MAX PLANCK INSTITUTE
FOR NUCLEAR PHYSICS

Recent highlights in Penning-trap mass spectrometry

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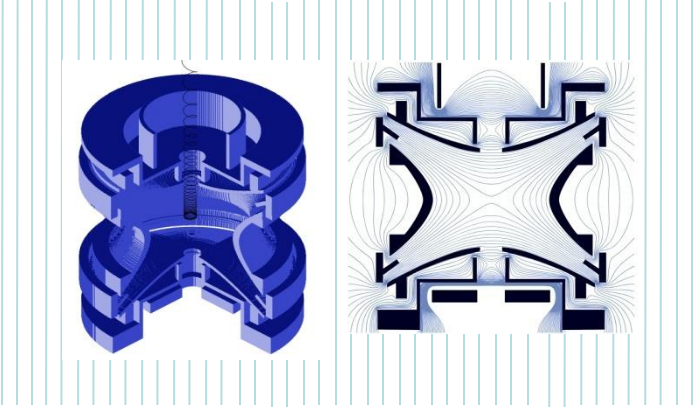


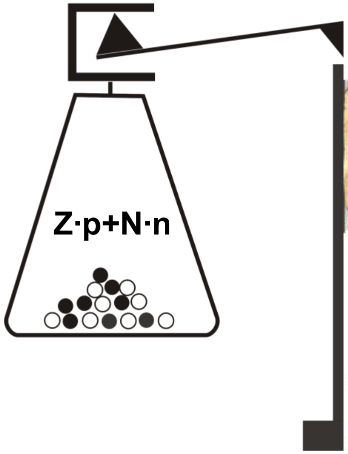
EMIS 2012 December 2-7 MATSUE, JAPAN

Szilard.Nagy@mpi-hd.mpg.de

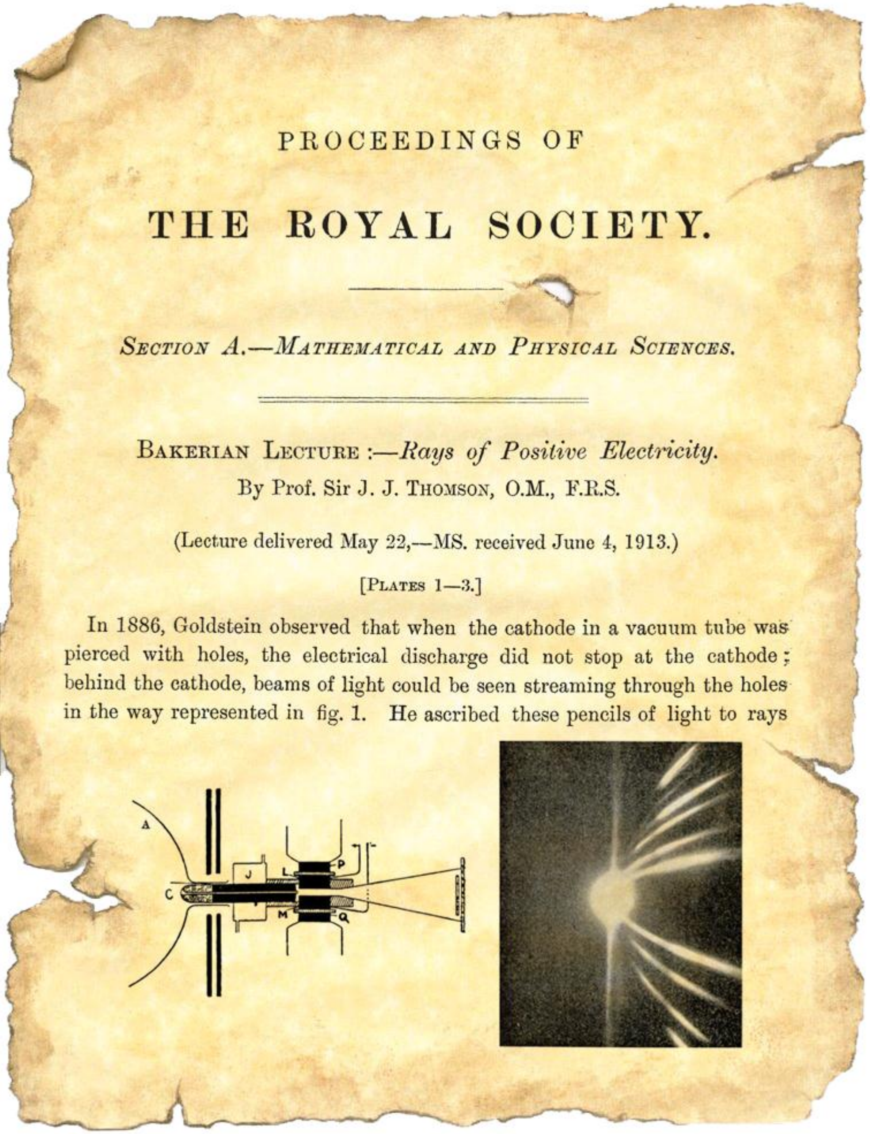
100 years of mass spectrometry

Macrocosm: r

Microcosm: r



$$B(N,Z)=[Nm_n$$



PROCEEDINGS OF

THE ROYAL SOCIETY.

Section A.—Mathematical and Physical Sciences.

Bakerian Lecture:—*Rays of Positive Electricity.*

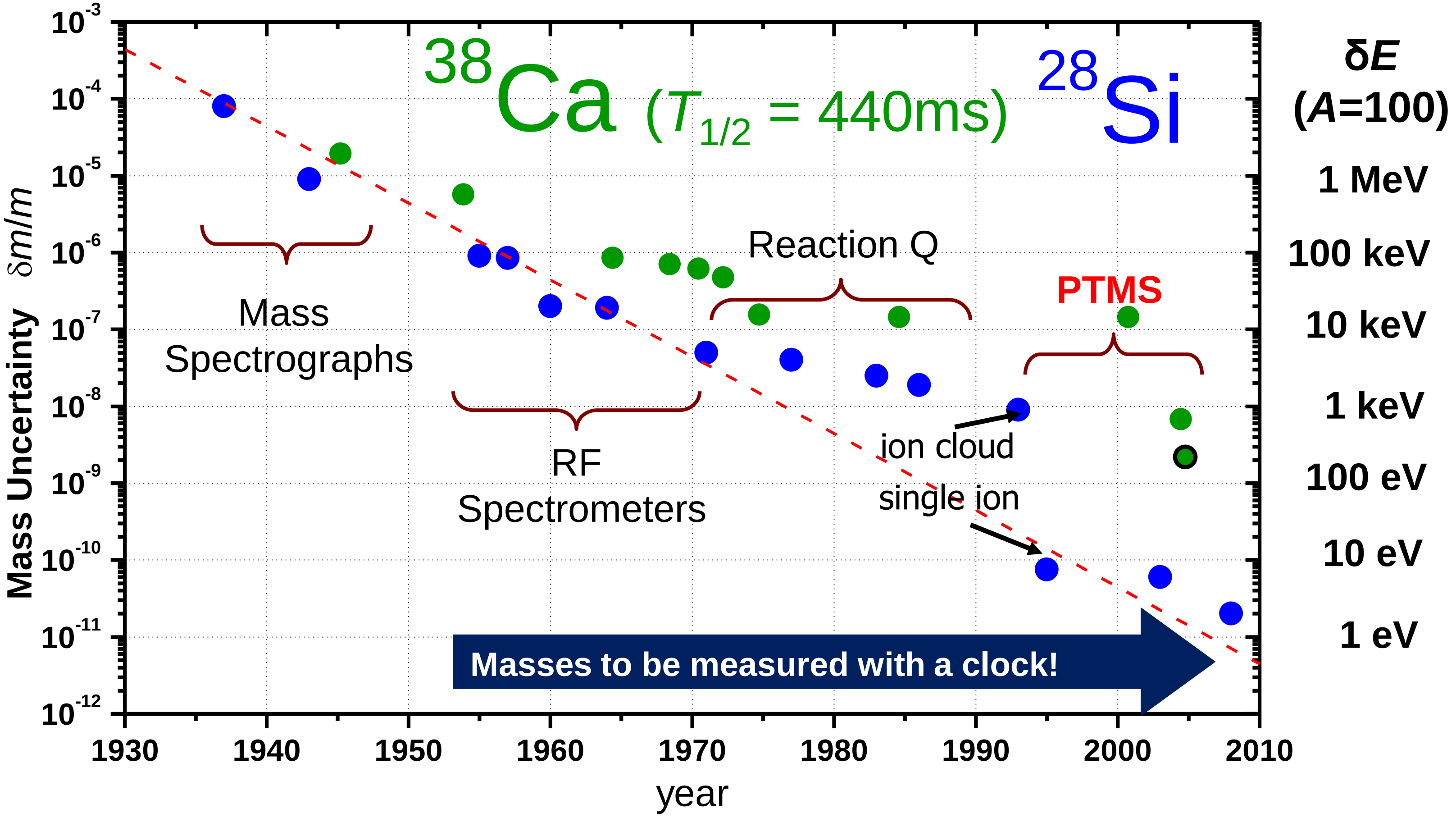
By Prof. Sir J. J. Thomson, O.M., F.R.S.

(Lecture delivered May 22,—MS. received June 4, 1913.)

[Plates 1—3.]

In 1886, Goldstein observed that when the cathode in a vacuum tube was pierced with holes, the electrical discharge did not stop at the cathode; behind the cathode, beams of light could be seen streaming through the holes in the way represented in fig. 1. He ascribed these pencils of light to rays

A century of progress

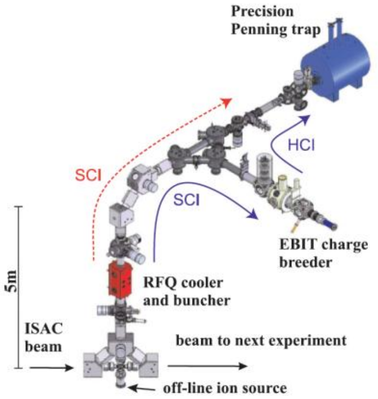


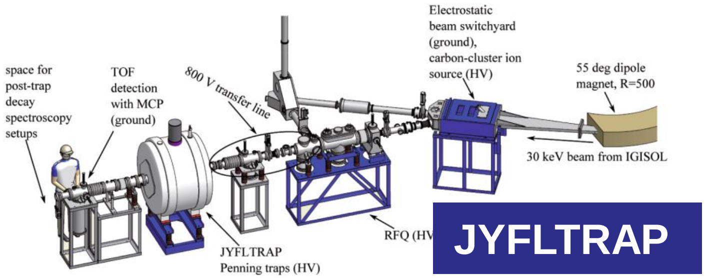
Examples of application

Field	Examples	δm/m

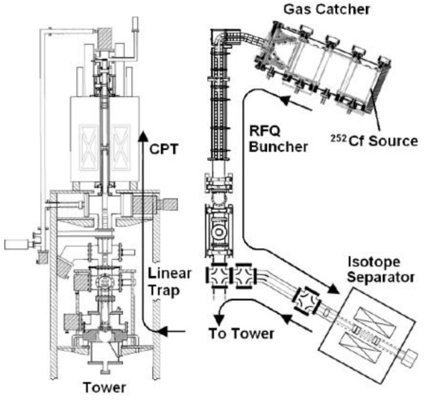
Growing  facilities

TITAN (TRIUMF)

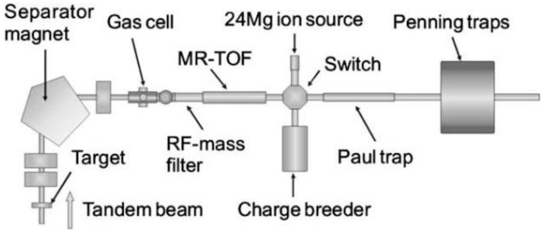




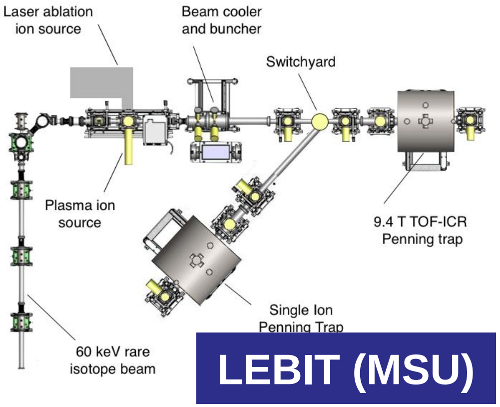
JYFLTRAP



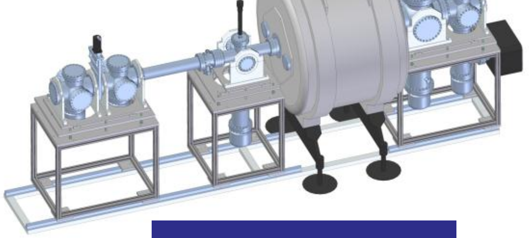
CPT (ARGONNE)



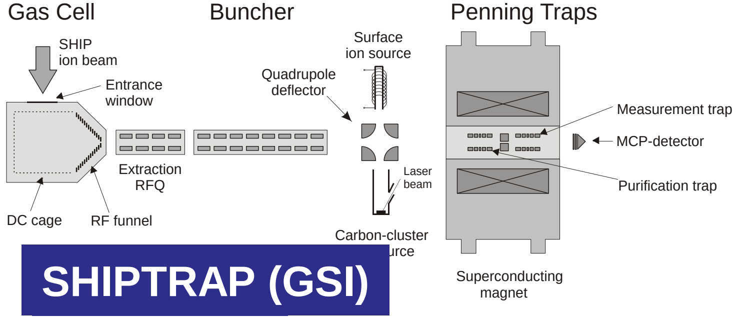
MLLTRAP



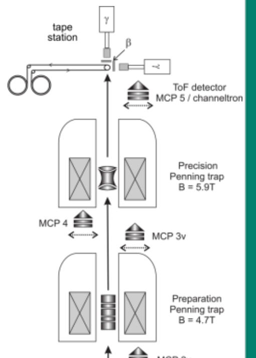
LEBIT (MSU)

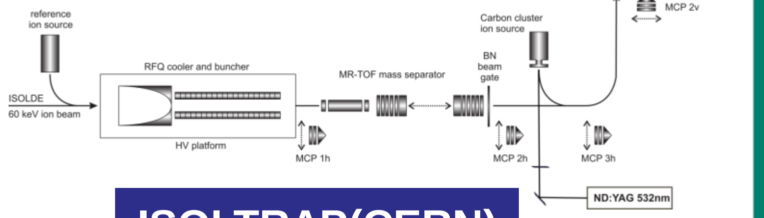


TRIGA-TRAP



SHIPTRAP (GSI)





ISOLTRAP(CERN)

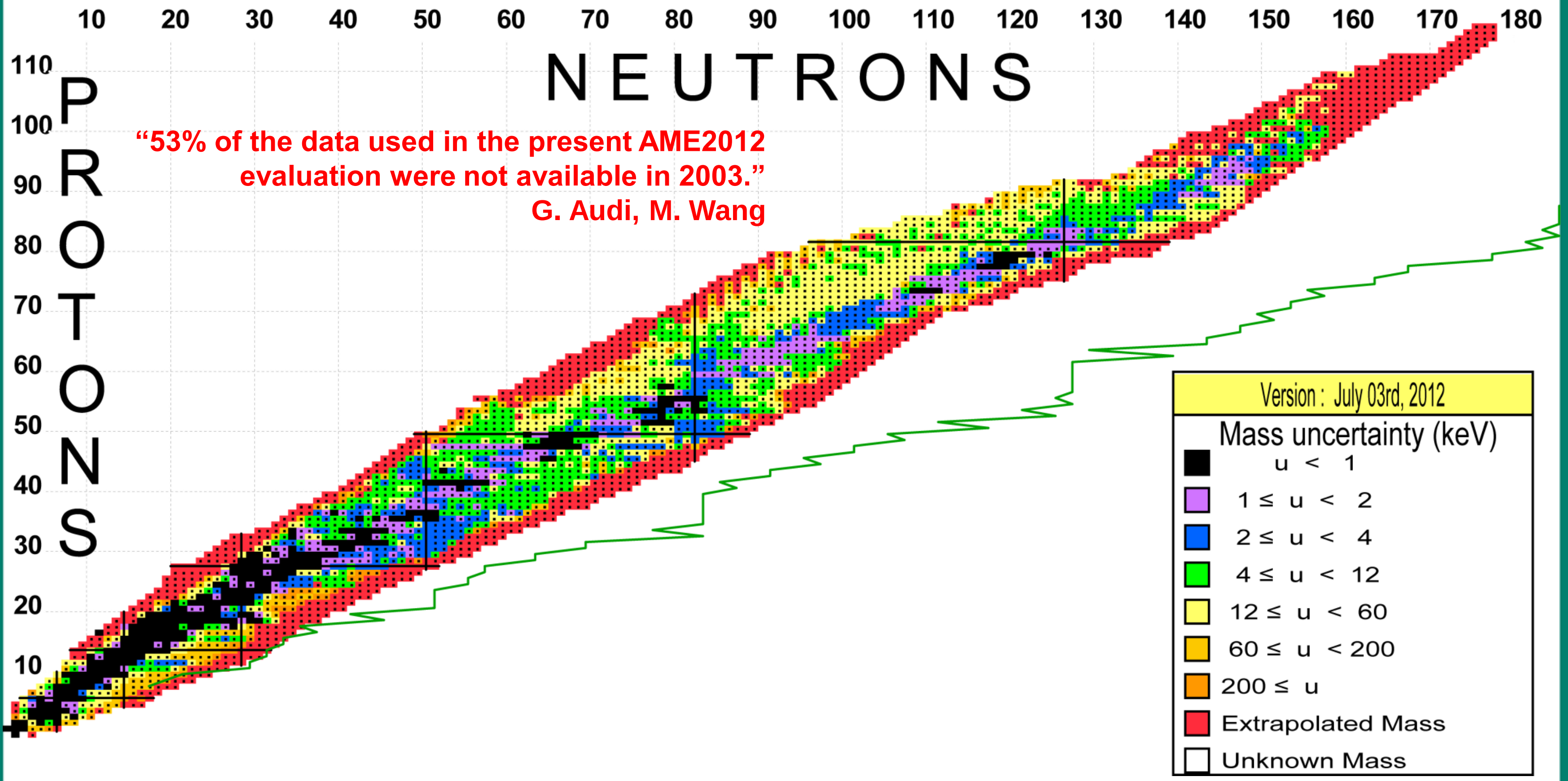
Complementarity of traps at radioactive ion beam facilities

Production	ISOLTRAP CERN	TITAN TRIUMF	SHIPTRAP GSI	MLLTRAP LMU	JYFLTRAP	LEBIT NSCL	CPT ANL	TRIGA-TRAP
ISOL	X	X						
Fusion-evaporation			X	X				
IGISOL					X			
Fragm.						X		
Spontan. fission							X	
Neutron induced fission								X
HCI		X						

THeTRAP, FSU-TRAP, SMILETRAP II

HITRAP, PENTATRAP, TRAPSENSOR, MATS, Lanzhou-TRAP, RIKEN-TRAP

Mass uncertainty in the latest Atomic-Mass Evaluation



“53% of the data used in the present AME2012 evaluation were not available in 2003.”
G. Audi, M. Wang

3350 nuclides
Data from: AME 2012
G. Audi, M. Wang, private communication

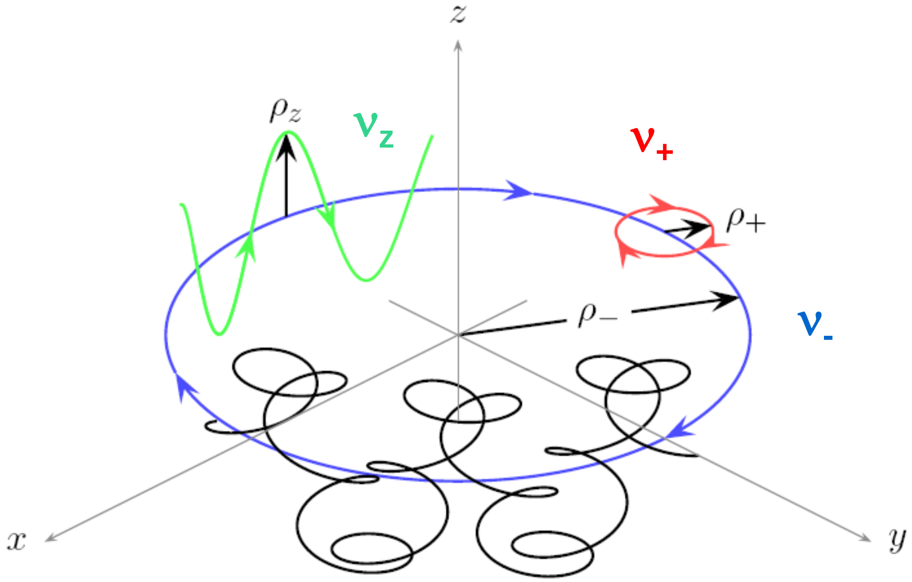
Penning Trap

the most accurate mass spectrometer

- **frequency measurement**
- **long storage times**
- **ion cooling**
- **single ion sensitivity**
- **high precision**

$$\nu_c = \frac{1}{2\pi}\frac{qB}{m} = \sqrt{\nu_-^2 + \nu_z^2 + \nu_+^2} \;;\; \nu_c = \nu_+ + \nu_-$$

L. S. Brown, G. Gabrielse, Phys. Rev. A, 25, 2423 (1982)



typical cyclotron frequency: q = 1+, m = 100 u, B = 7 T
⇒ ν_c = 1 MHz

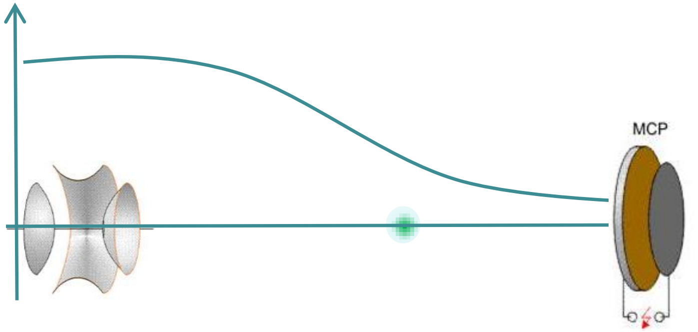
Penning-trap mass measurement in a nutshell

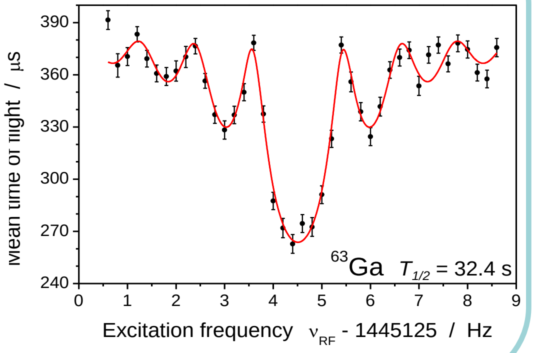
Time-of-flight ion-cyclotron resonance technique

$$\frac{\delta m}{m} \approx \frac{m}{T_{RF}\cdot q\cdot B\cdot\sqrt{N}}$$

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

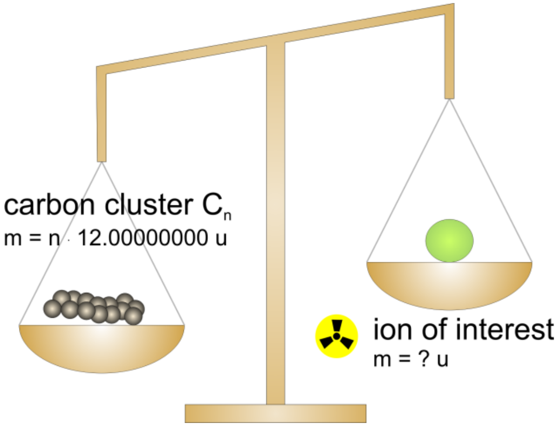
$$\nu_c = \frac{1}{2\pi}\frac{q\,B}{m}$$





G. Gräff et. al Z. Phys. 297 35 (1980)

calibration with C-cluster ions
@TRIGA-TRAP

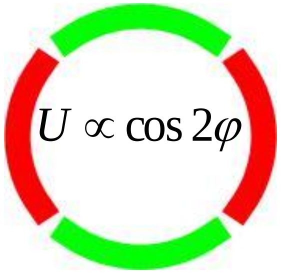


TOF-ICR already demonstrated:

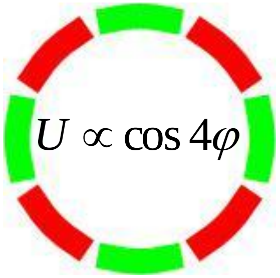
- **$t_{1/2}$=8.5 ms (^{11}Li @ TITAN)**
- **yield 2 ion/minute (^{256}Lr @ SHIPTRAP)**
- **$\delta m/m$ 10^{-9} - 10^{-10}**

Ultra-high resolving power

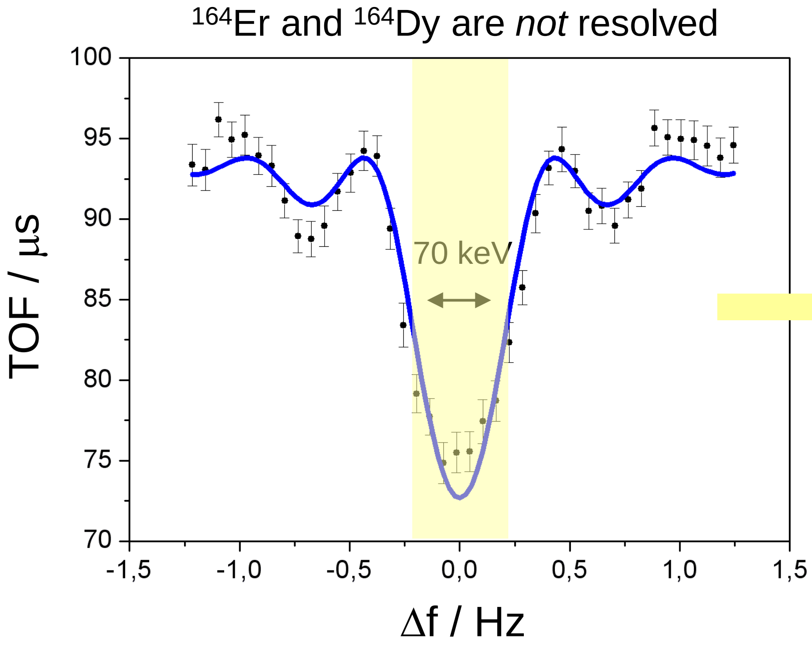
Quadrupolar excitation

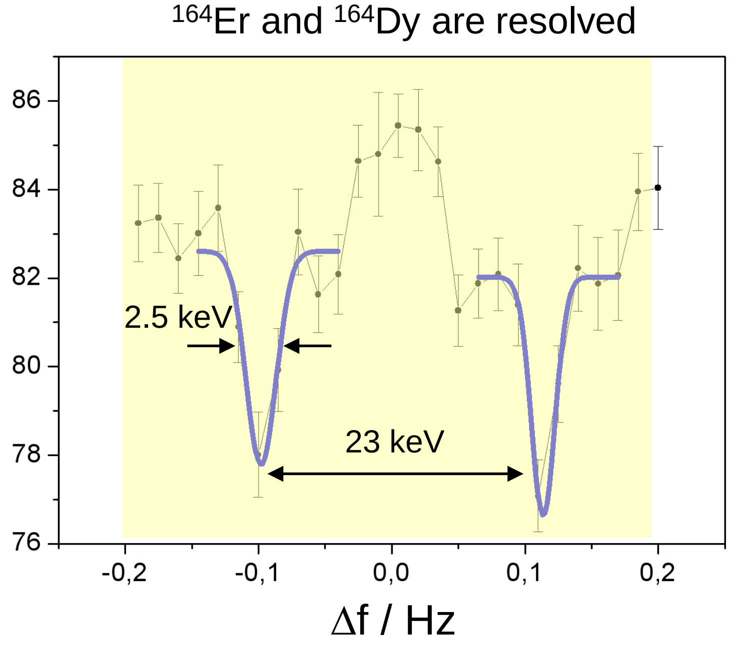


LEBIT (MSU)
SHIPTRAP (GSI)
MPIK (Heidelberg)



Octupolar excitation


^{164}Er and ^{164}Dy are *not* resolved


^{164}Er and ^{164}Dy are resolved

A resolving power of 10^8 has been demonstrated in a Penning trap.

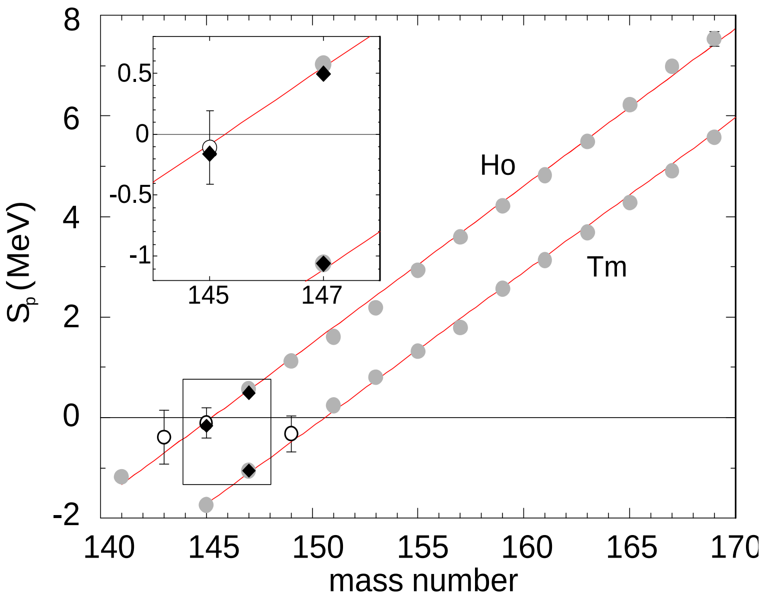
R. Ringle *et al.*, Int. J. Mass Spectrom. 262, 33 (2007)

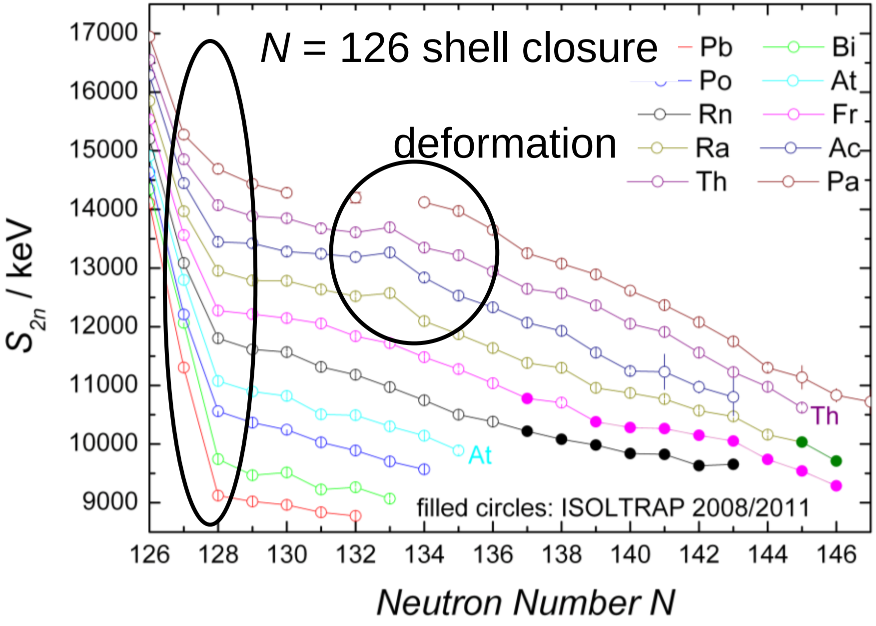
S. Eliseev *et al.*, Phys. Rev. Lett. 107, 152501 (2011).

Nuclear structure studies

$S_p = B(Z,N) - B(Z-1,N)$

$S_{2n} = B(Z,N) - B(Z,N-2)$





SHIPTRAP: First direct mass measurement beyond the proton dripline.

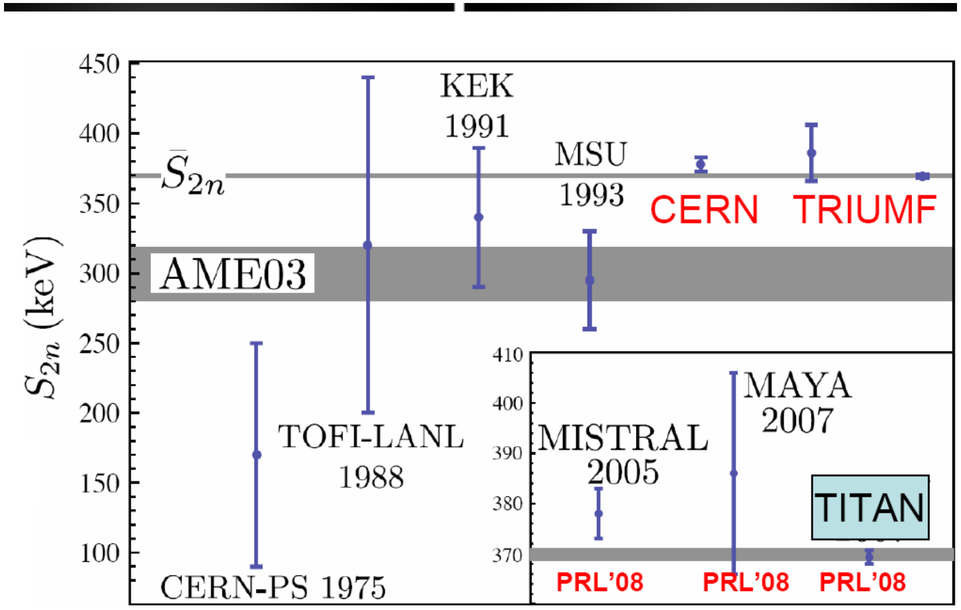
CPT/ISOLTRAP/JYFLTRAP/LEBIT/TITAN: Investigation of shell closures, halos, …

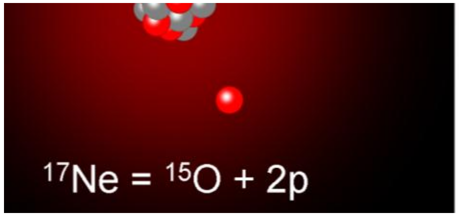
C. Rauth *et al*., Phys. Rev. Lett. 100, 012501 (2008)
M. Dworschak *et al*., Phys. Rev. Lett. 100, 072501 (2008)
W. Geithner *et al*., Phys. Rev. Lett. 101, 252502 (2008)
B. Cakirli *et al*., Phys. Rev. Lett. 102, 082501 (2009)

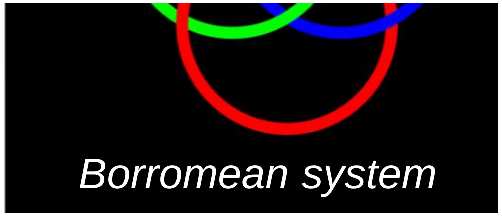
D. Neidherr *et al*., Phys. Rev. Lett. 102, 112501 (2009)
S. Naimi *et al*., Phys. Rev. Lett. 105, 032502 (2010)
J. Hakala *et al*., Phys. Rev. Lett. 109, 032501 (2012)
Fr data: S. Kreim *et al*., in preparation (2012)

Investigation of nuclear halos

Motivations:
1) guide nuclear theory and refine our understanding of the nucleus
2) mass is the ***major*** contribution to the charge radius error




^{17}Ne = ^{15}O + 2p


Borromean system

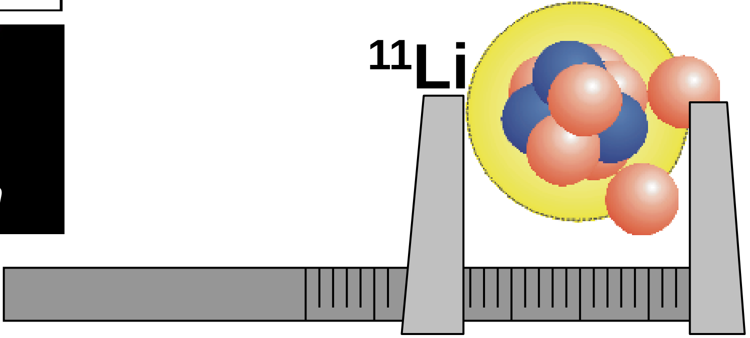
Argonne, GANIL, GSI, ISOLDE, TRIUMF

^{6,8}He
P. Mueller *et al*., PRL 99, 252501 (2007)
V.L. Ryjkov *et al*., PRL 101, 012501 (2008)
M. Brodeur et al. PRL 108, 052504 (2012)

^{9,11}Li:
R. Neugart *et al*., PRL 101, 132502 (2008)
M. Smith *et al*., PRL 101, 202501 (2008)

^{11,12}Be:
W. Nörtershäuser *et al*., PRL102, 062503 (2009)
R. Ringle *et al*., PLB 675, 170 (2009)
A. Krieger *et al*., PRL 108, 142501 (2012)

^{17}Ne:
W. Geithner *et al*., PRL102, 252502 (2008)

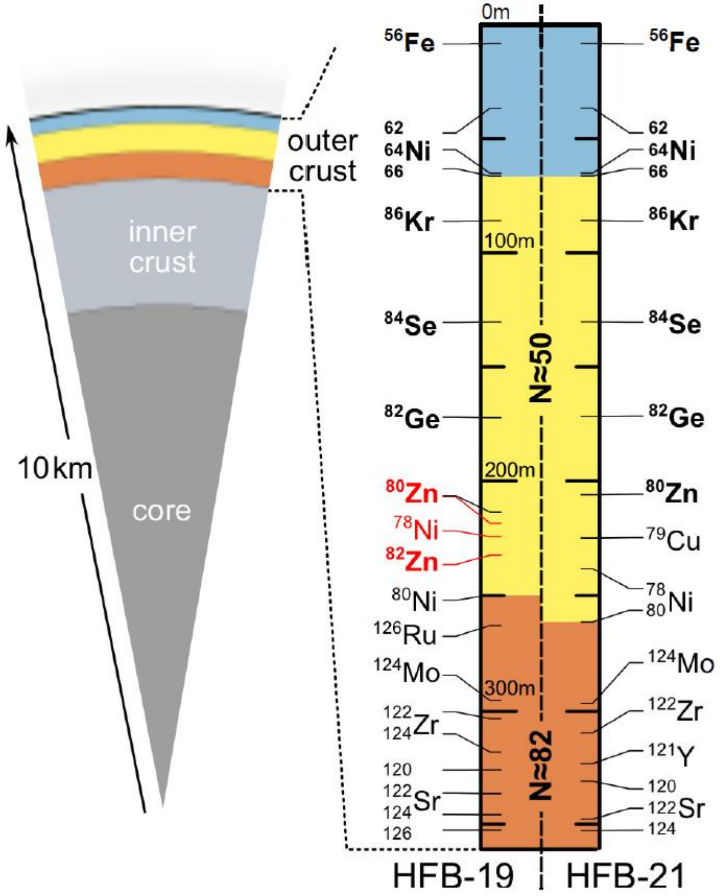


Plumbing neutron stars to new depths@ISOLTRAP

Composition of the outer crust of a neutron star

Depth profile of a neutron star

R. N. Wolf et al., PRL submitted (2012)



Calculations done by:
S. Goriely et al. A&A 531, A78 (2011)

^{82}Zn: most exotic nuclide at the N=50 shell closure

Microscopic mass models predicted ^{82}Zn to be a component of the outer crust of a neutron star

→ disproved with exp. mass

$\delta m/m \sim 10^{-8}$ (< 1 keV)

See talk by S. Kreim

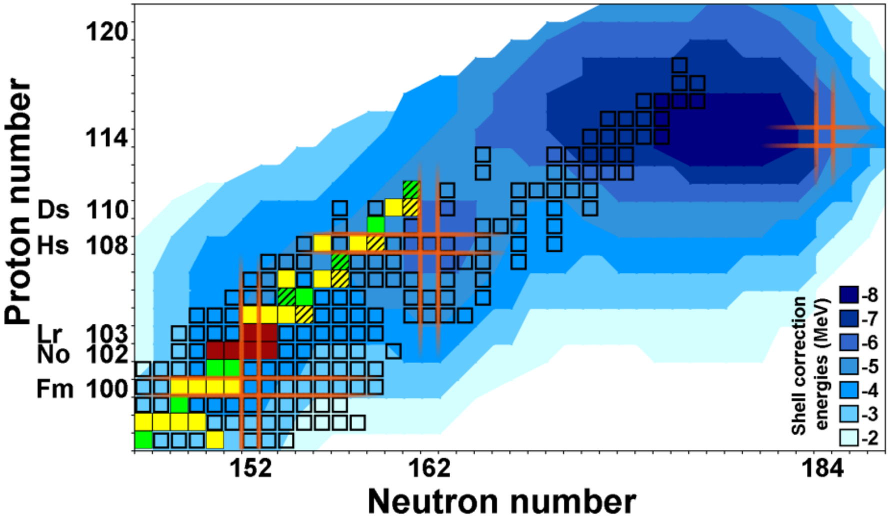
ISOLTRAP (ISOLDE)

Direct mapping of nuclear shell effects@SHIPTRAP

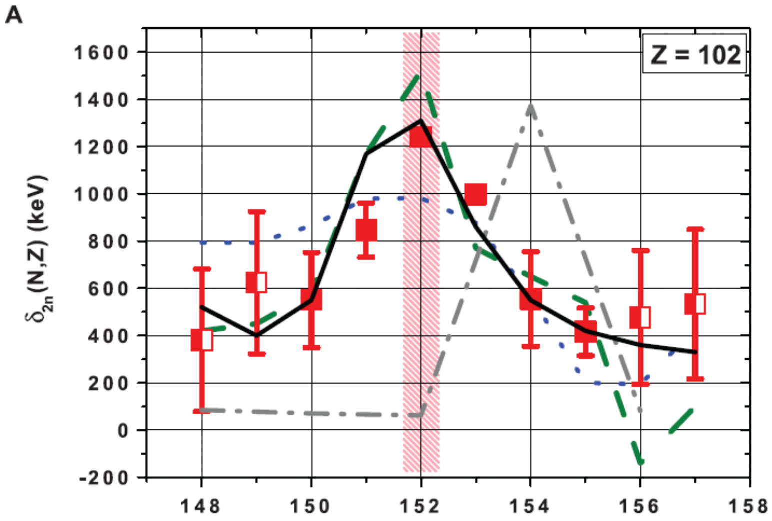
Sciencexpress
Science
AAAS

Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch Düllmann,[6,2,1] M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1] S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7] D. Rodríguez,[10] C Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]



ChemistryWorld:
Tweaked weighing scales help map the island of stability



See talk by M. Block

SHIPTRAP (GSI)

Neutrinoless double-electron capture ($0\nu\varepsilon\varepsilon$)

are extremely rare processes and have not been observed yet

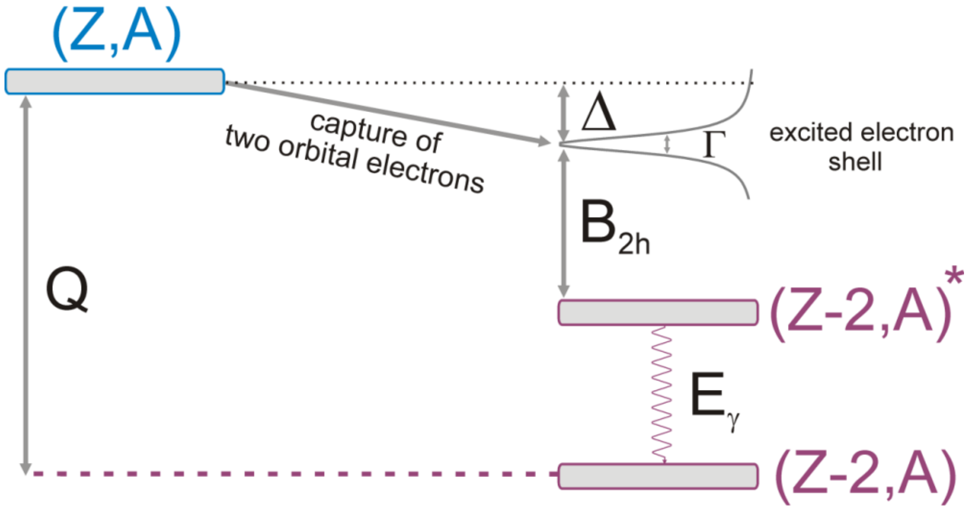
$0\nu\beta\beta$ ($T_{1/2}>10^{25}$y)

$0\nu\varepsilon\varepsilon$ ($T_{1/2}>10^{30}$y)

$$\frac{1}{T_{1/2}} = C \times \frac{\Gamma}{(Q - B_{2h} - E_{\gamma})^2 + \frac{1}{4}\Gamma^2} \times |M|^2 \times |\Psi_{1e}|^2 \times |\Psi_{2e}|^2 \times m_{\nu}^2$$

Resonant enhancement possible!

Search for nuclides with $\Delta=(Q_{\varepsilon\varepsilon}-B_{2h}-E_{\gamma})$ < 1 keV by measurements of $Q_{\varepsilon\varepsilon}$ –values

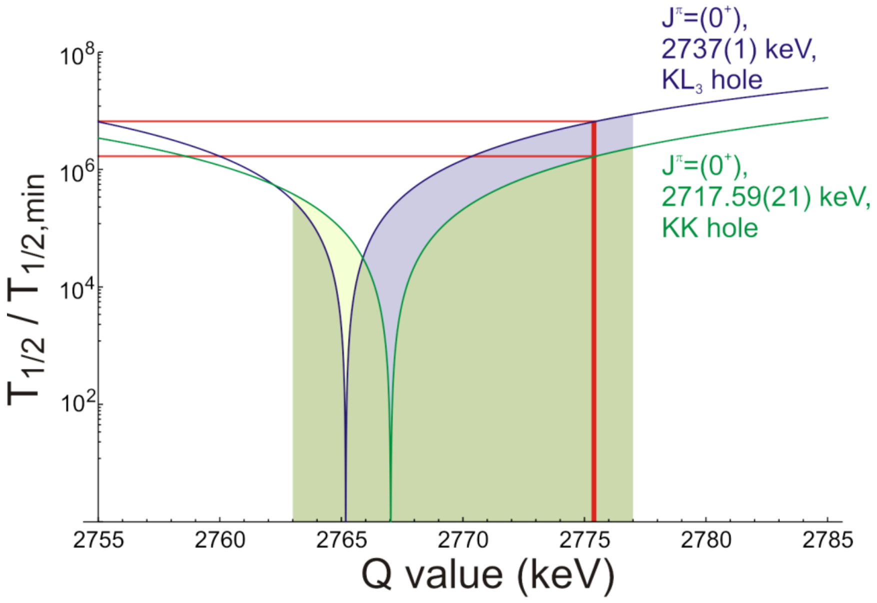


Accurate Q-values for neutrino physics

- inaccurate or imprecise Q-value is a limiting factor

➢**Direct Q-value measurements with traps**

$$Q/c^2 = \left(M_m - m_e\right)\left(1 - \frac{\nu_c(m)}{\nu_c(d)}\right)$$



Literature: **Q = 2770(7) keV**
TRAP: **Q = 2775.39(10) keV**

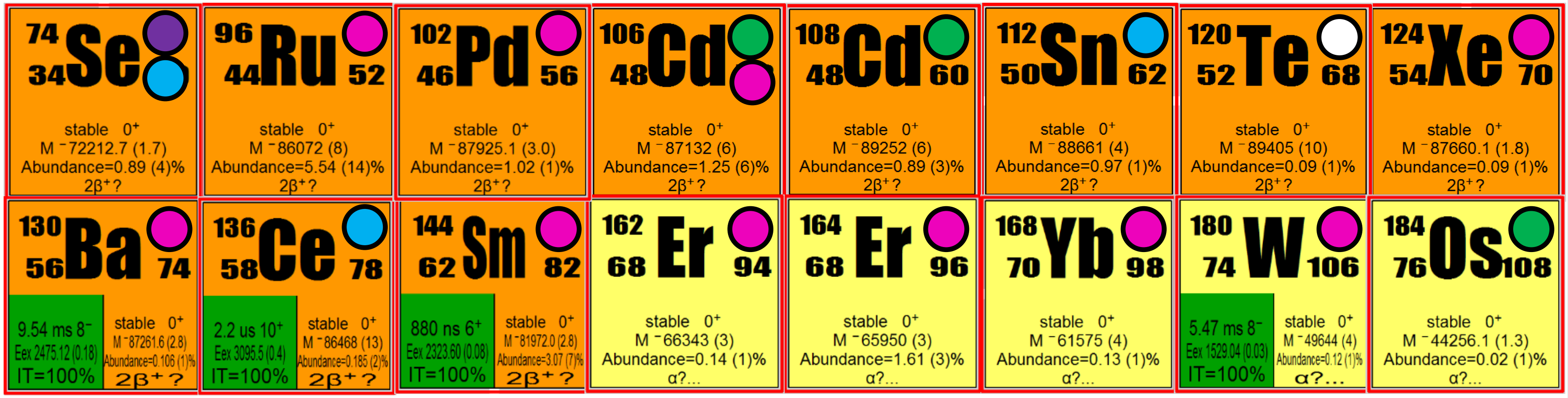
N. Scielzo et al., PRC 80, 025501 (2009)
V.S. Kolhinen et al., PLB 697 116 (2011)
S. Rahaman et al., PRL 103, 042501 (2009)
V.S. Kolhinen et al., PLB 684 17 (2010)
B. J. Mount et al., PRC 81, 032501 (2010)
S. Eliseev et al., PRC 83, 038501 (2011)
S. Eliseev et al., PRL 106, 052504 (2011)

S. Eliseev et al. PRC 84, 012501(R) (2011)
S. Eliseev et al., PRL. 107, 152501 (2011)
C.Smorra. et al., Phys. Rev. C 85, 027601 (2012)
C.Smorra. et al., Phys. Rev. C 86, 044604 (2012)
C. Droese et al., Nuclear Physics A 875 1–7 (2012)
M. Goncharov et al., 84, 028501 (2011)

Global search for 0νεε nuclides with Penning traps

Measurements @:

○ CPT, ● JYFLTRAP, ● FSU, ● SHIPTRAP and ● TRIGA-TRAP



$^{74}_{34}$Se 40
stable 0^+
M −72212.7 (1.7)
Abundance=0.89 (4)%
$2\beta^+$?

$^{96}_{44}$Ru 52
stable 0^+
M −86072 (8)
Abundance=5.54 (14)%
$2\beta^+$?

$^{102}_{46}$Pd 56
stable 0^+
M −87925.1 (3.0)
Abundance=1.02 (1)%
$2\beta^+$?

$^{106}_{48}$Cd 58
stable 0^+
M −87132 (6)
Abundance=1.25 (6)%
$2\beta^+$?

$^{108}_{48}$Cd 60
stable 0^+
M −89252 (6)
Abundance=0.89 (3)%
$2\beta^+$?

$^{112}_{50}$Sn 62
stable 0^+
M −88661 (4)
Abundance=0.97 (1)%
$2\beta^+$?

$^{120}_{52}$Te 68
stable 0^+
M −89405 (10)
Abundance=0.09 (1)%
$2\beta^+$?

$^{124}_{54}$Xe 70
stable 0^+
M −87660.1 (1.8)
Abundance=0.09 (1)%
$2\beta^+$?

$^{130}_{56}$Ba 74
9.54 ms 8^-
Eex 2475.12 (0.18)
IT=100%
stable 0^+
M −87261.6 (2.8)
Abundance=0.106 (1)%
$2\beta^+$?

$^{136}_{58}$Ce 78
2.2 us 10^+
Eex 3095.5 (0.4)
IT=100%
stable 0^+
M −86468 (13)
Abundance=0.185 (2)%
$2\beta^+$?

$^{144}_{62}$Sm 82
880 ns 6^+
Eex 2323.60 (0.08)
IT=100%
stable 0^+
M −81972.0 (2.8)
Abundance=3.07 (7)%
$2\beta^+$?

$^{162}_{68}$Er 94
stable 0^+
M −66343 (3)
Abundance=0.14 (1)%
α?...

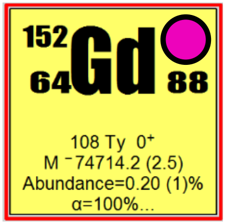
$^{164}_{68}$Er 96
stable 0^+
M −65950 (3)
Abundance=1.61 (3)%
α?...

$^{168}_{70}$Yb 98
stable 0^+
M −61575 (4)
Abundance=0.13 (1)%
α?...

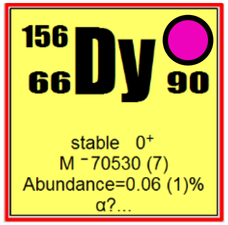
$^{180}_{74}$W 106
5.47 ms 8^-
Eex 1529.04 (0.03)
IT=100%
stable 0^+
M −49644 (4)
Abundance=0.12 (1)%
α?...

$^{184}_{76}$Os 108
stable 0^+
M −44256.1 (1.3)
Abundance=0.02 (1)%
α?...

Best candidates:



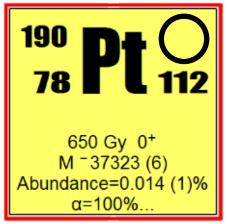
$^{152}_{64}$Gd 88
108 Ty 0^+
M −74714.2 (2.5)
Abundance=0.20 (1)%
α=100%...



$^{156}_{66}$Dy 90
stable 0^+
M −70530 (7)
Abundance=0.06 (1)%
α?...

$$T_{1/2} = 10^{28} – 10^{29}\ \text{y}$$

Left to do:



$^{190}_{78}$Pt 112
650 Gy 0^+
M −37323 (6)
Abundance=0.014 (1)%
α=100%...

Natural abundance: 0.014%

Summary

- **The „Penning-trap industry“ is booming!**
- **Huge progress, many exciting new results since the last EMIS!**
- **Novel technical developments ensure our future at the next generation RIB facilities.**

Examples of application highlighted in this talk:

- **nuclear structure,**
- **halos,**
- **neutron stars,**
- **stability of superheavy elements,**
- **neutrino physics.**

Material provided by colleagues is acknowledged!

THANK YOU!

ありがとう