TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Ion traps at rare-isotope-beam facilities

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Adjunct Asst. Professor, Univ. Victoria

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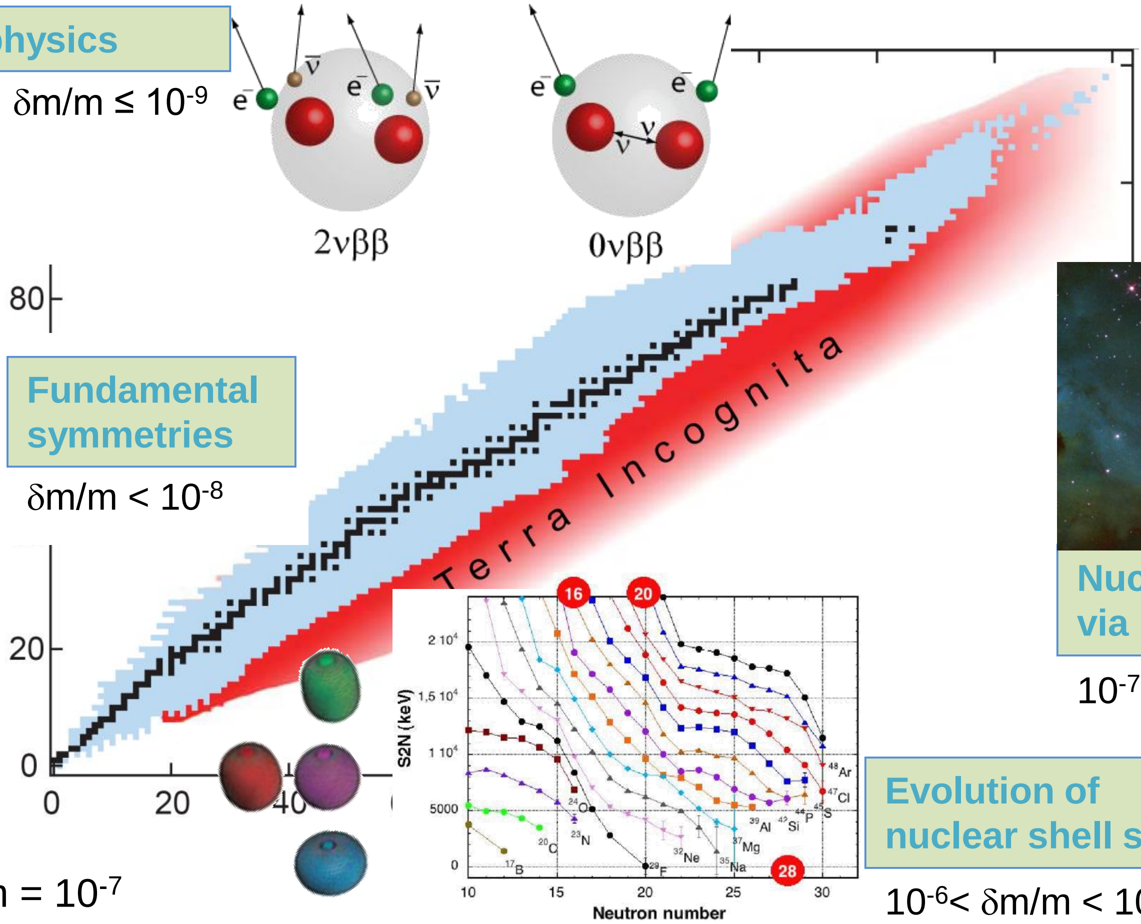
The atomic mass is needed input to understand …

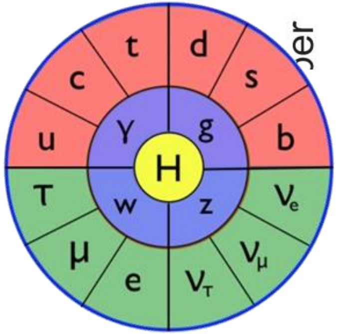
Neutrino physics

$\delta m/m \leq 10^{-9}$

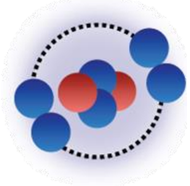


Fundamental symmetries

$\delta m/m < 10^{-8}$



Halos and skins



$\delta m/m = 10^{-7}$

Nucleosynthesis via r process

$10^{-7} < \delta m/m < 10^{-6}$

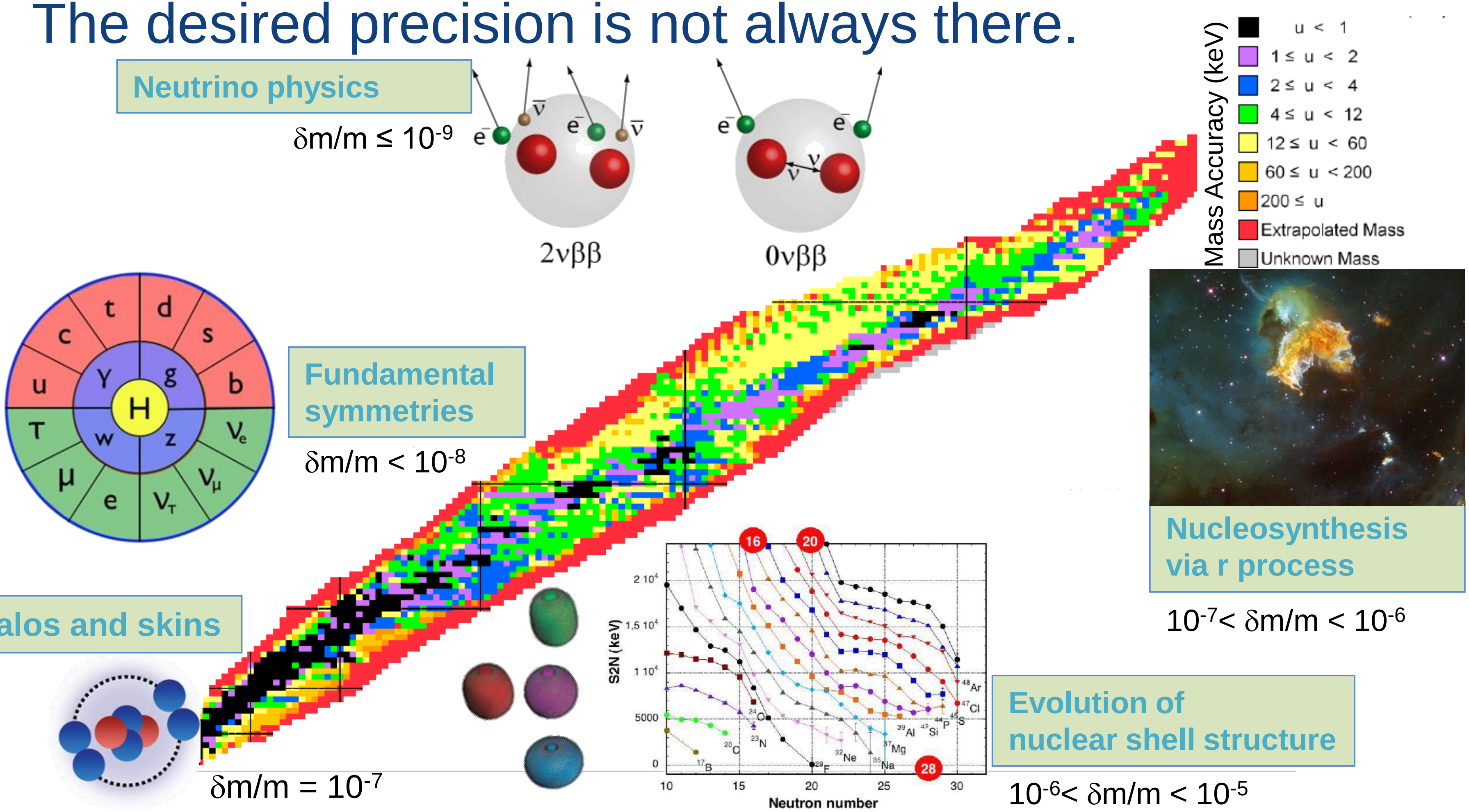
Evolution of nuclear shell structure

$10^{-6} < \delta m/m < 10^{-5}$

The desired precision is not always there.

Neutrino physics

$\delta m/m \leq 10^{-9}$



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How can we make high-precision measurements?

My wish list for an ideal laboratory

- easy & exact manipulation
- well-defined volume
- universal
- infinite observation time

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electromagnetic forces
+
good vacuum

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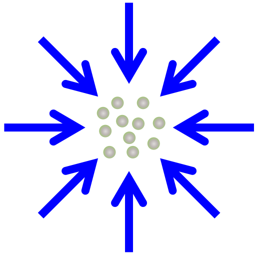
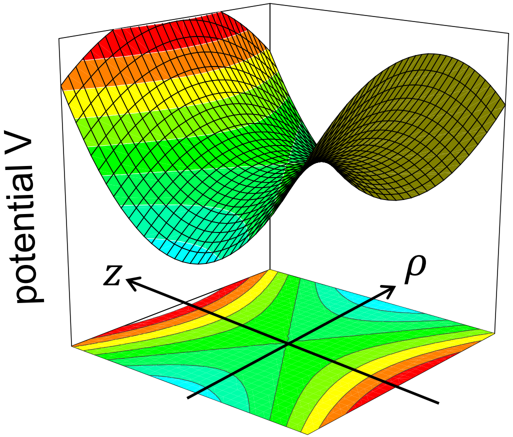
Want $\vec{F} = -q\nabla\varphi \propto -\vec{r}$



& satisfy $\Delta\varphi = 0$

→ find $\varphi \propto \frac{{\varphi_0}^2}{d^2}(\rho^2 - z^2)$



Four principal ion storage devices at RIB facilities.

Moving ions		“Stationary” ions	

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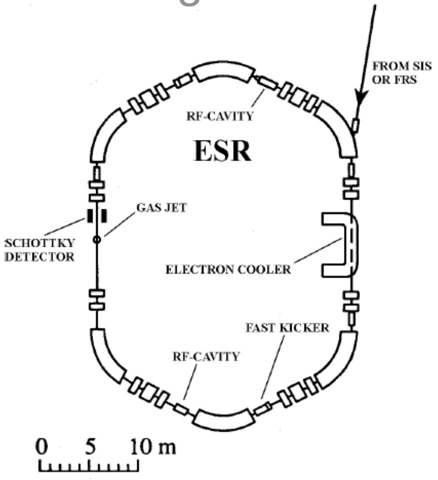
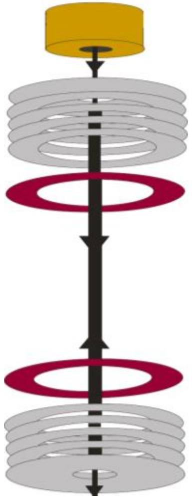
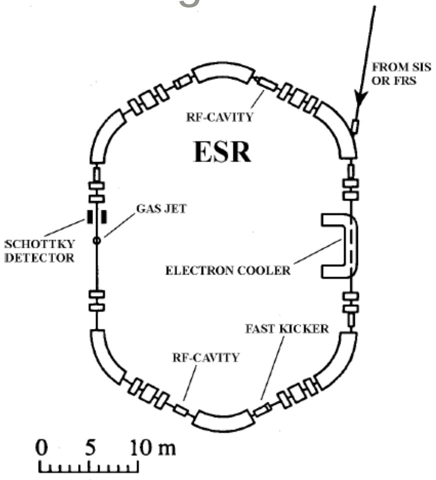
Moving ions		“Stationary” ions	
Storage Rings	Multi-reflection/ electrostatic traps		
Electromagnetic forces restrict ions to a ring.	Electrostatic mirrors trap ions.		

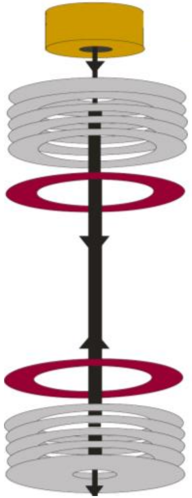


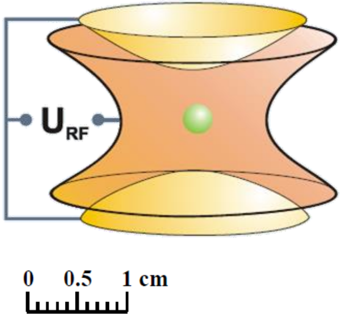


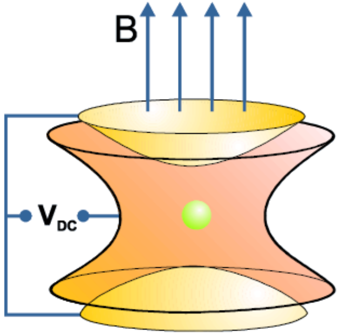
Four principal ion storage devices at RIB facilities.

Moving ions		“Stationary” ions	
Storage Rings	**Multi-reflection/ electrostatic traps**	**Paul trap**	**Penning trap**
Electromagnetic forces restrict ions to a ring.	Electrostatic mirrors trap ions.	Oscillating (RF) electric field between ring & end caps	Superposition of magnetic field (z) & electrostatic quadrupolar field







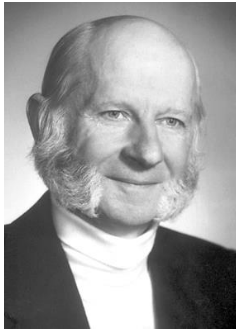


Ion traps are proliferating for a variety of purposes.

Frans Michel Penning

Foundation for Penning trap

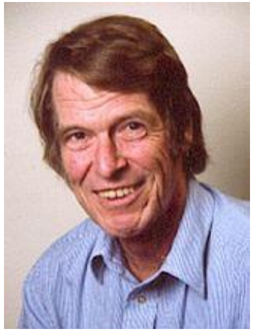
W. Paul



H. Dehmelt

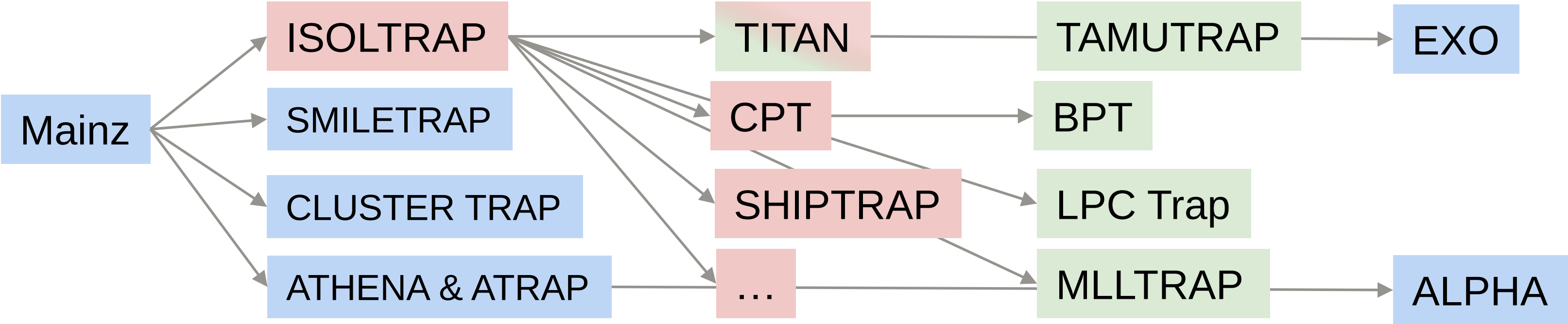
Nobel Prize 1989

Development of ion trap technique



H.-J. Kluge

Adaptation for RIB facilities



Mainz

ISOLTRAP

SMILETRAP

CLUSTER TRAP

ATHENA & ATRAP

TITAN

CPT

SHIPTRAP

…

TAMUTRAP

BPT

LPC Trap

MLLTRAP

EXO

ALPHA

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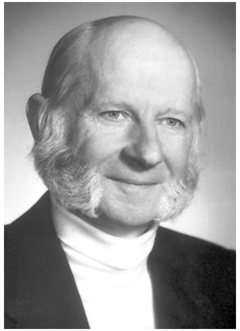

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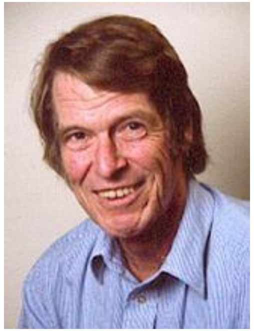

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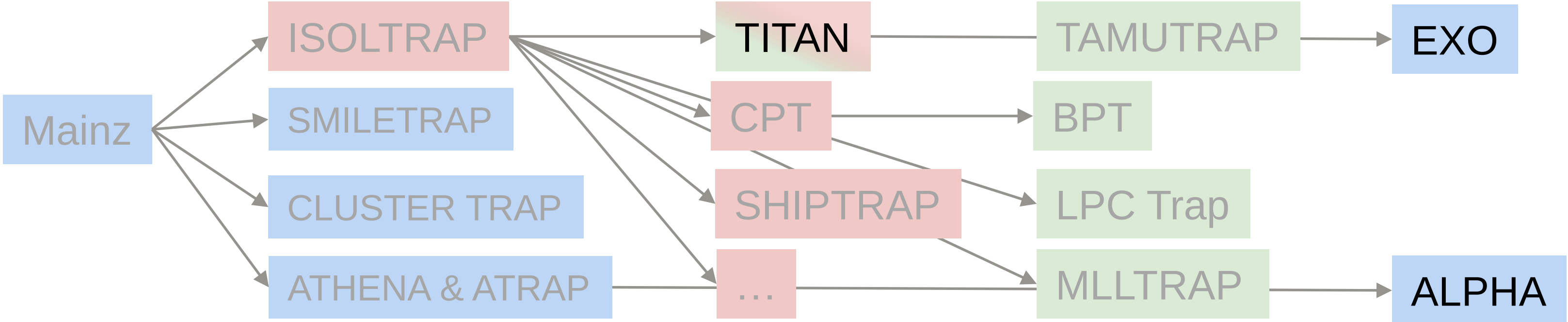
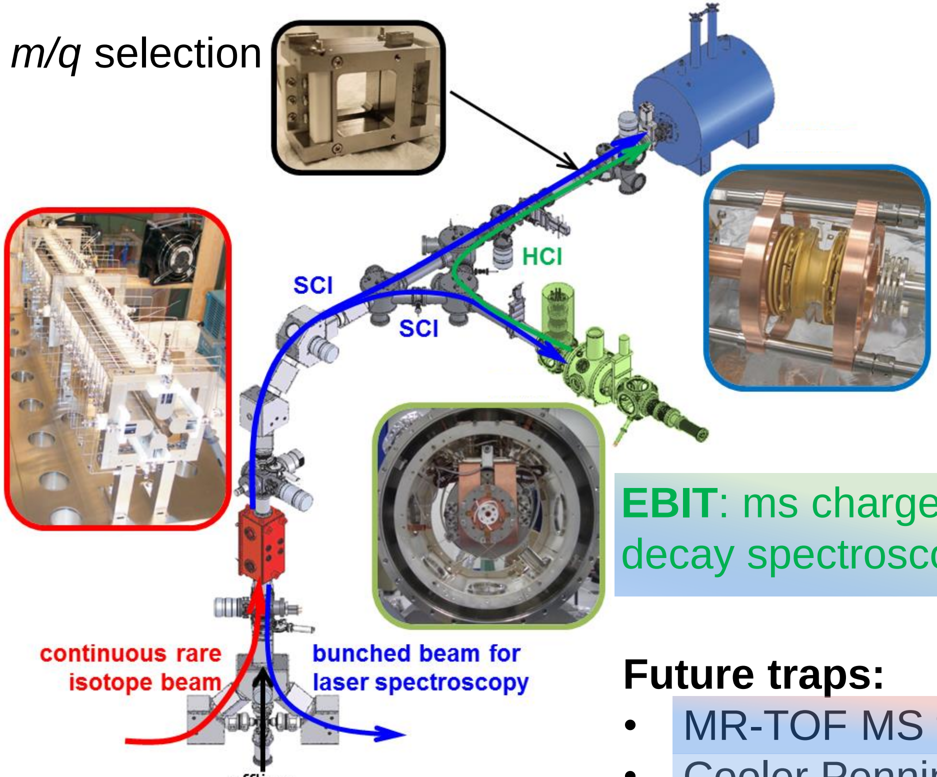


TRIUMF's Ion Trap for Atomic and Nuclear science uses 5 traps to prepare & measure RIB.



BNG: fast *m/q* selection

Cooler-Buncher: accumulation, cooling, and bunching

MPET: mass measurement via cyclotron frequency determination

EBIT: ms charge breeding decay spectroscopy

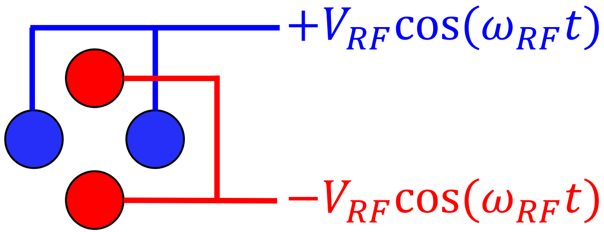
Future traps:

- MR-TOF MS for purification
- Cooler Penning trap to cool HCI

J. Dilling *et al.*, NIMB **204** (2003) 492

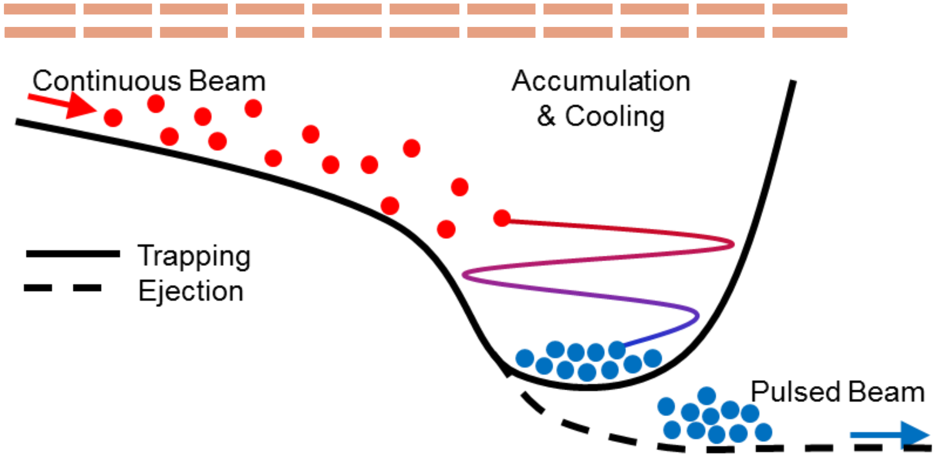
The buffer-gas-filled linear Paul trap accumulates, cools, & bunches the RIB.

- RadioFrequency Quadrupole → transverse confinement



- Segmentation → axial trapping

- Buffer gas → cooling



P.H. Dawson, *Quadrupole Mass Spectrometry and its Applications*, Elsevier Science, 1976

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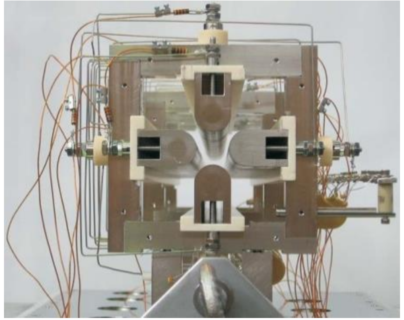

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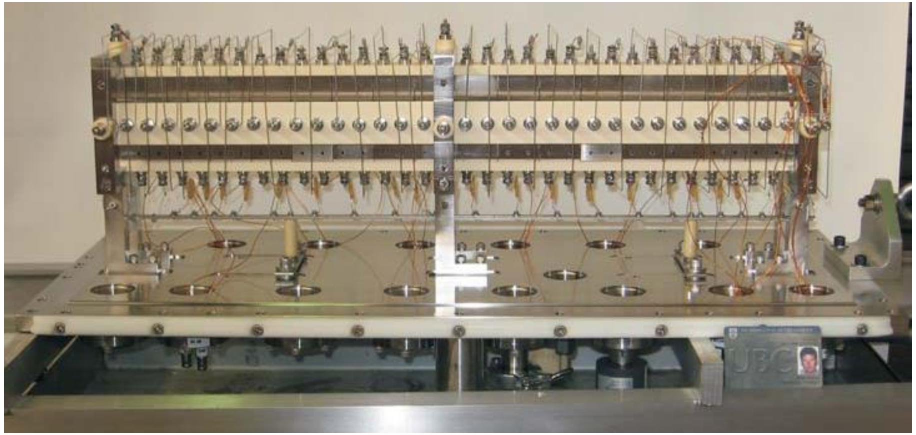


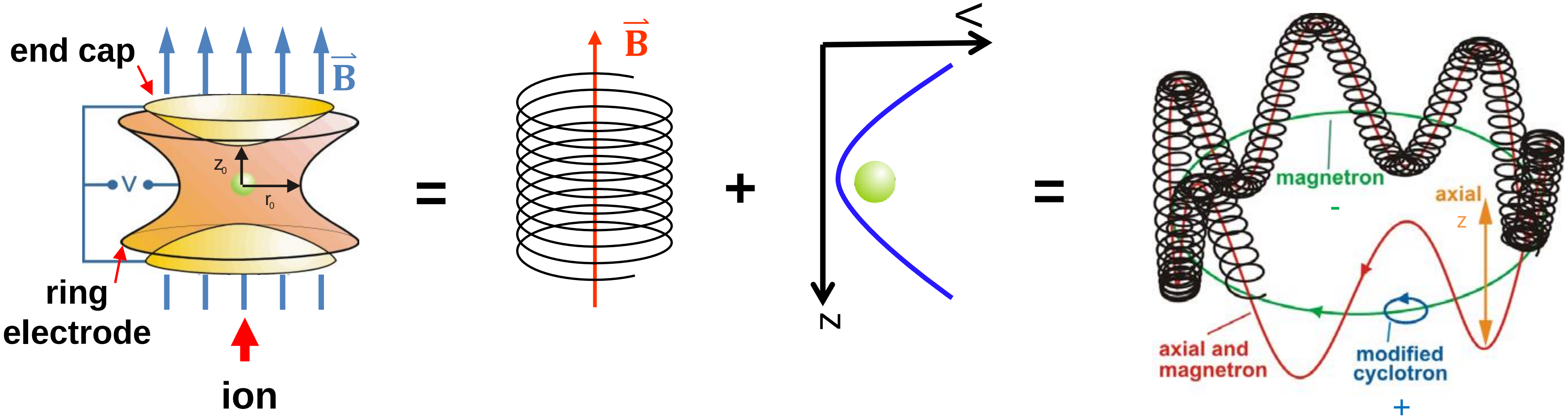
- Segmentation → axial trapping
- Buffer gas → cooling

T. Brunner *et al.*, NIMA **676** (2012) 32

A Penning trap accesses the cyclotron frequency & therefore the ion’s mass.

$2\pi\nu_c = (qe/m) \cdot B$

$\nu_c = \nu_+ + \nu_-$



RIB mass measurements with precisions up to ~10^{-9}
and for half-lives as low as 9 ms (^{11}Li^{+} @ TITAN)

L.S. Brown & G. Gabrielse, Rev. Mod. Phys., 58 (1986) 233

Measurement PEnning Trap accesses the cyclotron frequency & therefore the ion's mass.

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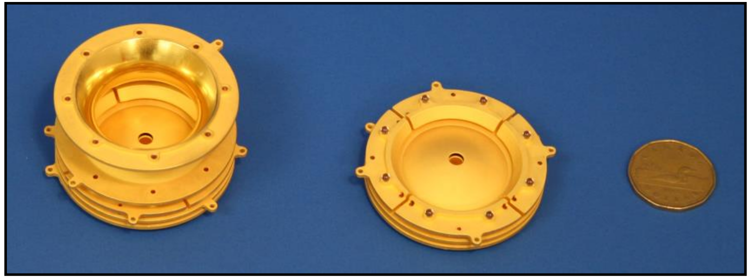
3.7 T

+



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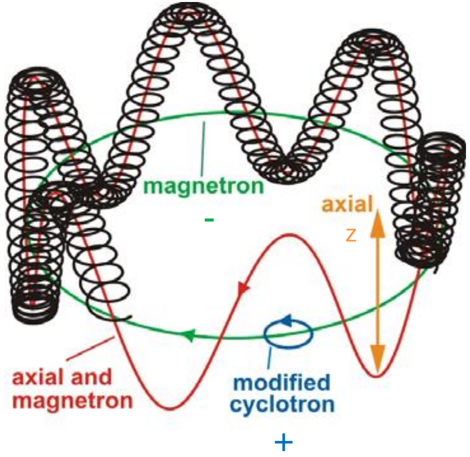
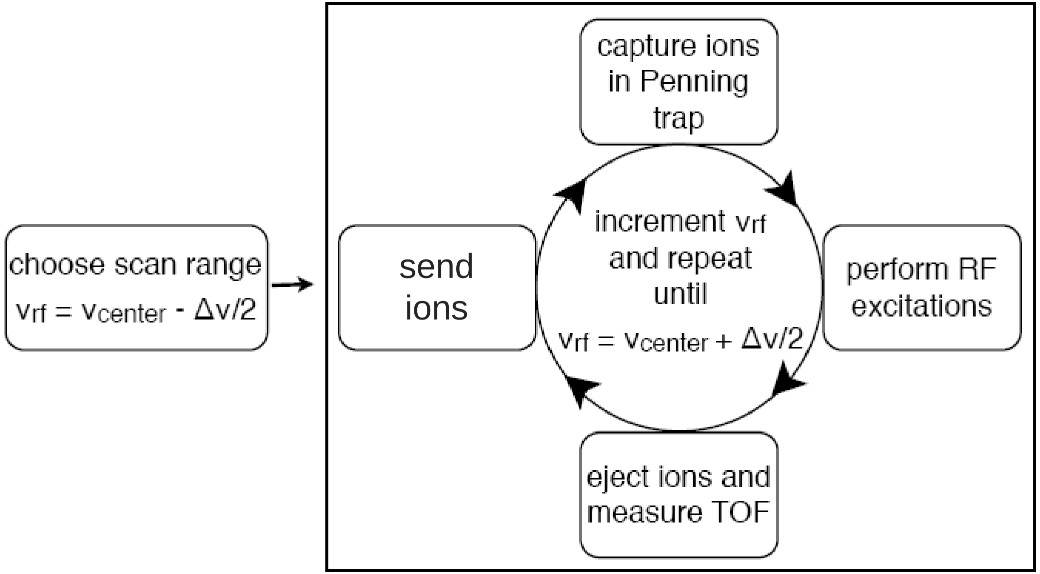


RIB mass measurements with precisions up to $\sim 10^{-9}$ and for half-lives as low as 9 ms ($^{11}Li^+$ @ TITAN)

M. Brodeur *et al.*, PRC **80** (2009) 024314; M. Brodeur *et al.*, IJMS **20** (2012) 310

Cyclotron frequency can be determined via Time-of-Flight Ion-Cyclotron-Resonance technique.



choose scan range
$\nu_{rf} = \nu_{center} - \Delta\nu/2$

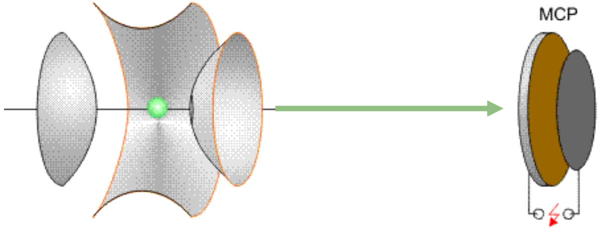
send ions

capture ions in Penning trap

perform RF excitations

eject ions and measure TOF

increment ν_{rf} and repeat until
$\nu_{rf} = \nu_{center} + \Delta\nu/2$



M. Konig, *et al.*, Int. J. Mass Spec. 142 (1995) 93

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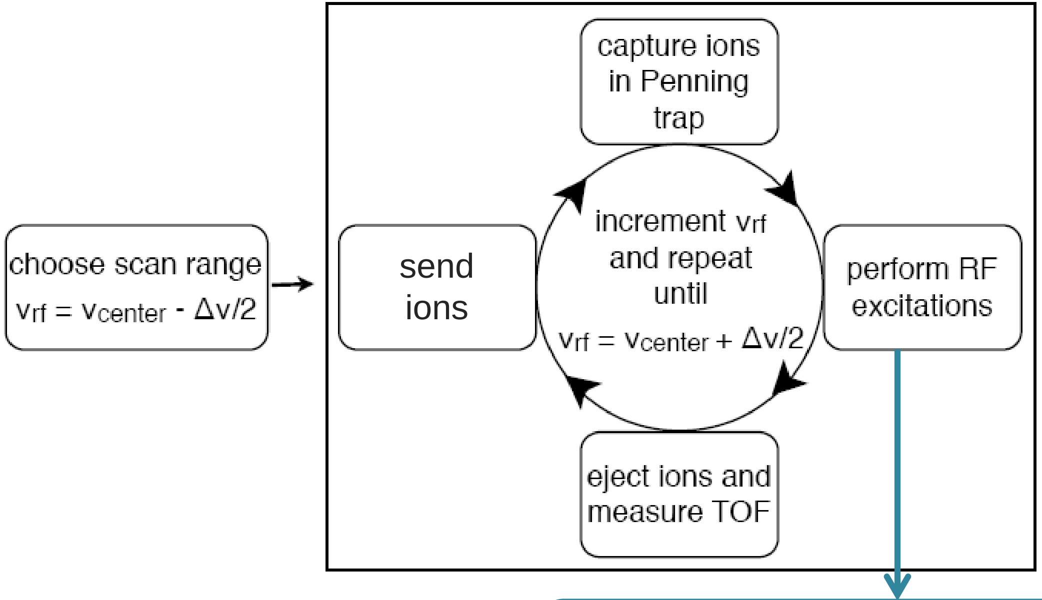

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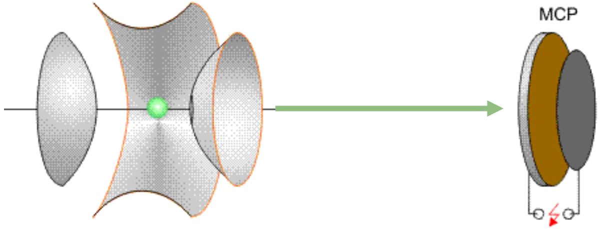
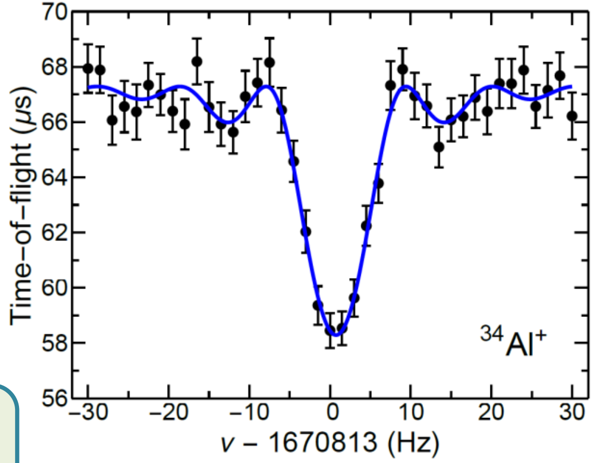


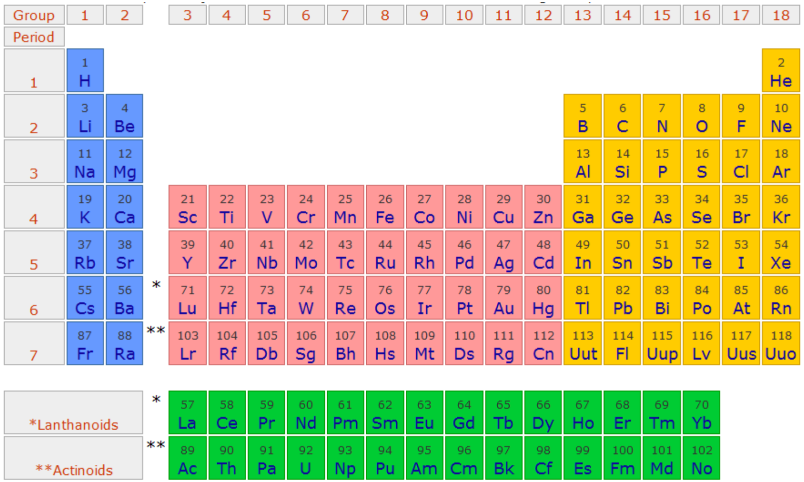


If $\nu_{rf} = \nu_c$, the ion's energy increases

M. Konig, *et al.*, Int. J. Mass Spec. 142 (1995) 93

What is special about ^{34}Al and its neighbours?

A brief aside in atomic physics: electrons occupy shells.



Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
*Lanthanoids			*	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		
**Actinoids			**	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		

www.webofelement.com; A. Bohr & B. Mottleson

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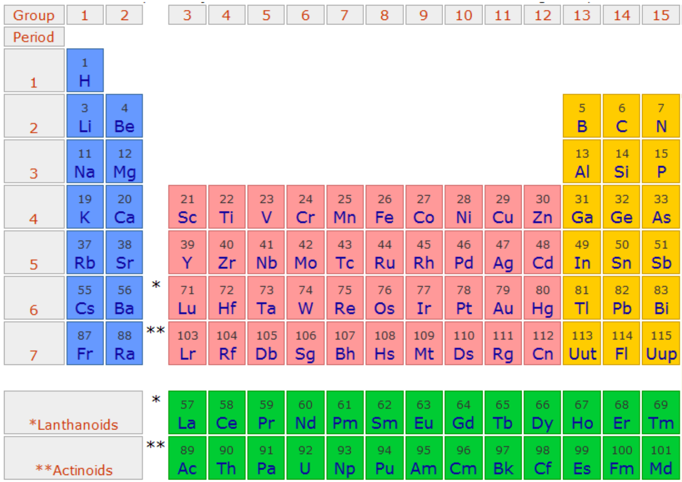

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4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As			
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb			
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi			
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup			
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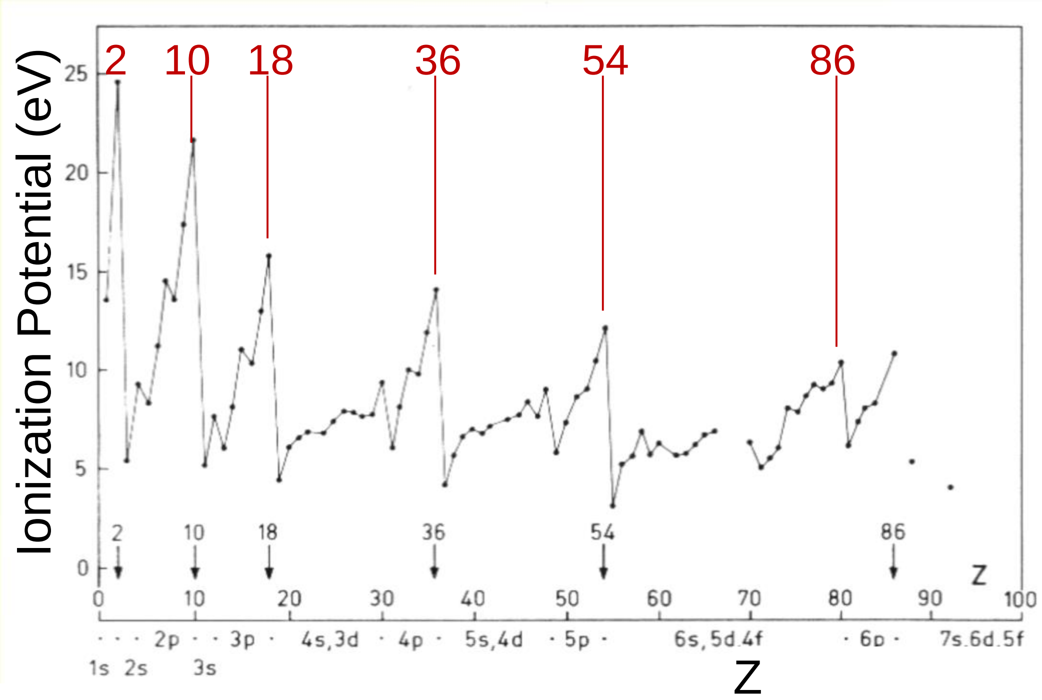
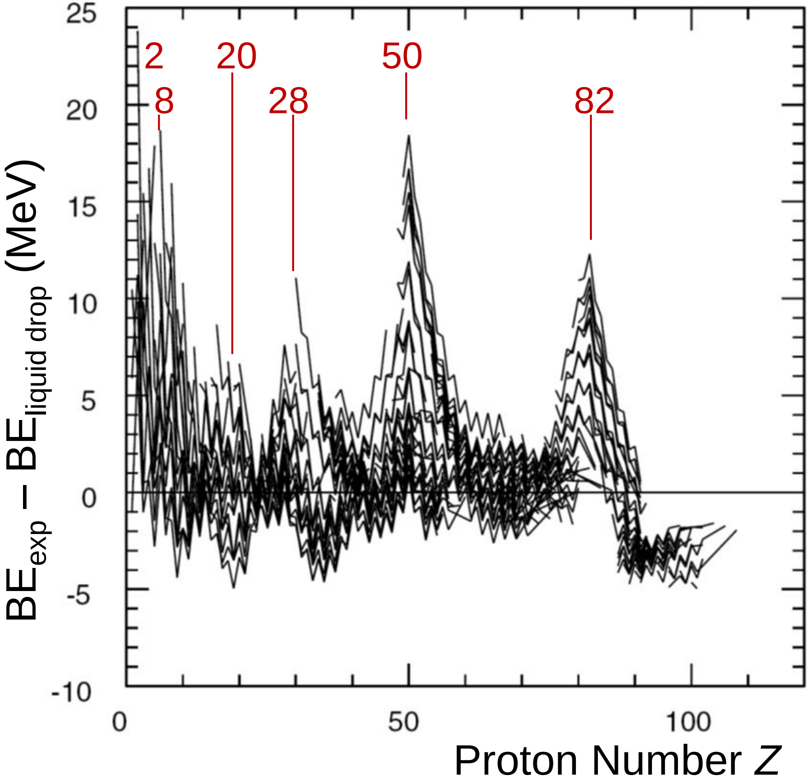
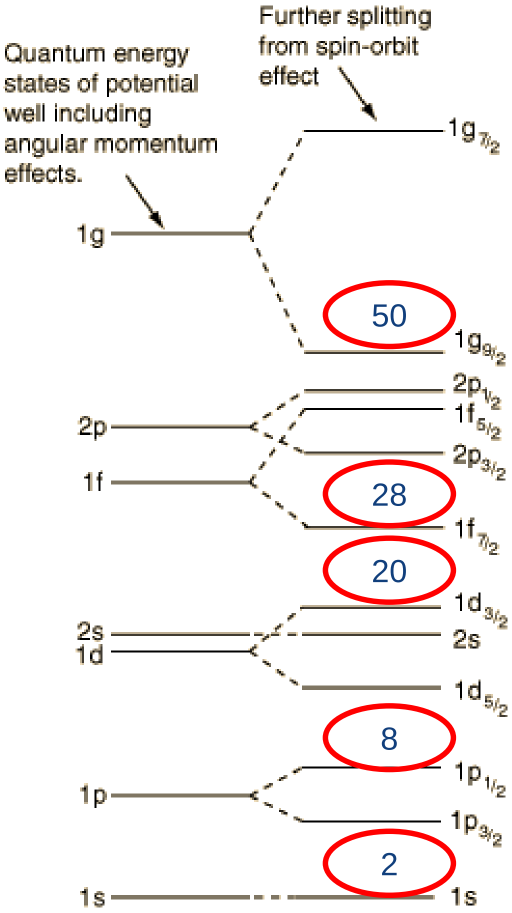


www.webofelement.com; A. Bohr & B. Mottleson

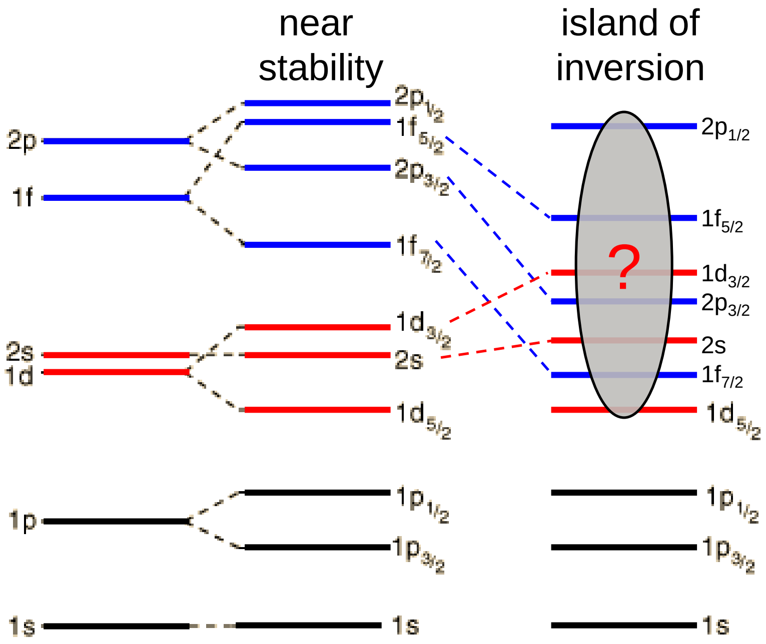
Neutrons & protons also occupy shells, which occur at "magic numbers."




Quantum energy states of potential well including angular momentum effects.

Further splitting from spin-orbit effect

Nuclear shells may evolve as the ratio of Z/N grows more unstable,



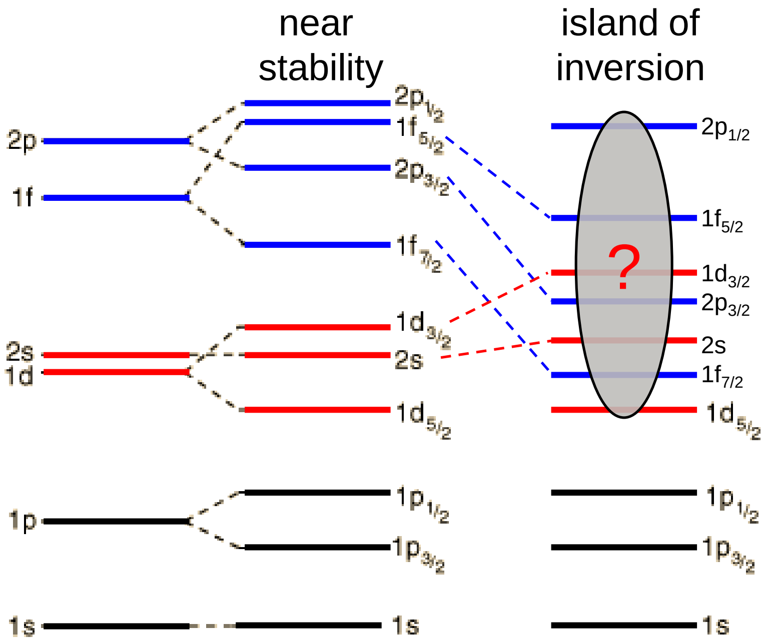
causing shells to disappear or new ones to emerge.

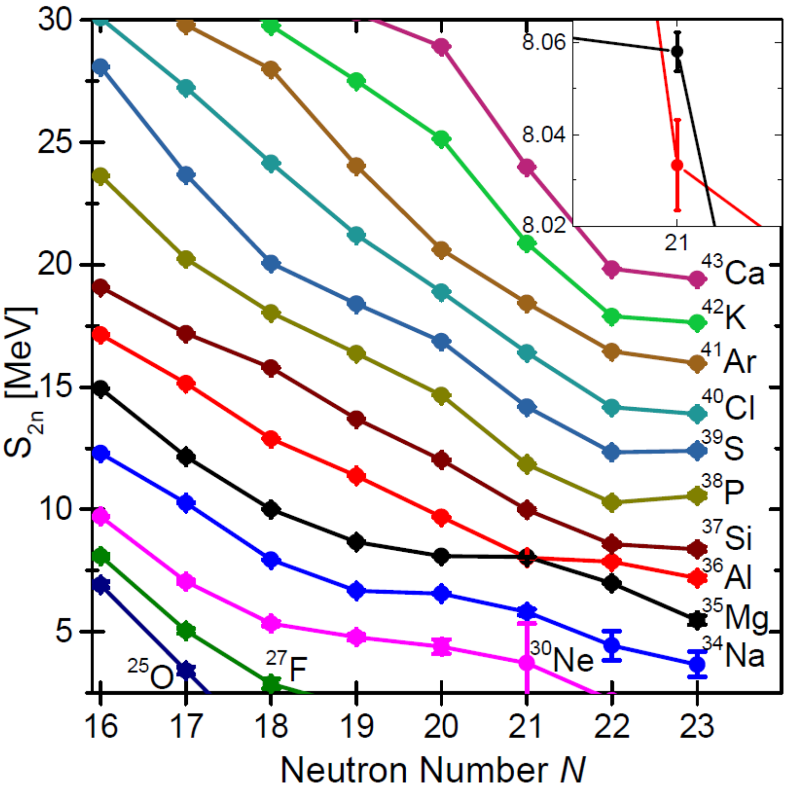
The TITAN campaign at $N = 20$ has measured masses of $^{29\text{-}32}$Na, $^{30\text{-}34}$Mg, $^{29\text{-}35}$Al ($T_{1/2} \geq$ 12.9 ms for ^{32}Na),

Improving precisions (often 10x) and finding deviations for Na & Mg from prior measurements.

A. Chaudhuri *et al*, PRC 88 (2013) 054317; AAK *et al*, *PRC* 92 (2015) 061301; A.T. Gallant, *et al*, in preparation

TITAN's values indicate the disappearance of the N = 20 shell and large gains in correlation energy.





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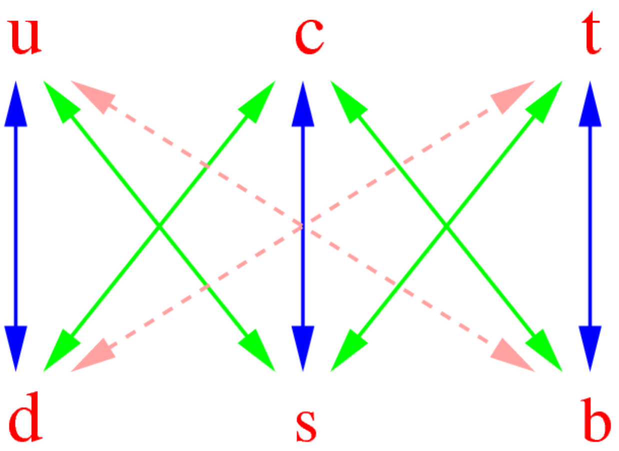
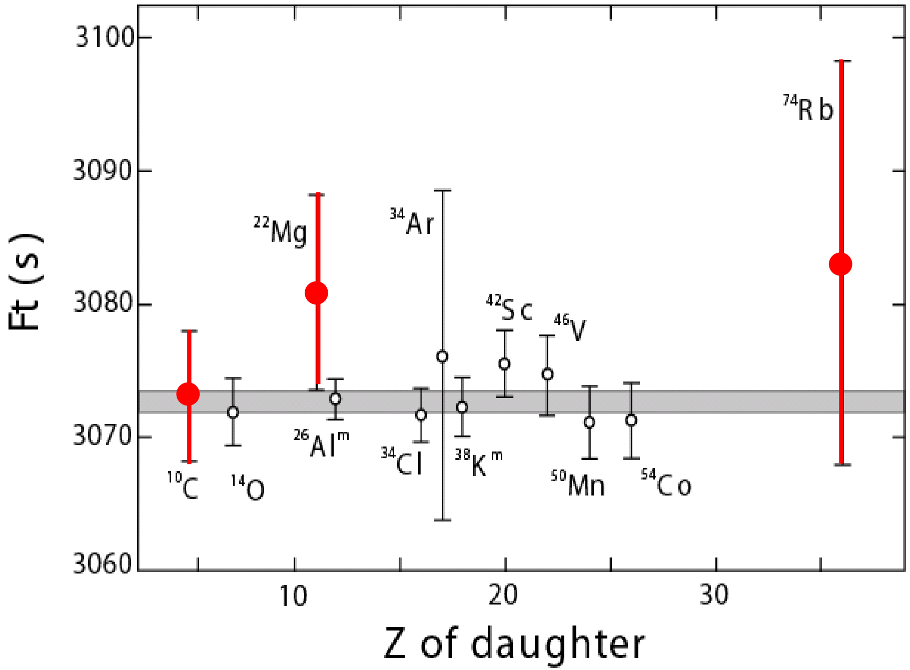
Precisions $\delta m/m$ of 10^{-7} are routine;
can we do better?

Testing the unitarity of the quark-mixing (CKM) matrix needs high-precision measurements.



Direct Q-values measured.

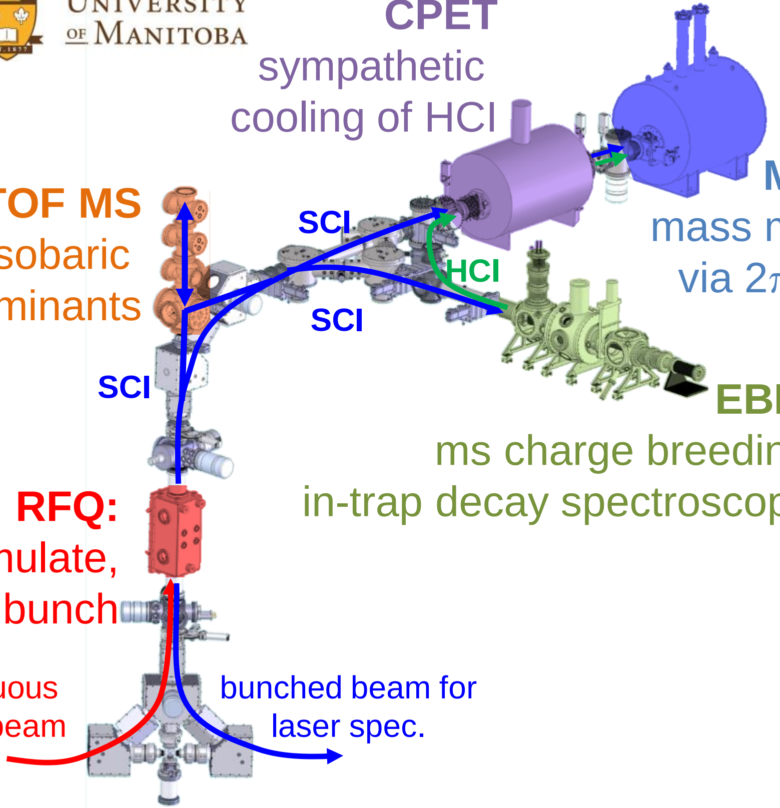
$\frac{\delta m}{m} \sim 10^{-9}$ demonstrated.



Figures adapted from https://inspirehep.net/record/1083304/plots; I. Towner & J.C. Hardy, PRC (2010)
S. Ettenauer, et al, PRL 107, 272501; A.A. Kwiatkowski, *et al*, AdP (2013); M.P. Reiter, under analysis

How can we purify the beam to the level required for high-precision experiments?

Two new traps will be added to extend the reach of TITAN.



UNIVERSITY OF MANITOBA

CPET
sympathetic
cooling of HCI

MPET:
mass measurement
via $2\pi \nu_c = q/m \cdot B$

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MR-TOF MS
remove isobaric
contaminants

EBIT
ms charge breeding
in-trap decay spectroscopy

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

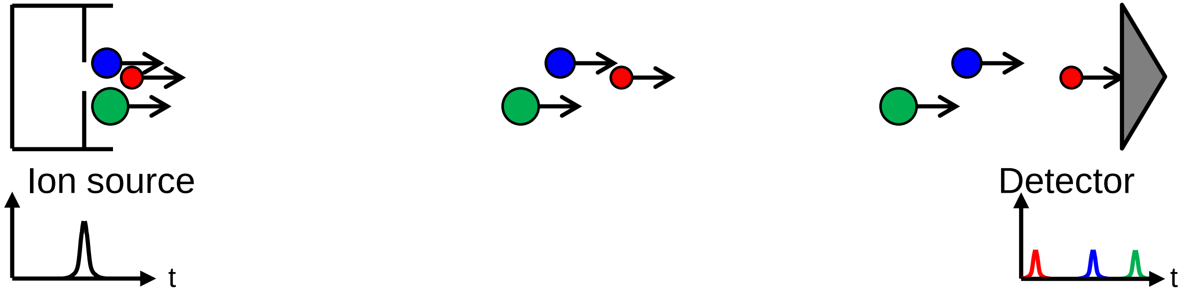
RFQ:
accumulate,
cool, & bunch

continuous
ISAC beam

bunched beam for
laser spec.

Multi-reflection time-of-flight mass spectrometers are based on simple kinematics.

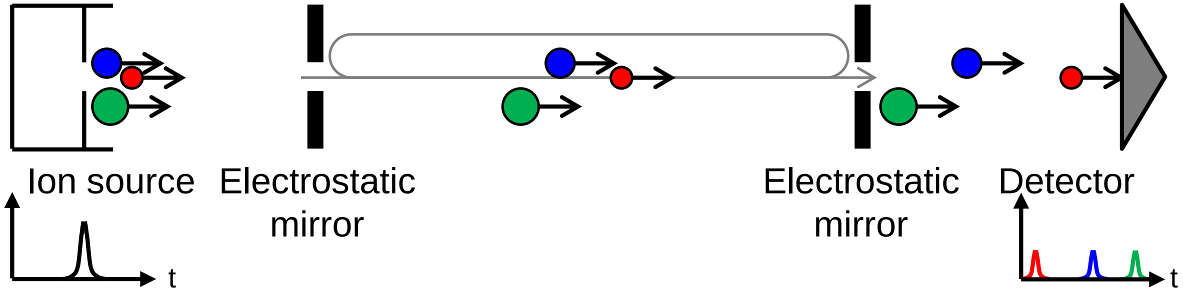
$$TOF = \frac{L}{v} = \frac{L}{\sqrt{2E}} = \sqrt{\frac{m}{q}} \int \frac{dz}{\sqrt{2V(z)}}$$



Separation increases with flight path → longer path length

Multi-reflection time-of-flight mass spectrometers are based on simple kinematics.

$$TOF = \frac{L}{v} = \frac{L}{\sqrt{2E}} = \sqrt{\frac{m}{q}} \int \frac{dz}{\sqrt{2V(z)}}$$



Separation increases with flight path → longer path length OR multiple passes on same path

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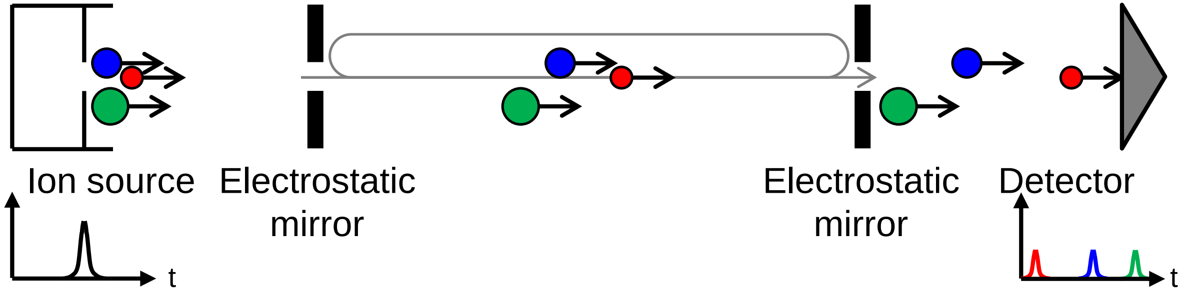

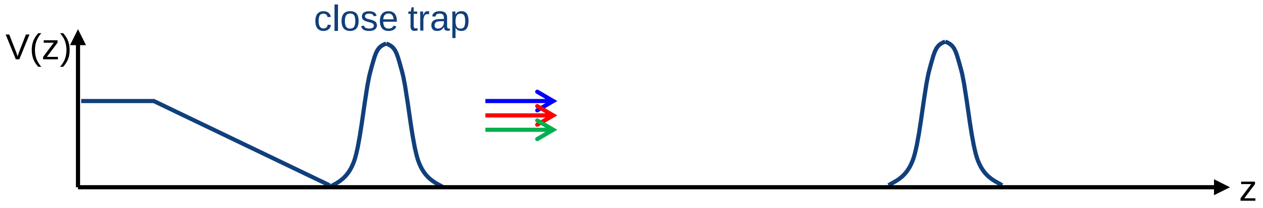

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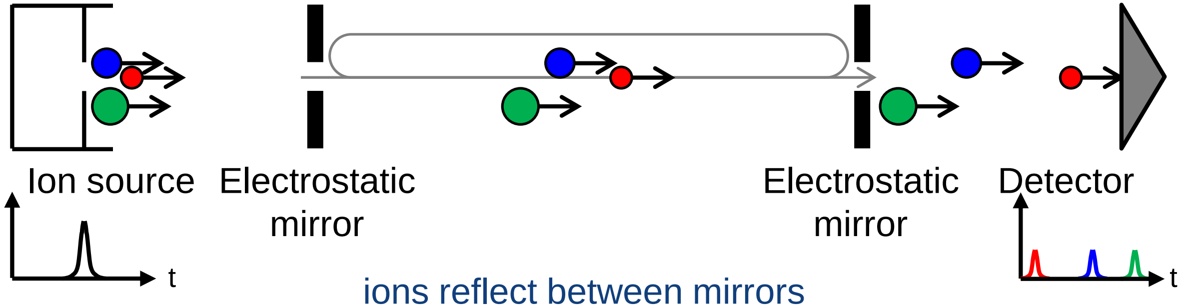
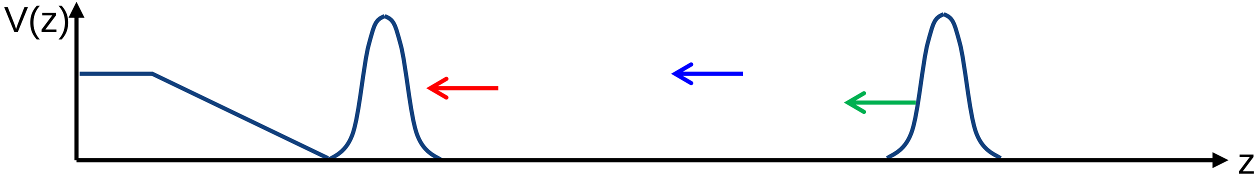


ions reflect between mirrors
& separate by *m/q*



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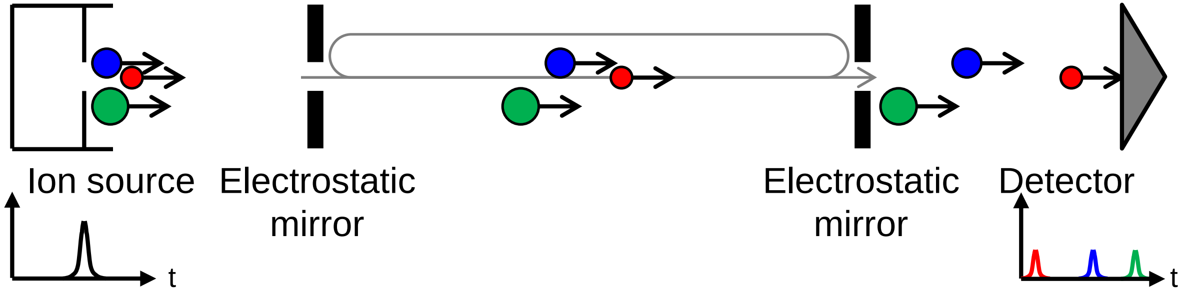
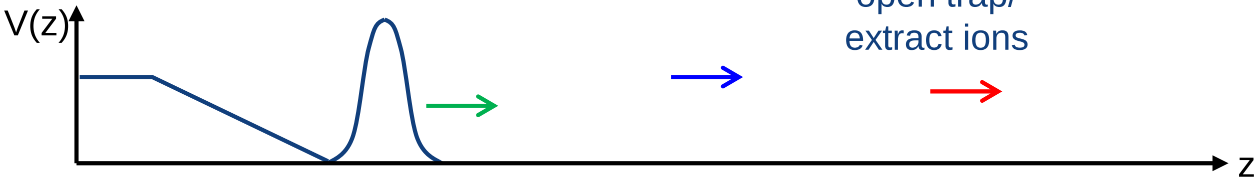
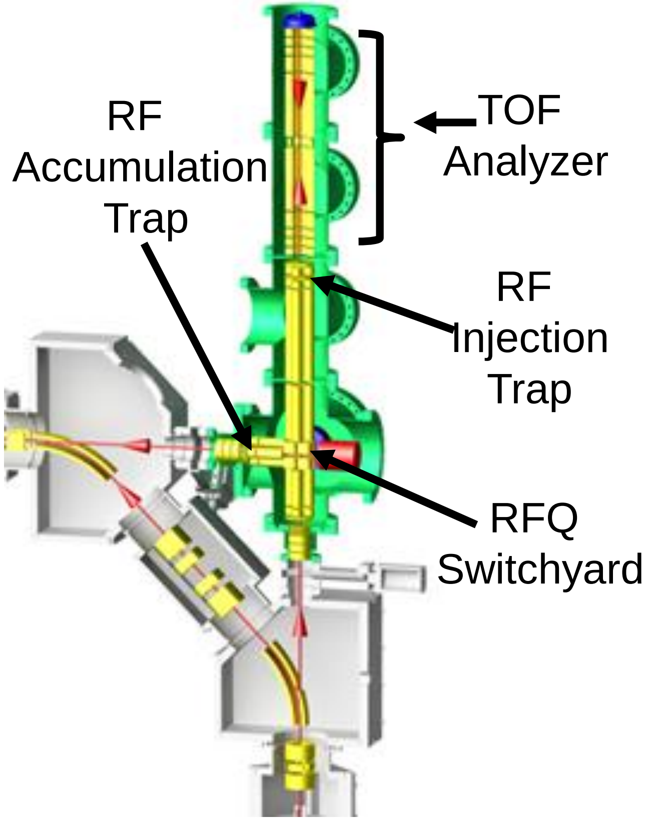


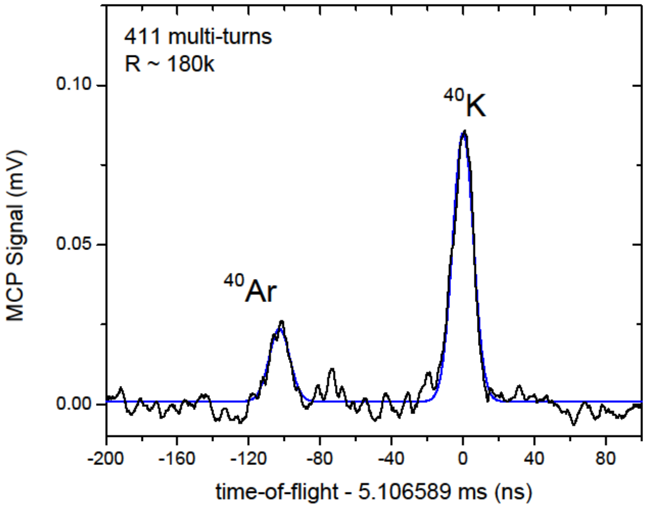


Separation increases with flight path → longer path length OR multiple passes on same path

MR-TOF demonstrated to be a fast, broadband isobar separator off-line

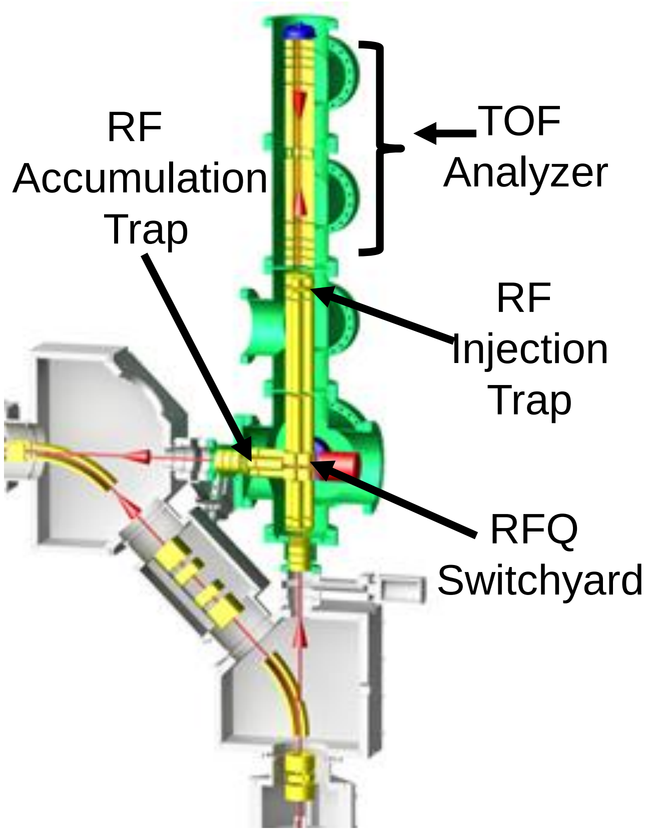


- Resolving power depends on number of passes or multi-turns
- R ~10^5 achieved in a few ms for A = 40



C. Jesch, Hyper. Int. 235 (2015) 97; D.A. Short for M.Sc. thesis, SFU

MR-TOF will be used for fast mass measurements.



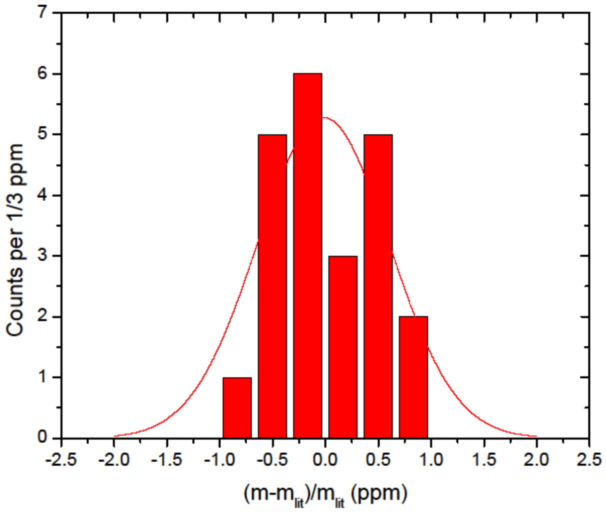
RF Accumulation Trap

TOF Analyzer

RF Injection Trap

RFQ Switchyard

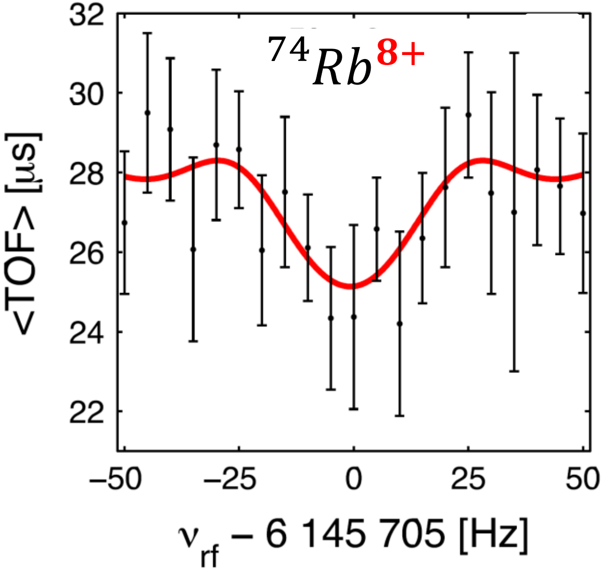
$^{40}Ar^{+}$ ($^{40}K^{+}$ for reference) agrees with AME 2012

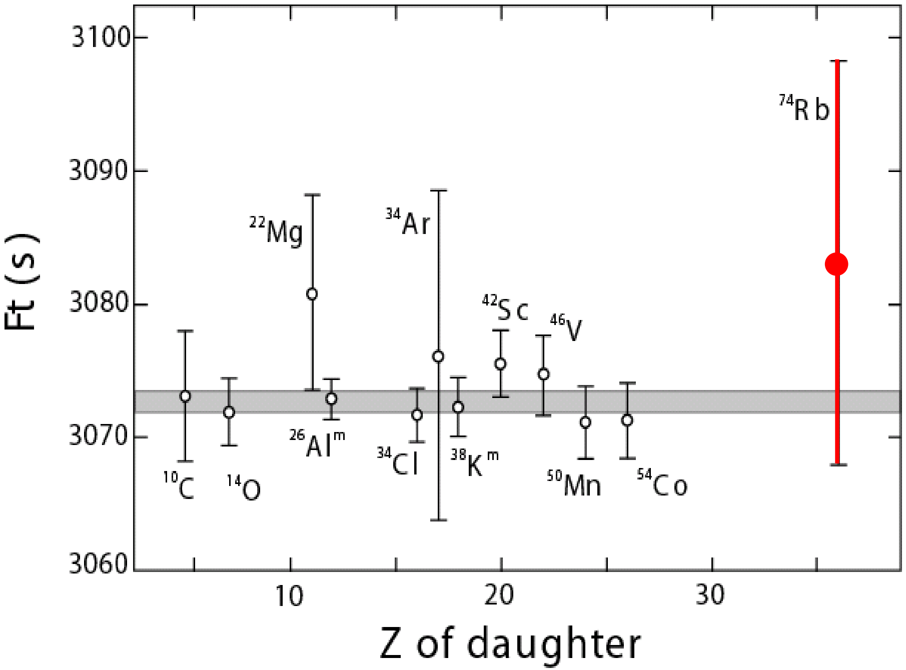


C. Jesch, Hyper. Int. 235 (2015) 97; D.A. Short for M.Sc. thesis, SFU

What else can be done to boost measurement precision?

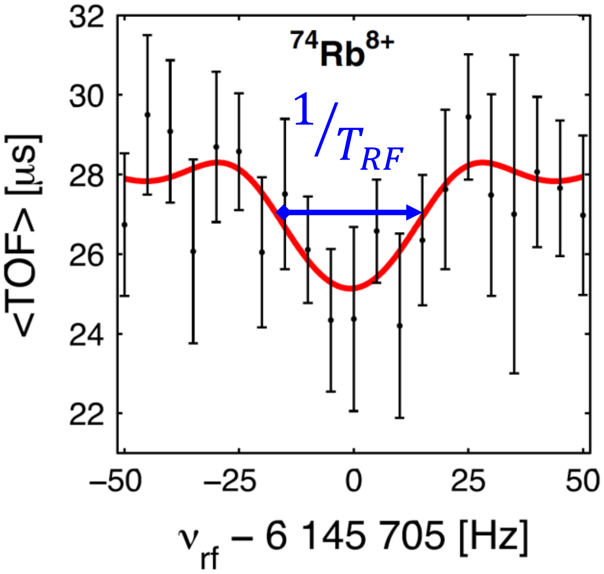
Testing the unitarity of the quark-mixing (CKM) matrix needs high-precision mass determinations.





I. Towner & J.C. Hardy, PRC (2010); S. Ettenauer, et al, PRL 107, 272501

Higher charge states can improve precision or reduce beam time requirements.



$$\frac{\delta m}{m} \propto \frac{m}{q\,e\,B\,T_{RF}\sqrt{N}}$$

N = statistics → limited by yield

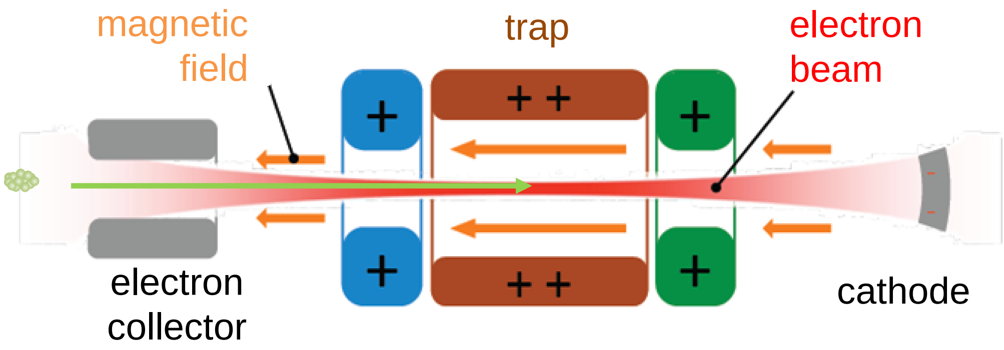
T_{RF} = measurement time → limited by half life

B = magnetic field → limited by technology

q = charge state → limited by Z

M.C. Simon, *et al*, RSI 83 (2012) 02A912

Ions are charge bred in the Electron Beam Ion Trap, a Penning trap with an electron beam.



Maximum charge state depends on *Z*, electron beam energy, electron beam current, & charge breeding time

A. Lapierre *et al.*, NIMA **624** (2010) 54

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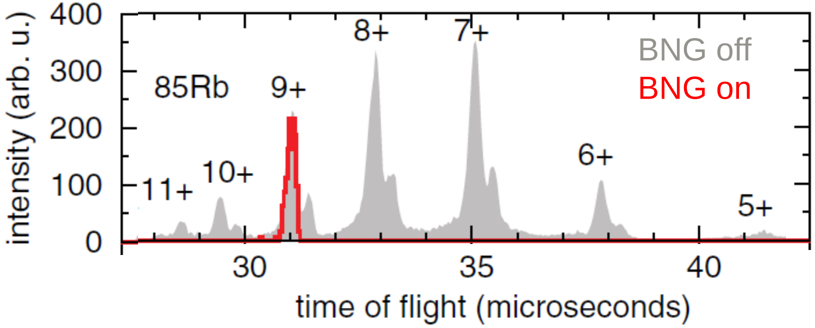
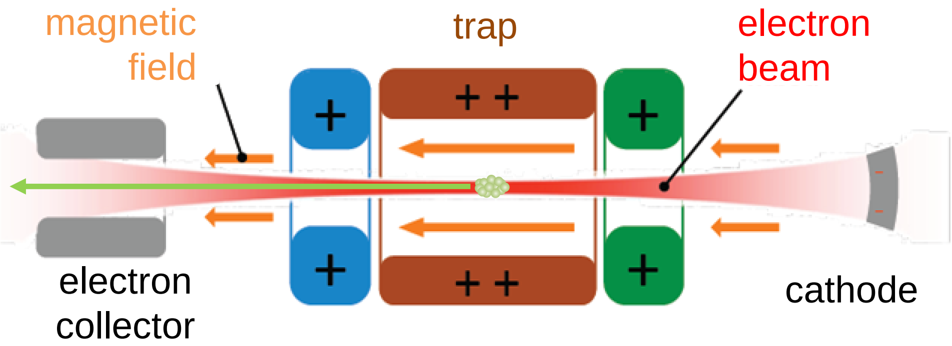

extract highly charged ions



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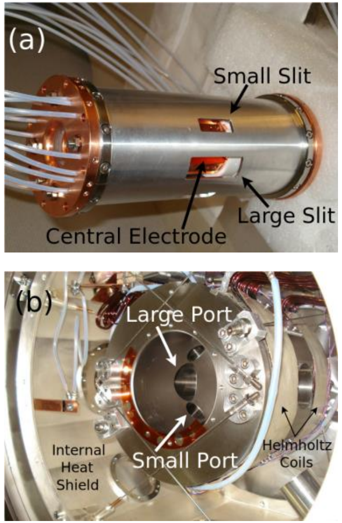
TITAN’s EBIT provides optical access, allowing for in-trap decay spectroscopy.



Objective: benchmark $2\beta 2\nu$ nuclear matrix elements

Advantages: no backing material
- β’s directed away from γ detectors
- trapper techniques/manipulation
- high purity
- HCI compatible

A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, NIMA, 780 (2015) 91

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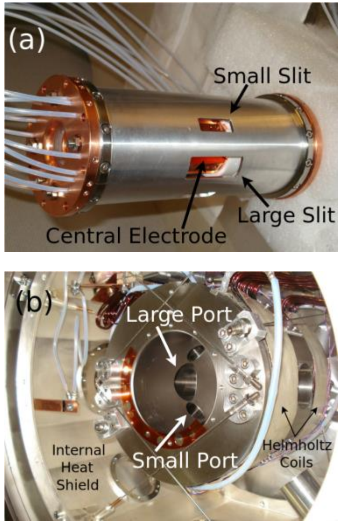
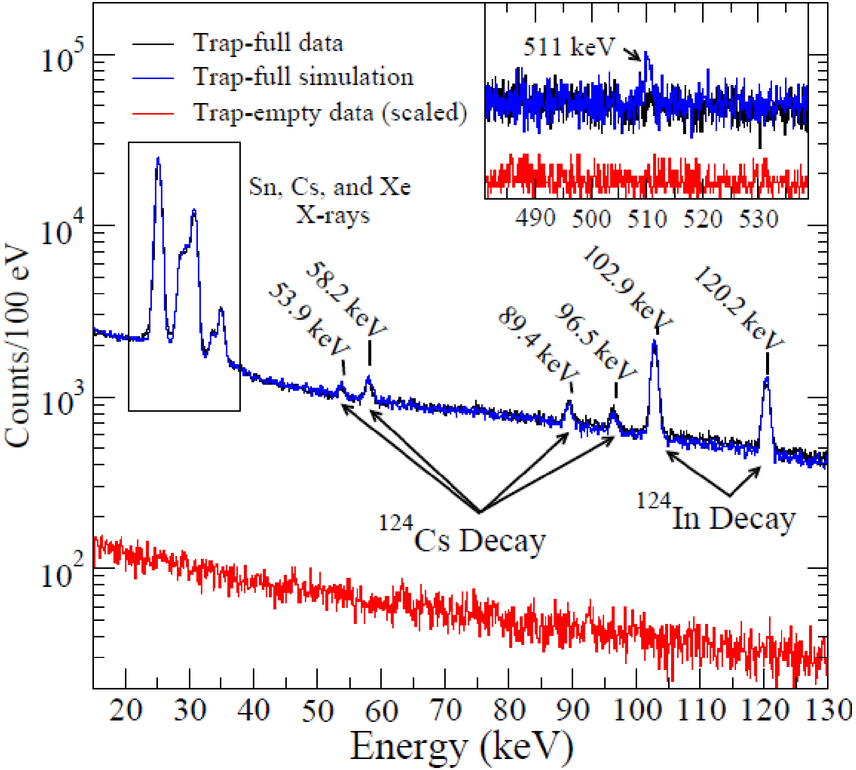




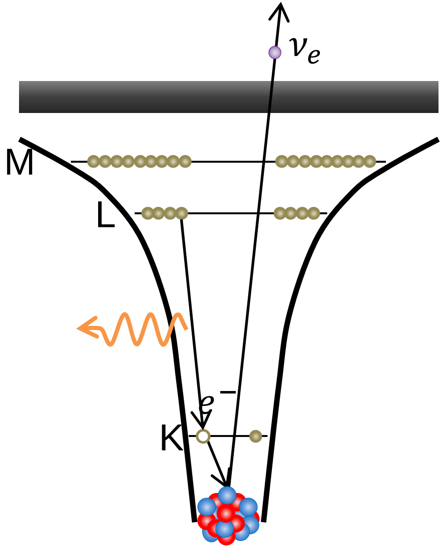
A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, NIMA, 780 (2015) 91

Highly Charged Ions have intrinsic scientific value.

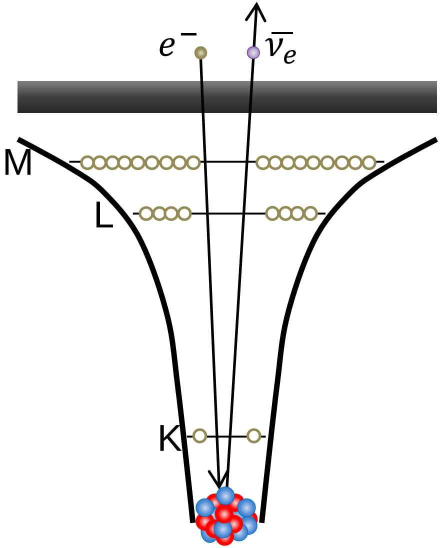
$$(N,Z) + e^- \rightarrow (N+1,Z-1) + \nu_e$$

In a neutral atom, the nucleus captures a K-shell e^-; then the atom emits an x-ray as a higher e^- fills vacancy

Orbital Electron Capture



Free Electron Capture



For bare ions, orbital EC is forbidden

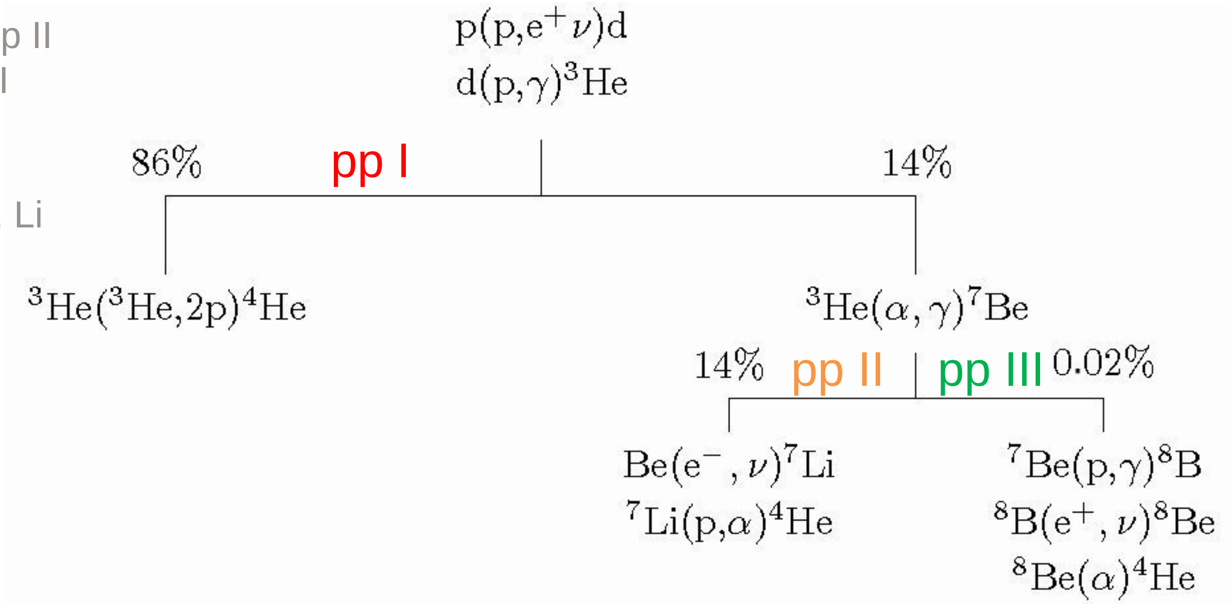
- decay only by β^+ decay if allowed
- or by capturing a free electron

The charge state impacts the decay and consequently nucleosynthesis.

pp-chains describe how to form an α from protons

T = 10-25 MK → pp II
T > 25 MK → pp III

$T_\odot \approx 15$ MK
→ ionize Be, Li



$p(p,e^+\nu)d$
$d(p,\gamma)^3He$

86% pp I 14%

$^3He(^3He,2p)^4He$

$^3He(\alpha,\gamma)^7Be$

14% pp II pp III 0.02%

$Be(e^-,\nu)^7Li$
$^7Li(p,\alpha)^4He$

$^7Be(p,\gamma)^8B$
$^8B(e^+,\nu)^8Be$
$^8Be(\alpha)^4He$

Ion traps at TITAN are used for

beam preparation

- cooling
- bunching
- charge breeding
- purifying
- in-trap decay and recapture

& precision measurements.

- Penning trap mass spectrometry → $N = 20$ shell, testing CKM matrix, nuclear astrophysics
- in-trap decay spectroscopy → $2\nu2\beta$ problem
- studies of highly charged ions → radioactive decay, stellar evolution

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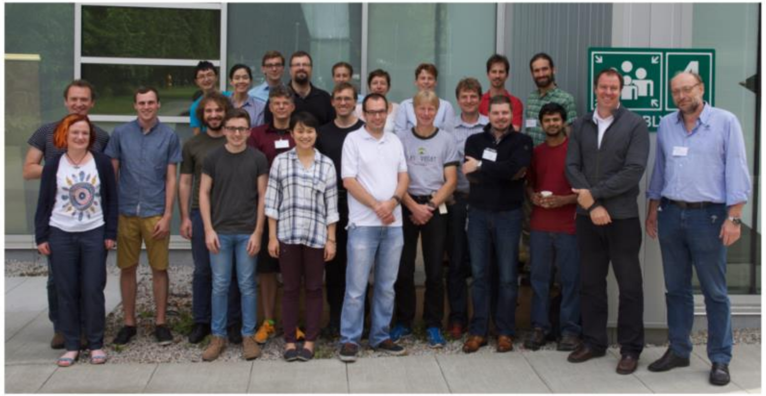
Canada’s national laboratory for particle and nuclear physics
and accelerator-based science

The TITAN collaboration



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