUTRAP – FACILITY



Trap for Proton decay studies

TAMUTRAP – FACILITY

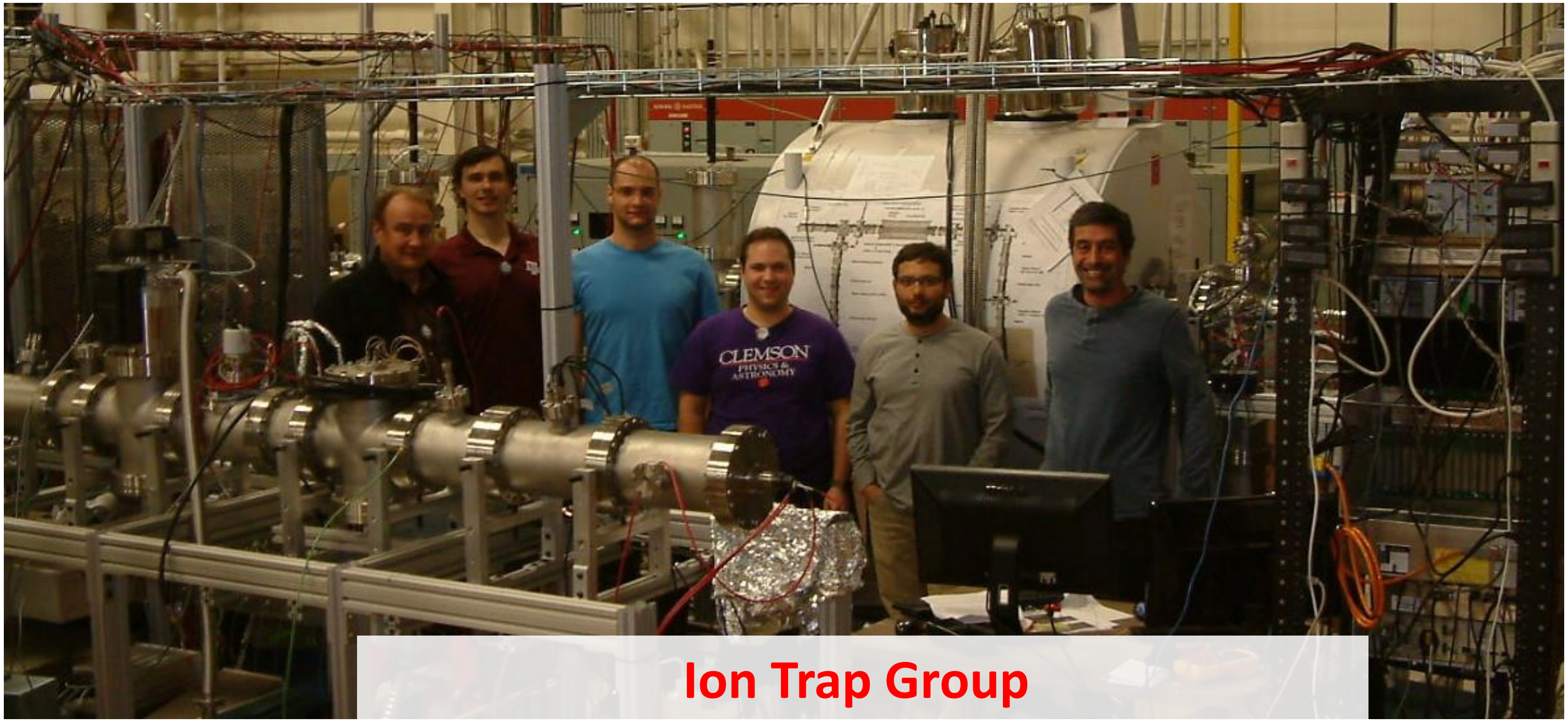
- world's largest open geometry Penning trap facility (Unique Design).
- Correlation measurements (β-delayed proton decay).
- *ft*-value measurement



Trap for Proton decay studies

Summary & Conclusions

- **High precision measurements using ion traps provide a valuable input to weak interaction studies.**
- **Several ideas and extension to the existing ion trap techniques are being implemented.**
- **Several Ion trap facilities are getting ready for measuring correlation parameter @ 0.1% level.**
- **TAMUTRAP facility is a unique facility :**
  - **Measurement of correlation parameter ($a_{\beta\nu}$)**
  - ***ft* value measurement (mass, half-life, branching ratio)**
  - **decay station.....**



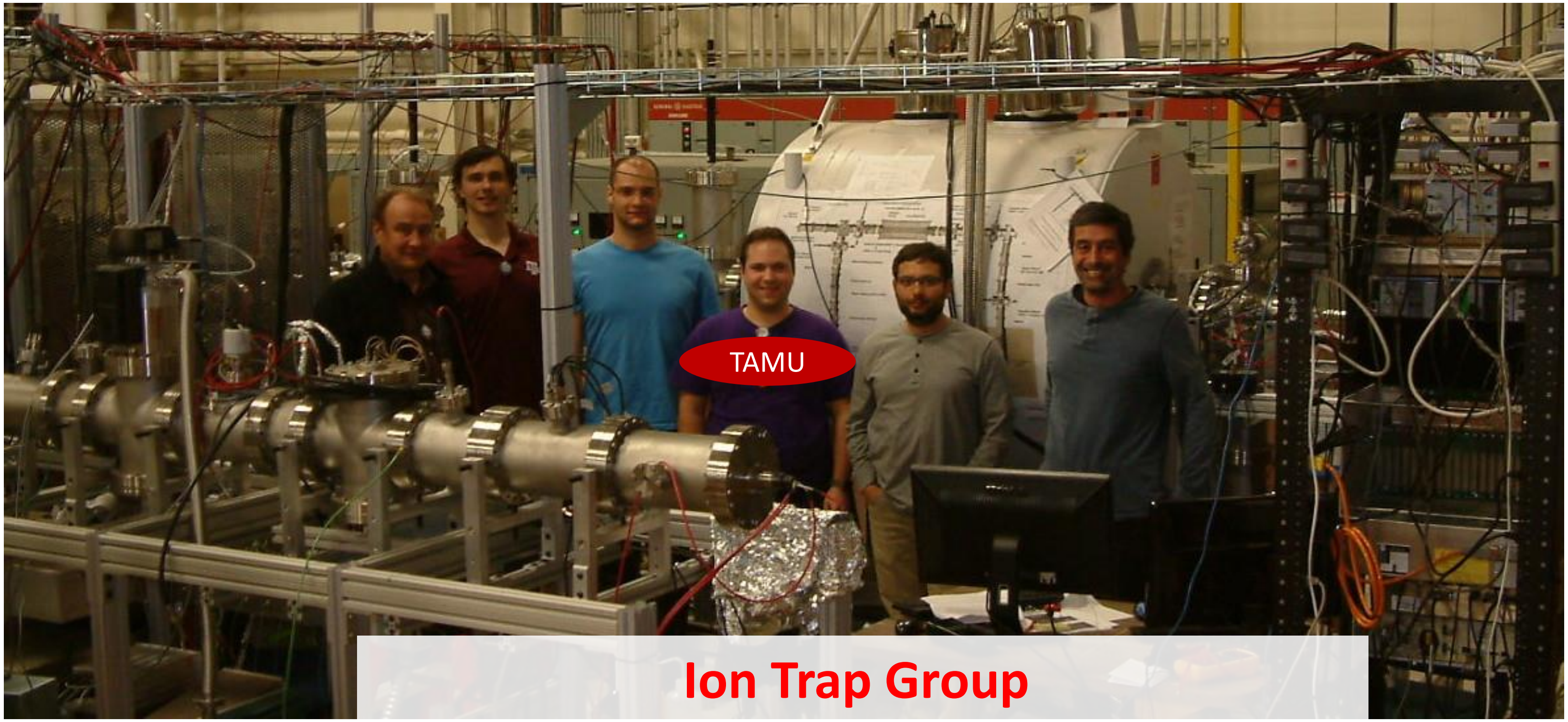
Ion Trap Group

@

Cyclotron institute, Texas A&M University

Funding Support:
The DOE and State of Texas

DOE DE-FG02-93ER40773, Early Career ER41747



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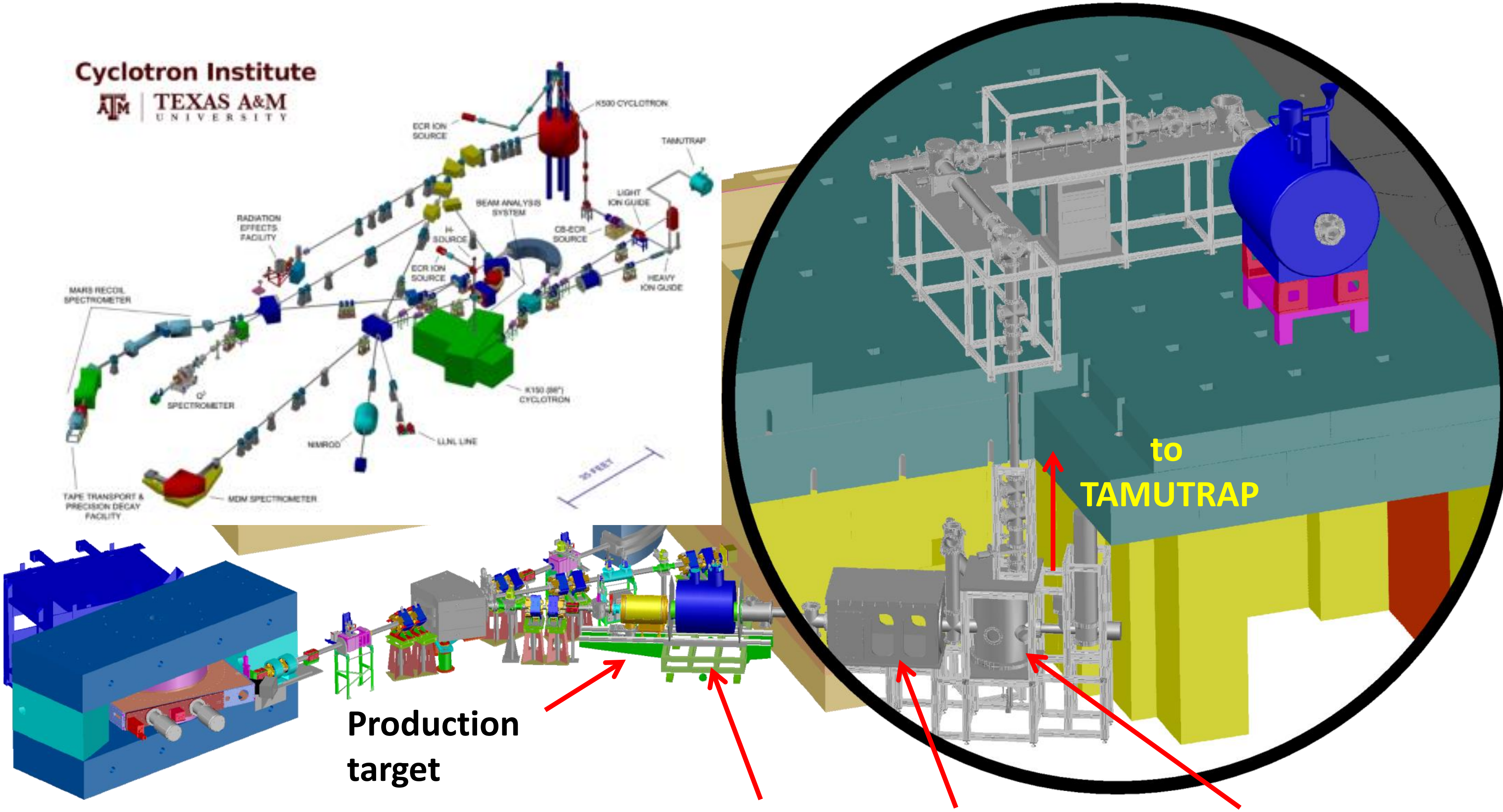
TAMUTRAP Facility



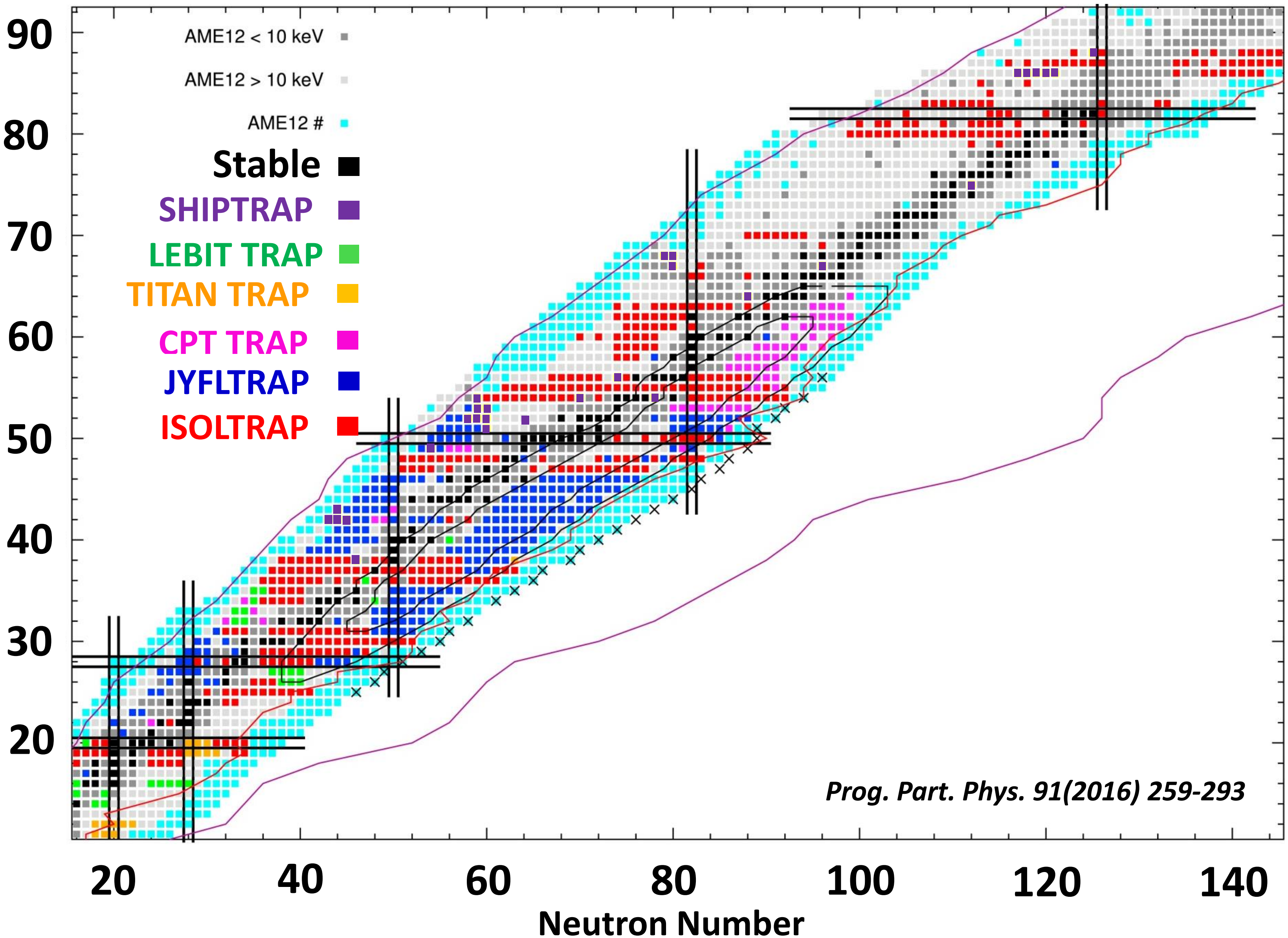
K150 Cyclotron

In-Flight (Heavy Ion Guide)

Or

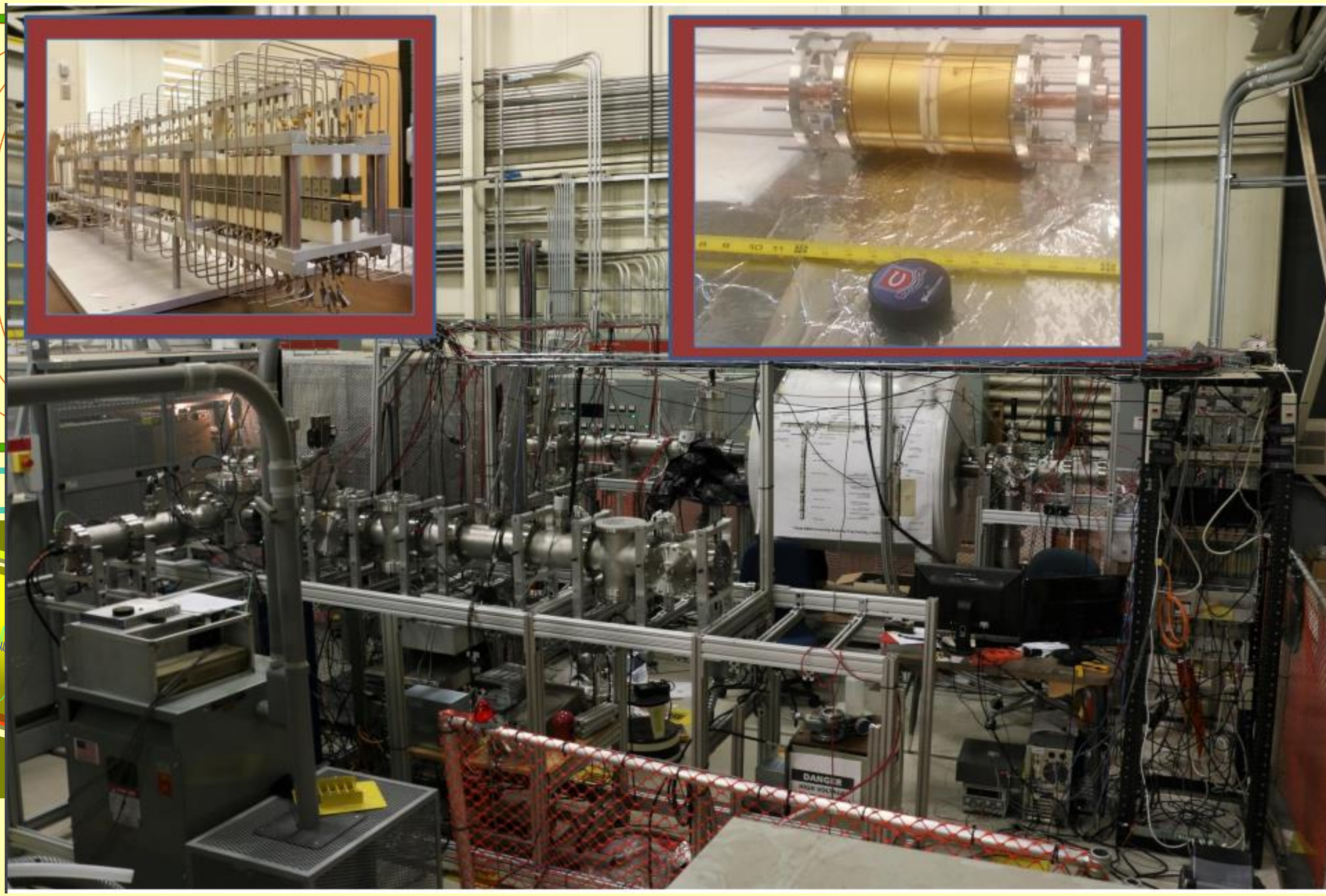
ISOL type (Light Ion Guide)

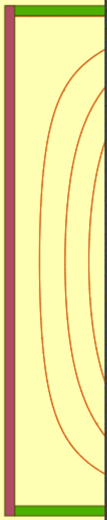
Ion trap facilities for mass measurements

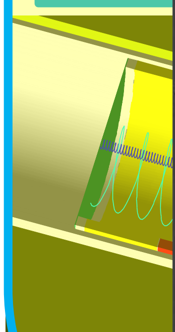


Penning trap for correlation & ft measurements

TAMUTRAP Facility aiming to perform $a_{\beta\nu}$ & *ft*-value measurements for β-delayed proton emitters







Beta &

misphere