

ISOLTRAP harvest 2008



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Marie Curie IEF Programme



ISOLDE
CERN



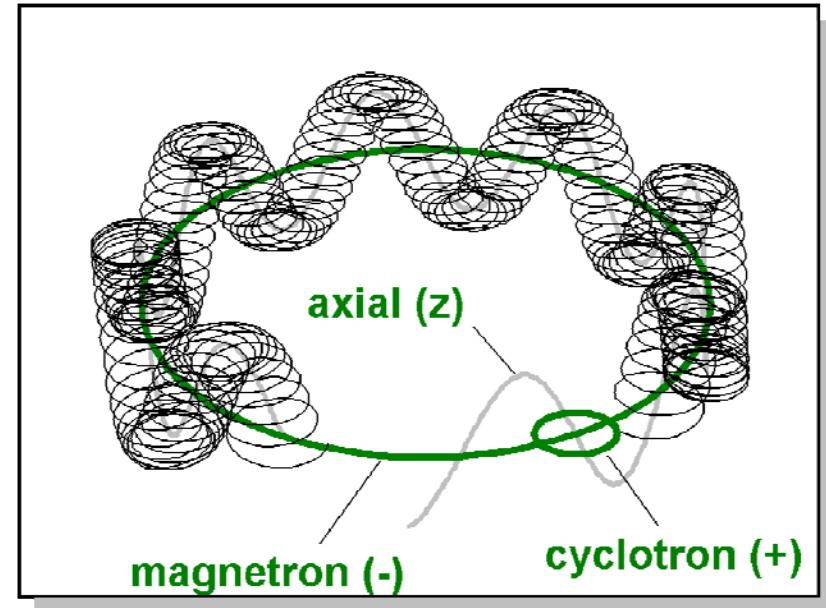
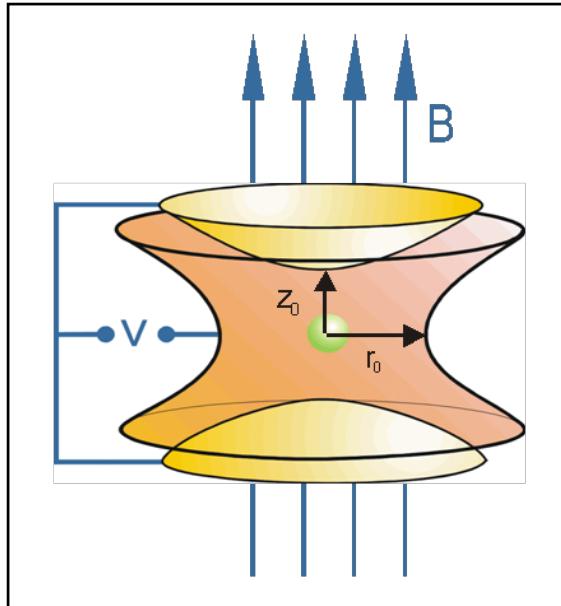
ISOLTRAP: principle

Determination of nuclear mass by measuring the cyclotron frequency:

Ions are trapped in crossed magnetic and electric field

The frequency of the ion motion is inversely proportional to its mass

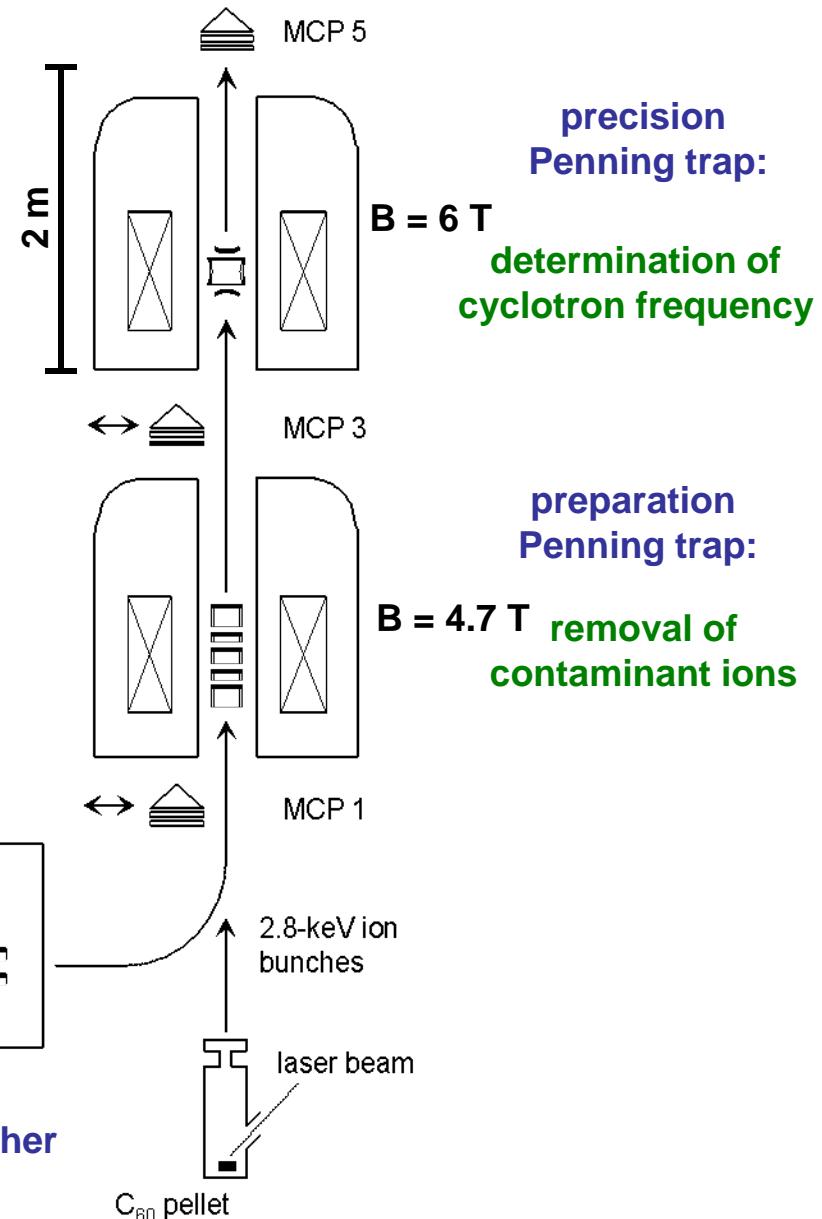
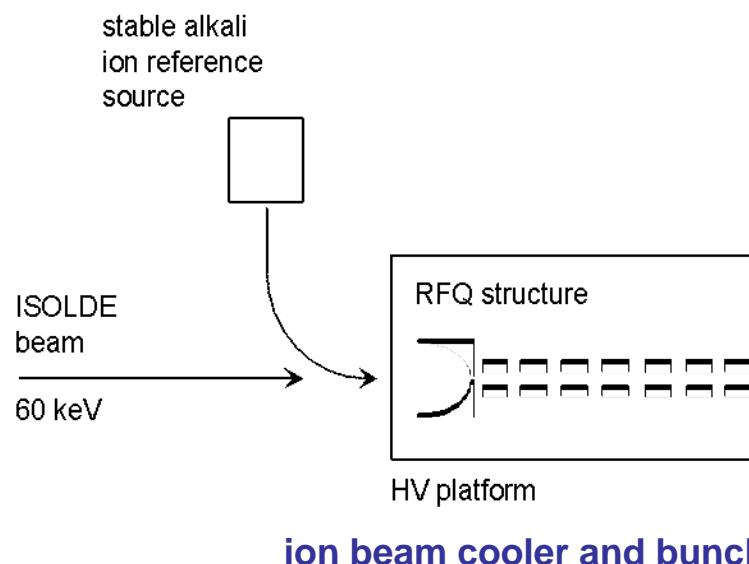
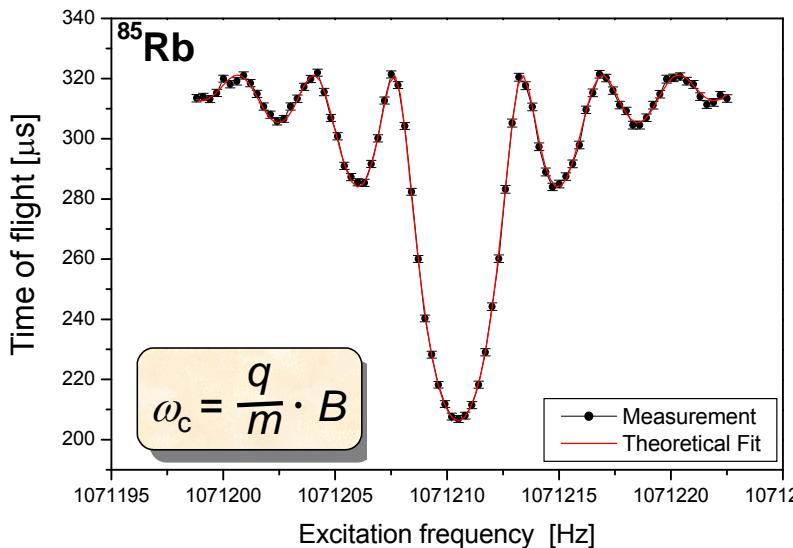
$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$



$$A=100, B=6\text{T}$$

- $\nu_+ \approx 1 \text{ MHz}$
- $\nu_- \approx 1 \text{ kHz}$
- $\nu_z \approx 44 \text{ kHz}$

Experimental setup



Highlights 2004-2008

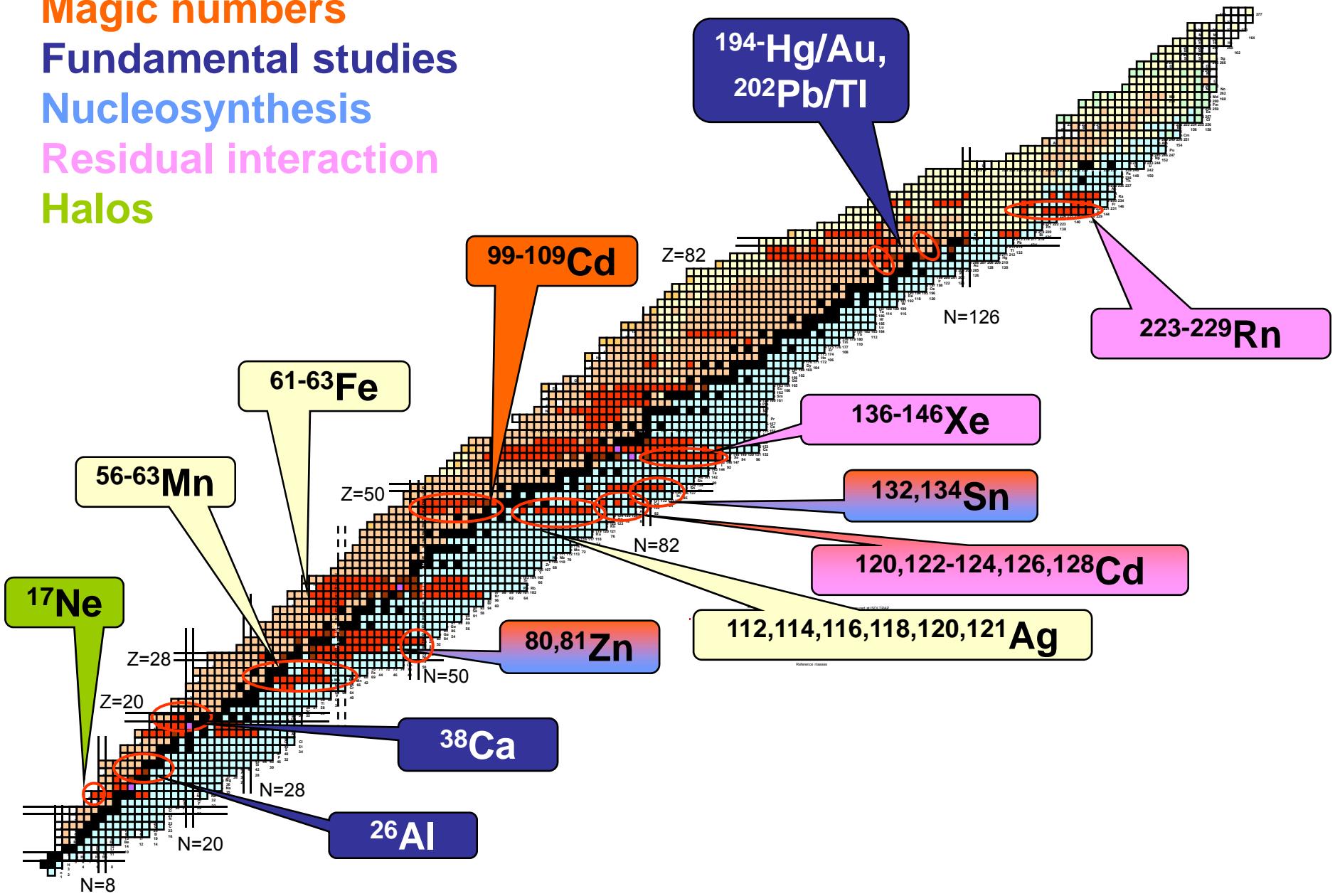
Magic numbers

Fundamental studies

Nucleosynthesis

Residual interaction

Halos



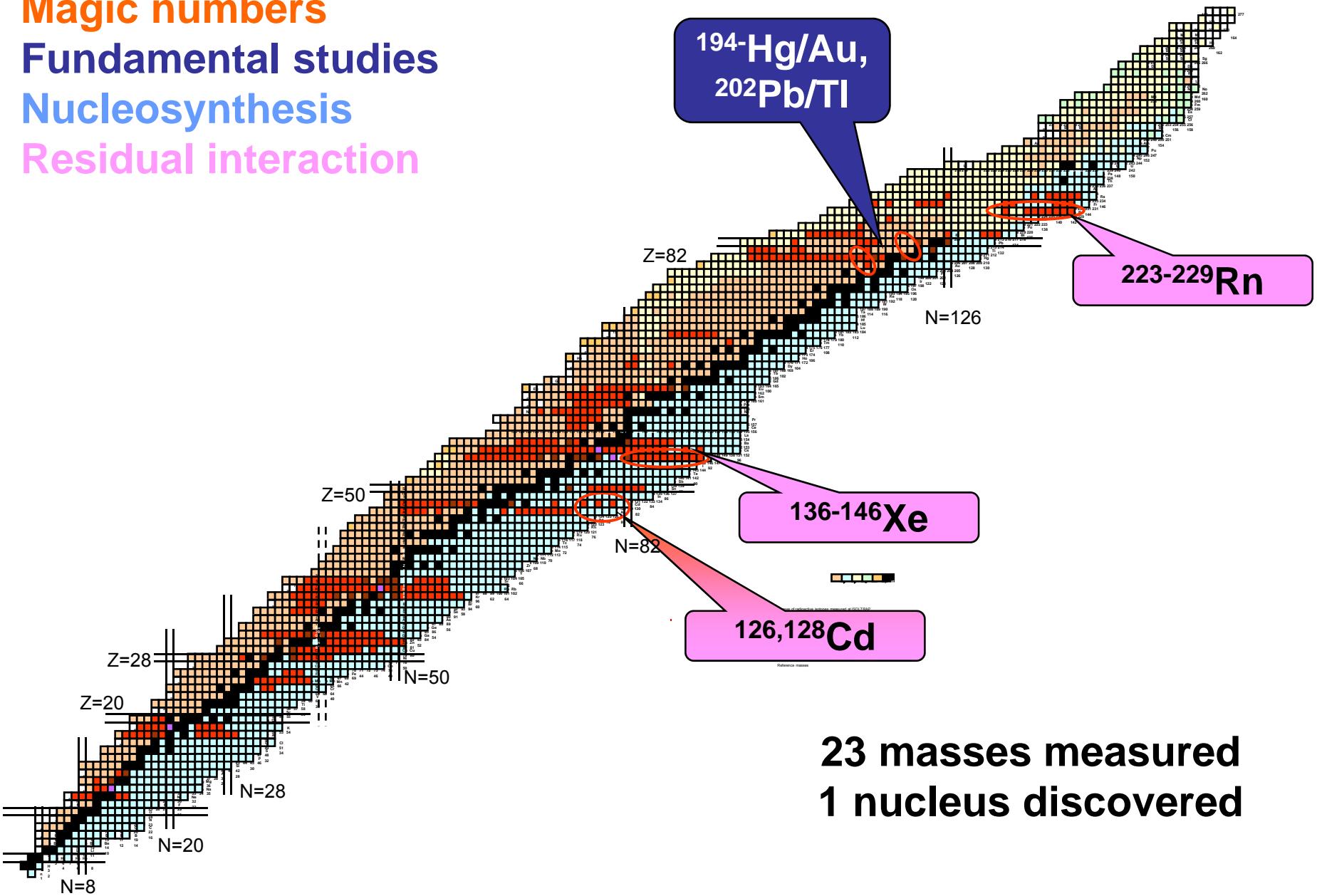
Measured in 2008

Magic numbers

Fundamental studies

Nucleosynthesis

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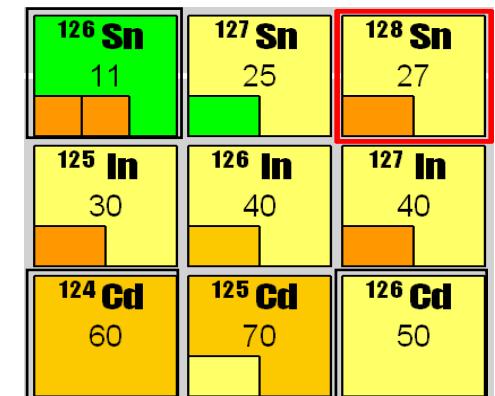
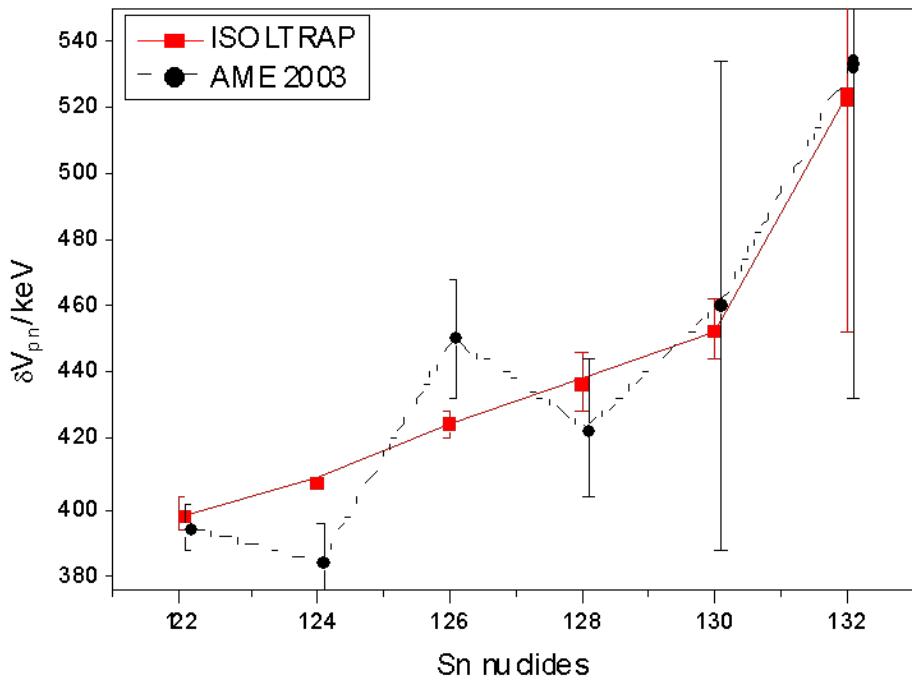


23 masses measured
1 nucleus discovered

126,128Cd

Motivation: δV_{pn} values around ^{132}Sn ; proportional to the valence proton-neutron interaction

Method: ‘classical’ ToF resonance
to clean Cs contamination: laser ionization, n-converter, quartz-transfer line



δV_{pn} trend around ^{132}Sn smoothens, as expected

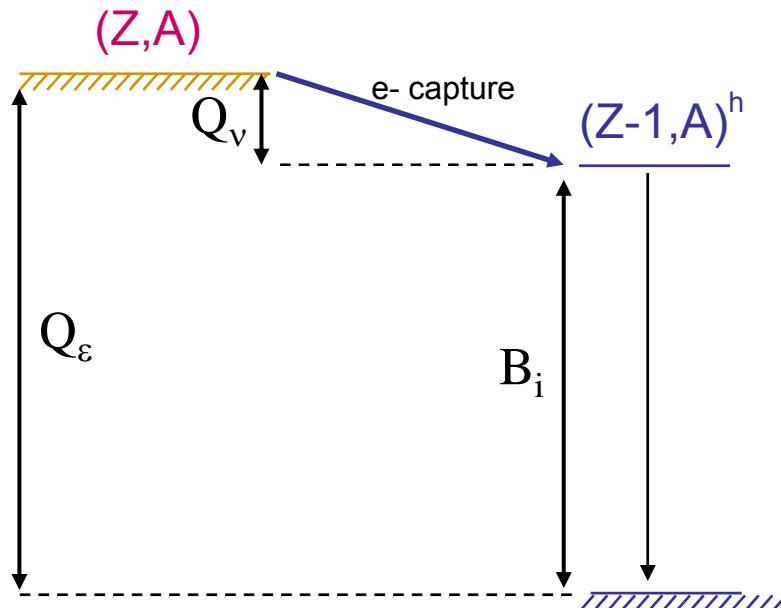
^{194}Hg & Au and ^{202}TI & Pb

Motivation: electron antineutrino: upper mass limit ~ 2 eV, neutrino: still 225 eV

Determination of neutrino mass from Q-value measurements

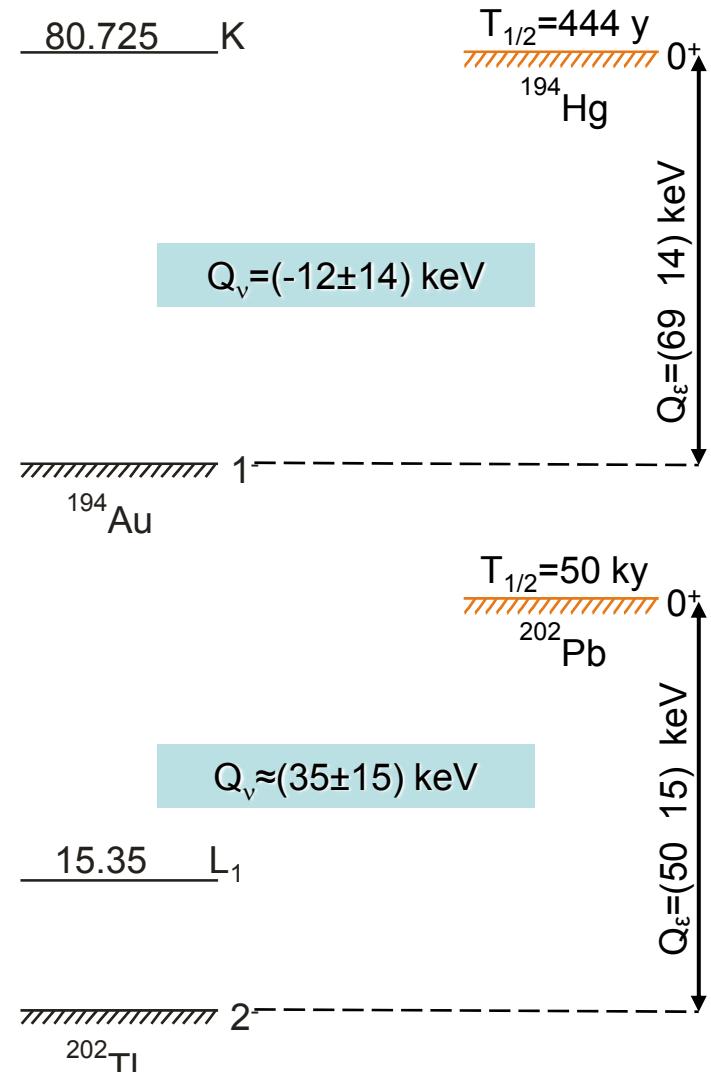
ISOLTRAP can say if the given pair is a good candidate for future studies

Electron capture:



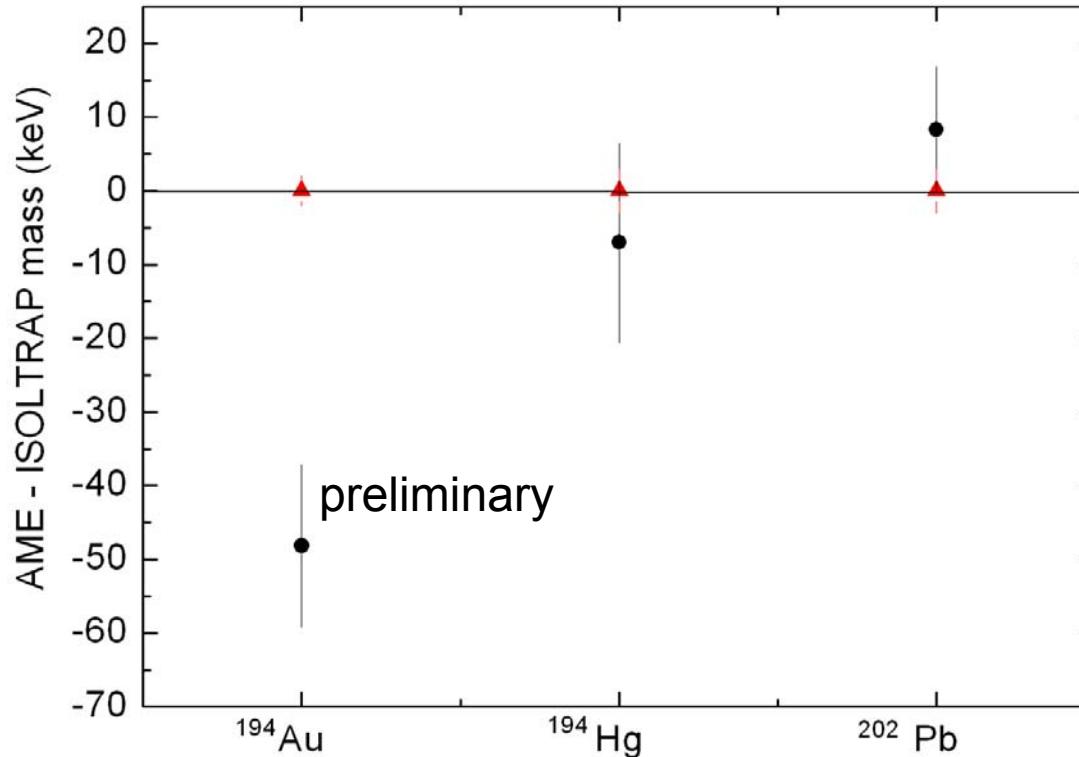
$$Q_v = E_\nu + m_\nu = Q_e - B_i$$

To be a candidate for neutrino-mass determination $Q_e - B_i < 1$ keV



^{194}Hg & Au and ^{204}TI & Pb

Method: ‘classical’ ToF resonance
long excitation times, partly offline measurements



$^{194}\text{Hg-194Au}:$

$$Q_{\varepsilon} = 27.8 \pm 3.6 \text{ keV}$$

$$Q_{\varepsilon-B(L)} \sim 15 \pm 4 \text{ keV}$$

^{194}Hg does not seem to be a good candidate

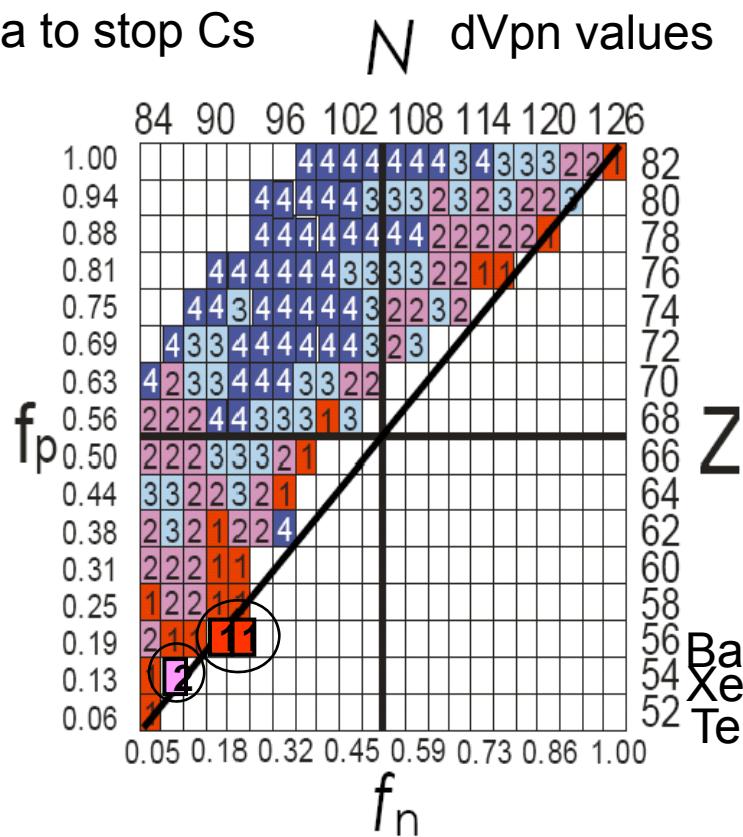
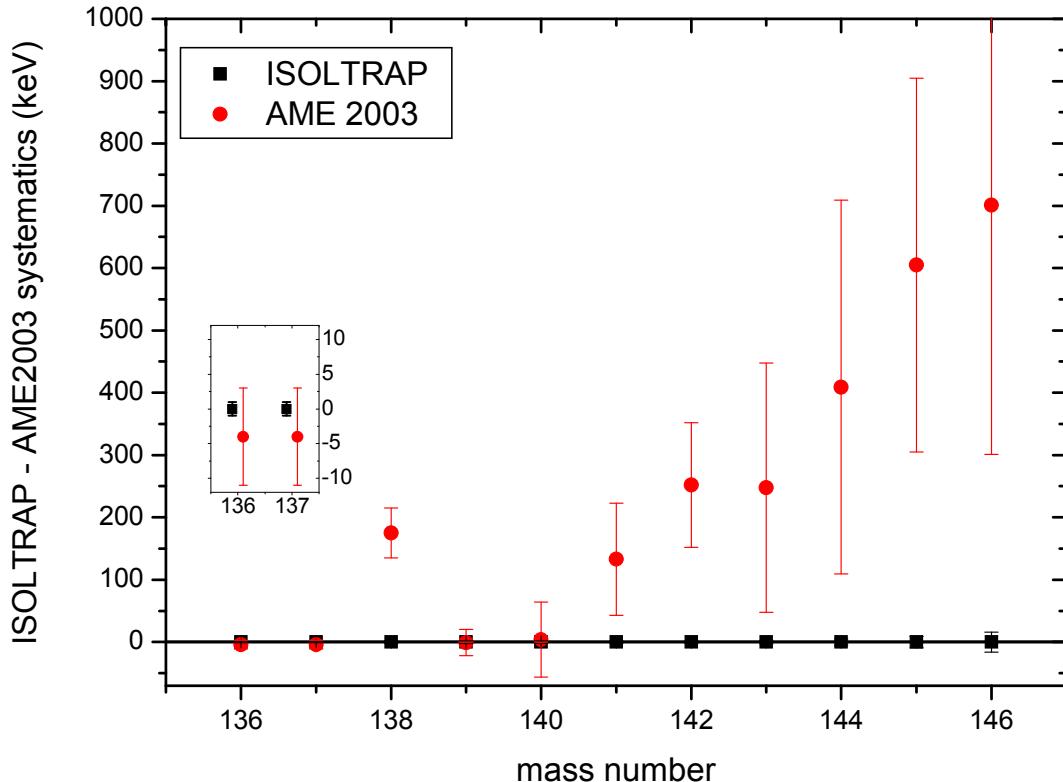
$^{202}\text{TI-202Pb}:$ precise TI mass still missing

$^{136-146}\text{Xe}$

Motivation: p-n residual interaction and δV_{pn} values, region of possible octupole deformation

Talk by Dennis Neidherr

Method: ‘classical’ ToF resonance, HRS& cold plasma to stop Cs



11 new masses in the middle of the shell

4 masses measured directly for the first time

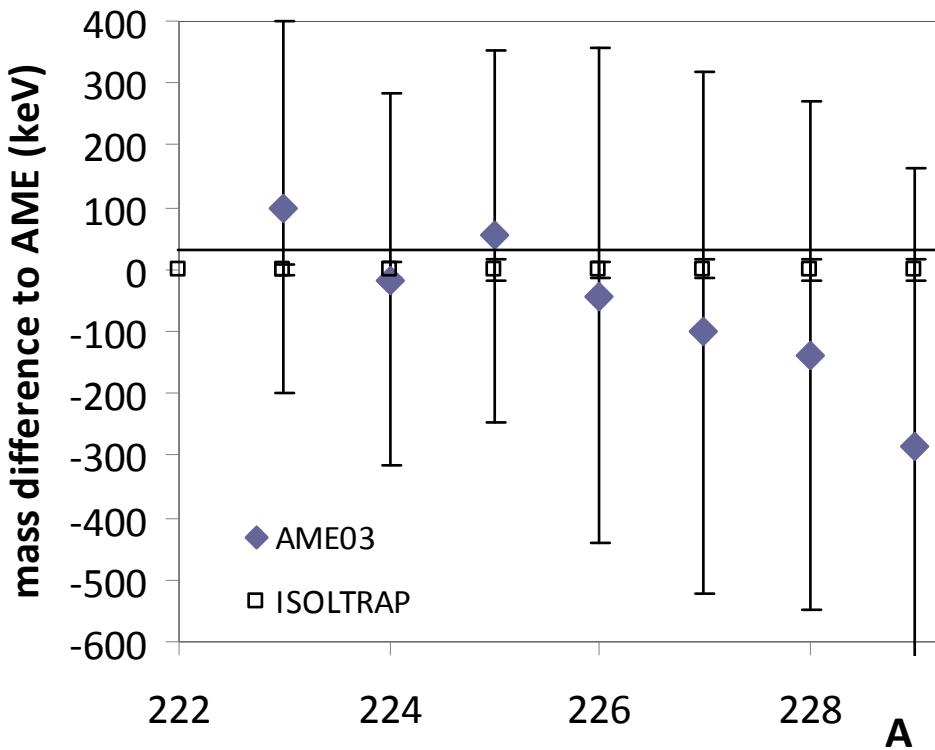
Masses deviate from extrapolations: interesting physics?

223-229Rn

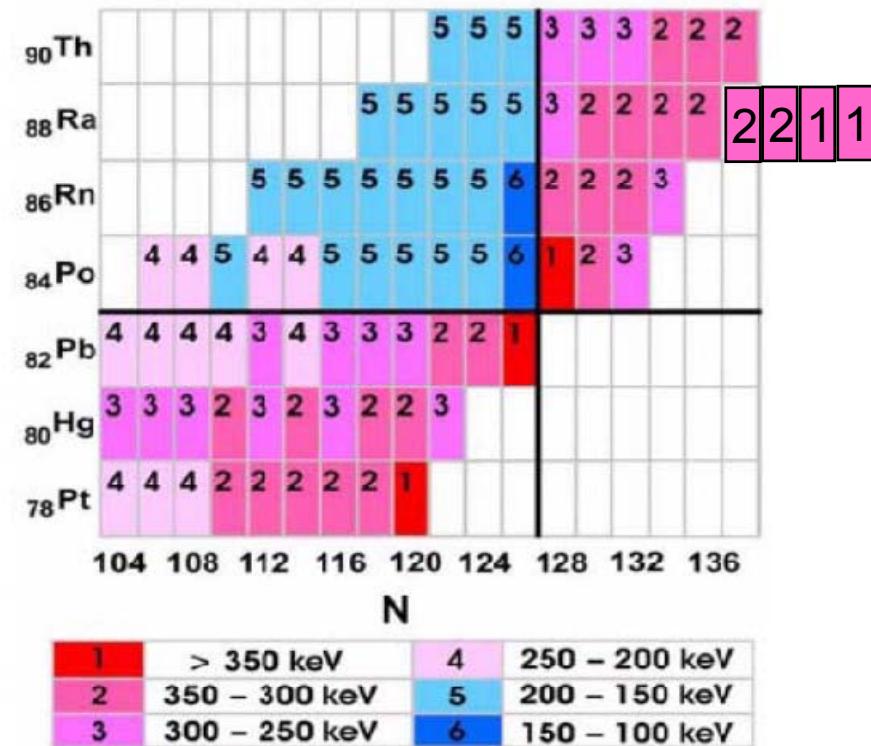
Motivation: p-n residual interaction and δV_{pn} values, region of possible octupole deformation

Talk by Dennis Neidherr

Method: ‘classical’ ToF resonance, HRS& cold plasma to stop Fr



7 new masses with $\sigma < 20$ keV,
All never measured directly before



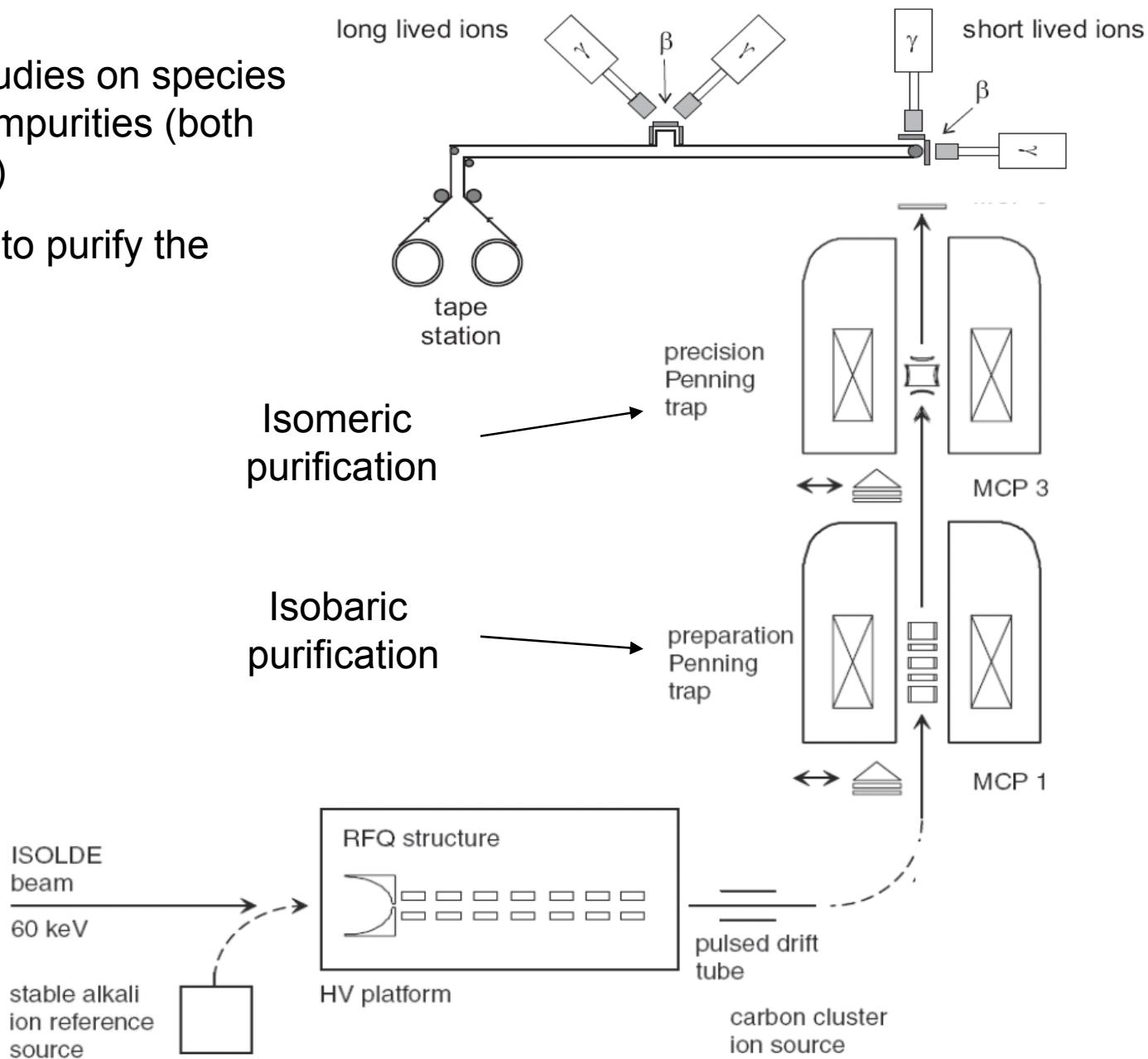
A new isotope of radon discovered: ^{229}Rn

D. Neidherr *et al.*, submitted to PRL

Tape-station at ISOLTRAP

Motivation: decay studies on species suffering from beam impurities (both isobaric and isomeric)

Method: use Isoltrap to purify the beam



Tape station: 1st region of interest

n-rich mercury and thallium isotopes above N=126

208 83 Bi 125	209 83 Bi 126	210 83 Bi 127	211 83 Bi 128	212 83 Bi 129	213 83 Bi 130	214 83 Bi 131	215 83 Bi 132	216 83 Bi 133	217 83 Bi 134	218 83 Bi 135				
2.58 ms 10 ² * β ⁻ 10% IT=100%	368 ky (5)* β ⁻ 100% IT=100%	19 Eyr 9/2 ⁺ M=16256.5 (1.4) Abundance=100% α=100%	57.4 ms 7 ⁺ β ⁻ 100% IT=100%	50241 1 ⁺ M=160844 β ⁻ 100% IT=100%	24 m 1/2 ⁺ β ⁻ 100% IT=100%	24.3 m 9/2 ⁺ β ⁻ 100% IT=100%	7.8 m >15 β ⁻ 100% IT=100%	45.59 m 9/2 ⁺ M=5231 (5) β ⁻ =97.91 (3%) α=2.09 (3%)	19.9 m 1 ⁺ M=1200 (11) β ⁻ ~100% α=0.021 (1%)	36.9 (22) β ⁻ 100% IT=? β ⁻ → ?	7.6 m 9/2 ⁺ M=1649 (15) β ⁻ 100%	2.17 m 1 ⁺ # M=5874 (11) β ⁻ 100%	97 s 9/2 ⁺ # M=8820# (200#) β ⁻ 100%	33 s 1 ⁺ # M=13340# (360#) β ⁻ 100%
207 82 Pb 125	208 82 Pb 126	209 82 Pb 127	210 82 Pb 128	211 82 Pb 129	212 82 Pb 130	213 82 Pb 131	214 82 Pb 132	215 82 Pb 133						
805 ms 13/2 ⁺ β ⁻ 100% IT=100%	stable 1/2 ⁺ M=22461.9 (1.2) Abundance=21%	500 ms 10 ² * stable 0 ⁺ Eyr 4805 (2) M=21485 (1.2) Abundance=24%	3.253 h 9/2 ⁺ M=17614.4 (4.5) β ⁻ 100%	201 ms 8 ⁺ 22.29 yr 9 ⁺ M=16471.5 (4.5) β ⁻ 100% IT=100%	36.4 m 9/2 ⁺ M=10491.4 (2.7) β ⁻ 100%	5 us (8 ⁺) 10.64 h 0 ⁺ M=1504 (2.2) β ⁻ 100% IT=100%	10.2 m (9/2 ⁺) M=3184 (8) β ⁻ 100%	26.8 m 0 ⁺ M=1813 (2.4) β ⁻ 100%	2.45 m 5/2 ⁺ # M=4480# (410#) β ⁻ 100%					
206 81 Tl 125	207 81 Tl 126	208 81 Tl 127	209 81 Tl 128	210 81 Tl 129	211 81 Tl 130	212 81 Tl 131								
3.74 m (12) β ⁻ 100% IT=100%	4.200 m 0 ⁺ β ⁻ 100% IT=100%	1.33 s 11/2 ⁺ β ⁻ 100% IT=100%	4.77 m 10 ² * M=2222 (1.4) β ⁻ 100%	3.053 m 5(⁺) M=16749.5 (2.0) β ⁻ 100%	2.161 m (1/2 ⁺) M=13638 (8) β ⁻ 100%	1.30 m 5 ⁺ # M=9246 (12) β ⁻ 100% IT=n=0.009 (6%)	1# m 1/2 ⁺ # M=6080# (200#) β ⁻ ?	30# s 5 ⁺ # M=1650# (300#) β ⁻ ?						
205 80 Hg 125	206 80 Hg 126	207 80 Hg 127	208 80 Hg 128	209 80 Hg 129	210 80 Hg 130									
1.12 ms 13/2 ⁺ β ⁻ 100% IT=100%	5.2 m 10 ² * M=22287 (4) β ⁻ 100%	8.15 ms 4 ⁺ M=20946 (20) β ⁻ 100%	2.9 m (9/2 ⁺) M=16220 (150) β ⁻ 100%	42 m 0 ⁺ M=13100# (300#) β ⁻ 100%	37 s 9/2 ⁺ # M=8350# (200#) β ⁻ 100%	10# m 0 ⁺ M=5110# (300#) β ⁻ ?								
204 79 Au 125	205 79 Au 126													
39.8 s (2 ⁺) M=20750# (200#) β ⁻ 100%	31 s 3/2 ⁺ M=18750# (300#) β ⁻ 100%													

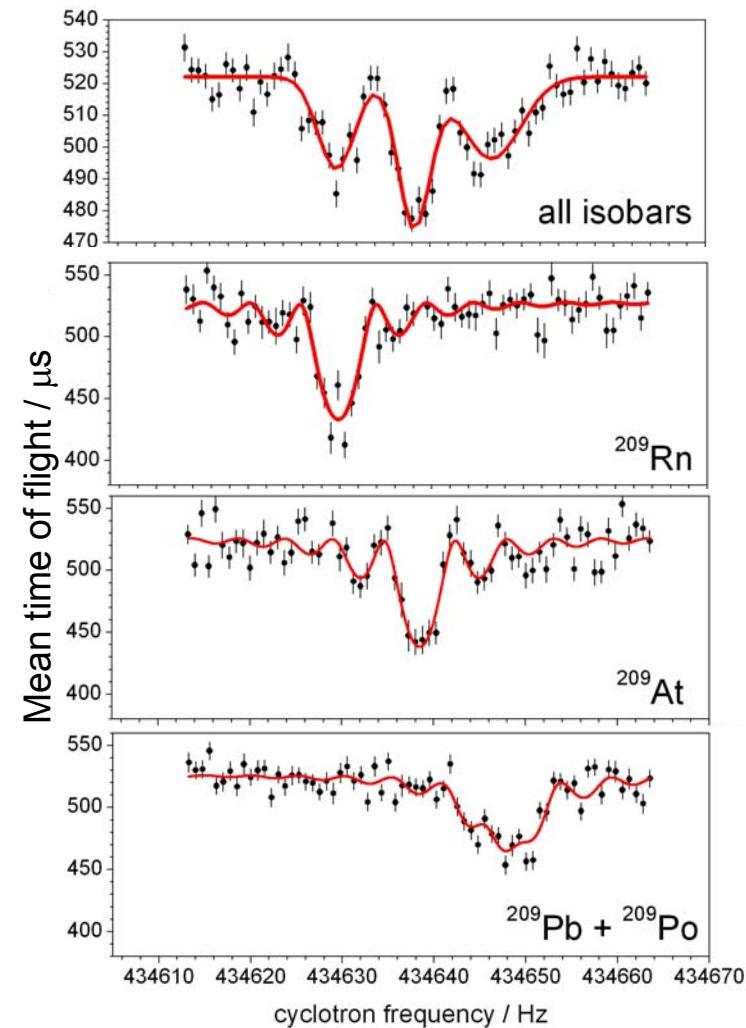
Z=82

N=126

Problem: very large contamination from surface-ionized francium

Tape station: October beamtime

Many problems at Isolde and Isoltrap:
No n-rich Tl and Hg seen
Tape-station problems



Performed proof-of-principle measurements at:
 $A=209$: isobaric purification
 $A=138$: beta- and gamma- spectroscopy on Xe

Presently: fixing problems and getting ready for next year

Published in 2008

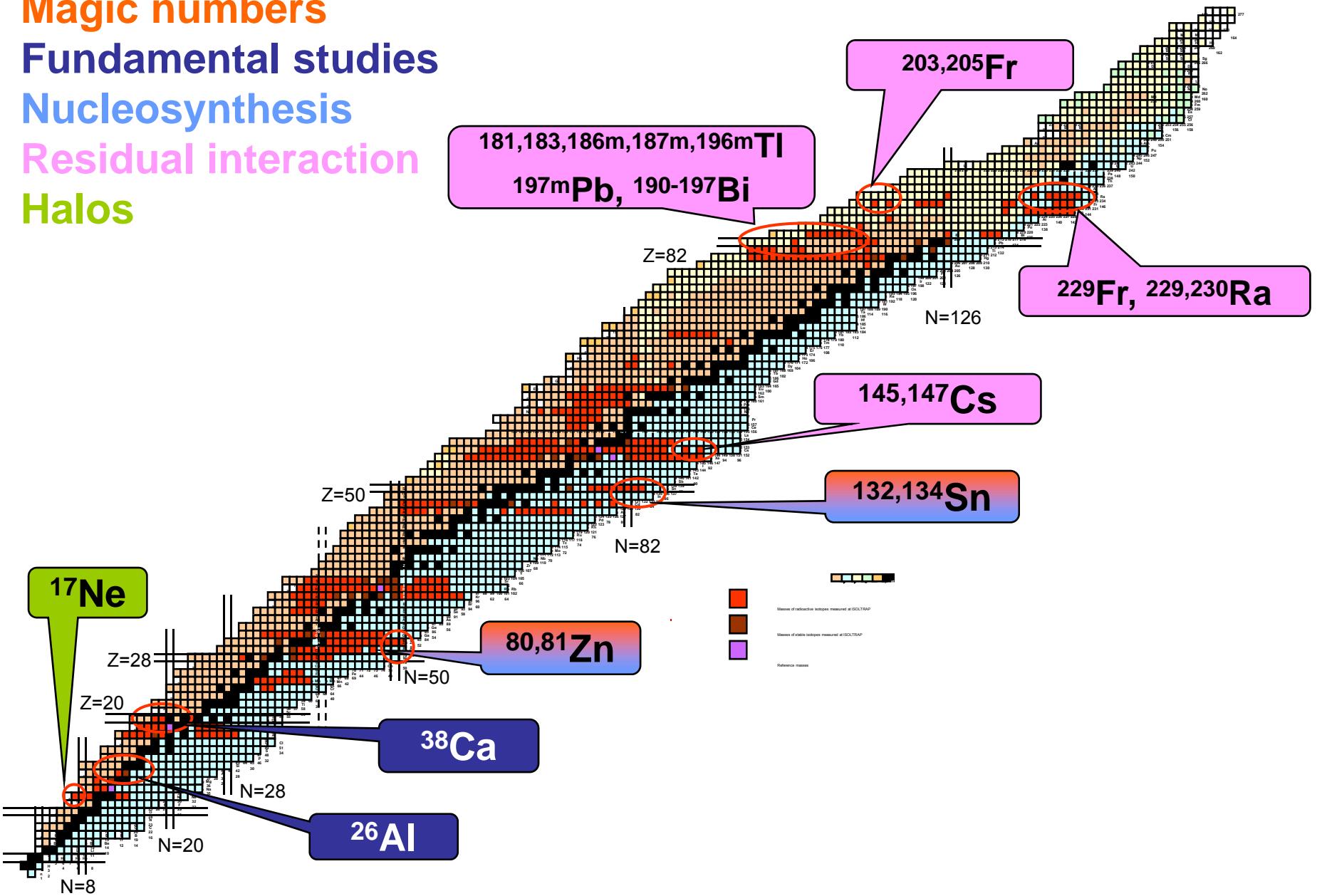
Magic numbers

Fundamental studies

Nucleosynthesis

Residual interaction

Halos



^{17}Ne

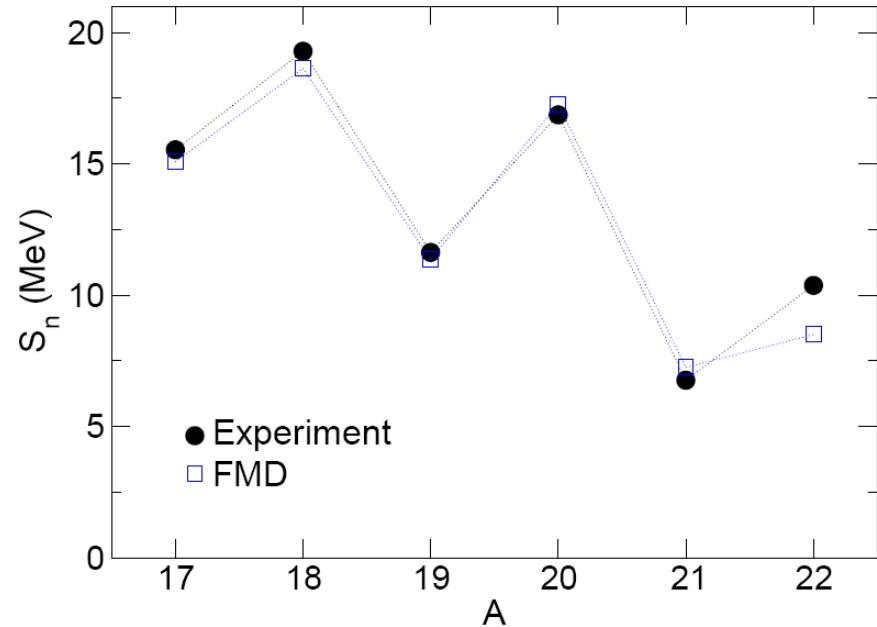
Motivation: investigate 2-proton halo behaviour of ^{17}Ne

Method: precise mass measurement used to derive charge radius from isotope-shift investigation

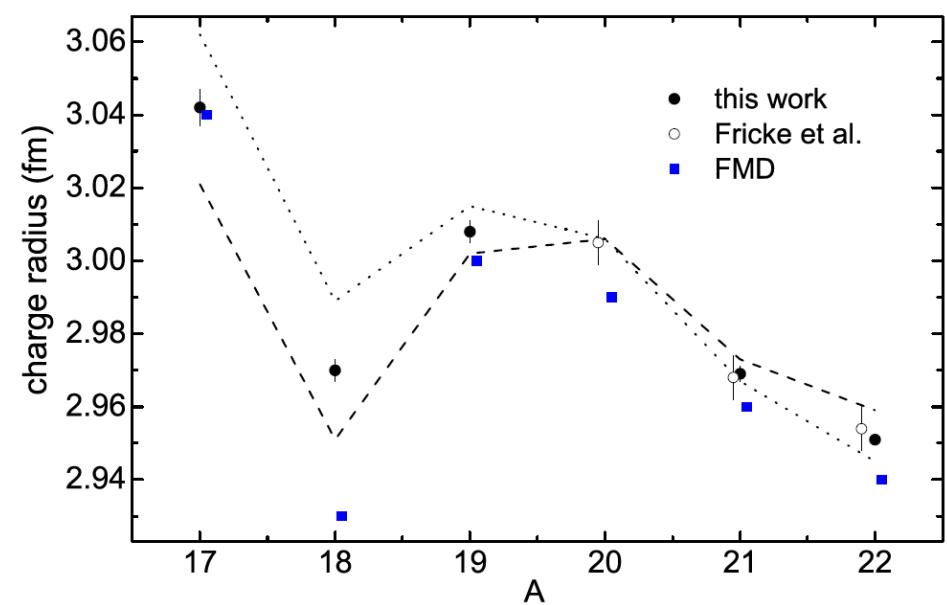
Theory: FMD (fermionic molecular dynamics), T. Neff (GSI)

(reproduces very well binding energies, charge and matter radii of $^{17-22}\text{Ne}$)

One-neutron separation energy

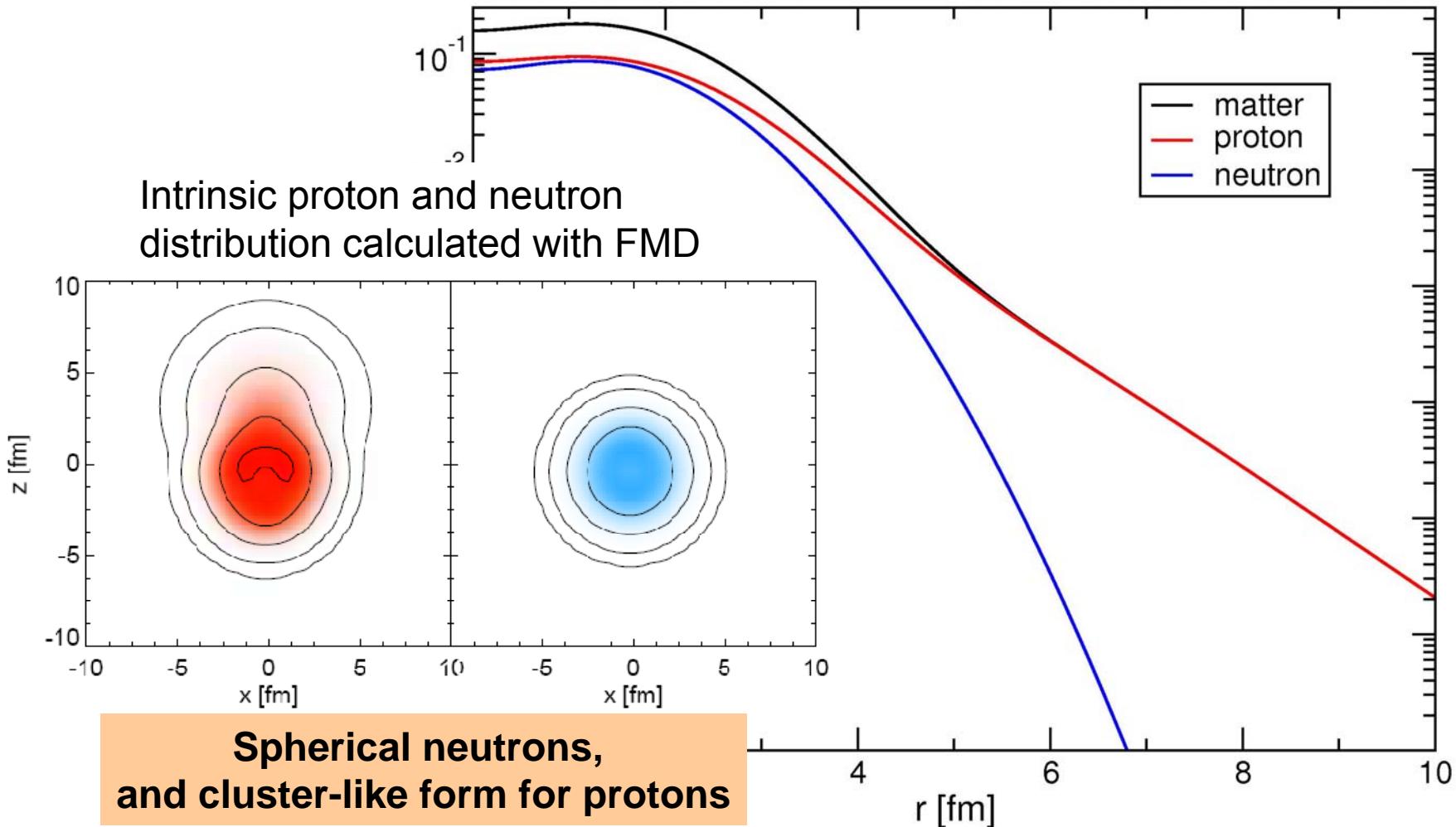


Charge radii



^{17}Ne

FMD Matter, proton and neutron density distributions in ^{17}Ne g.s.



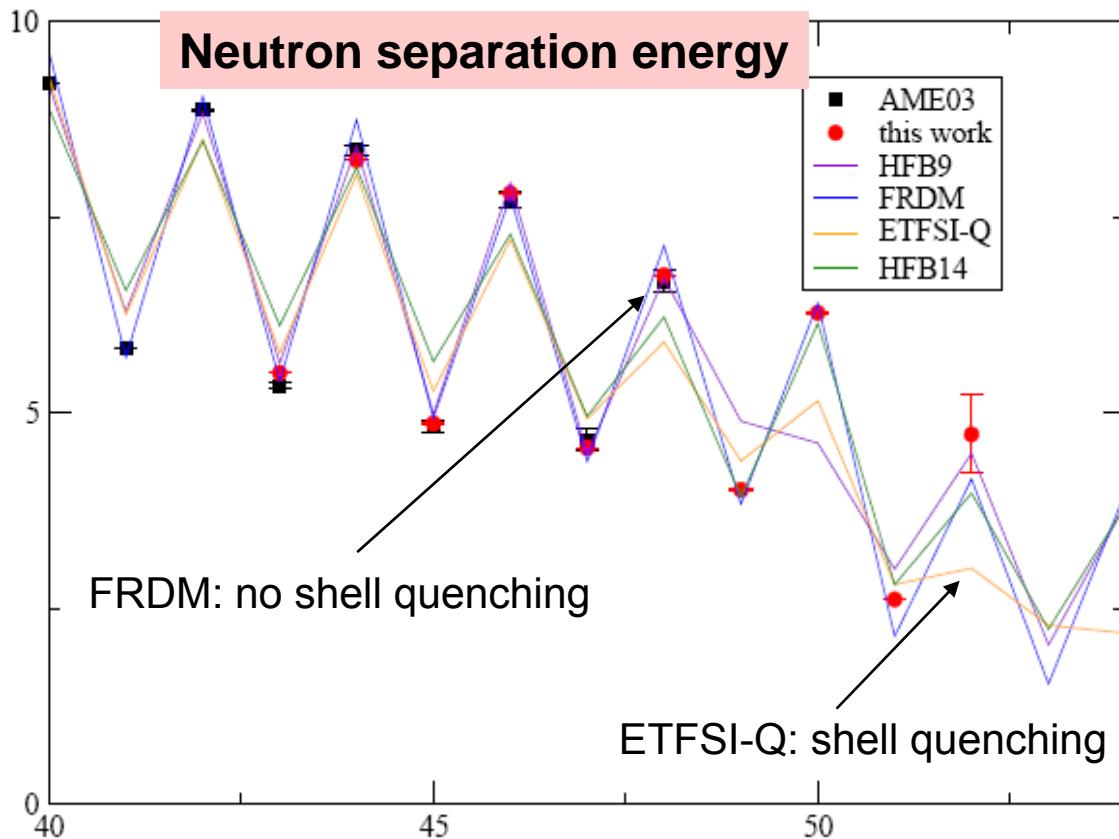
s^2 proton contribution in g.s. around 35% -> extended proton distribution =>
Onset of halo-like structure

$^{80,81}\text{Zn}$

Motivation: ^{80}Zn as r process ‘waiting-point’, N=50 shell

Method: ‘classical’ ToF resonance

to clean Rb contamination: laser ionization, n-converter, quartz-transfer line



mass of ^{82}Zn : derived from systematic trends

No evidence for shell quenching:
N=50 is a good magic number

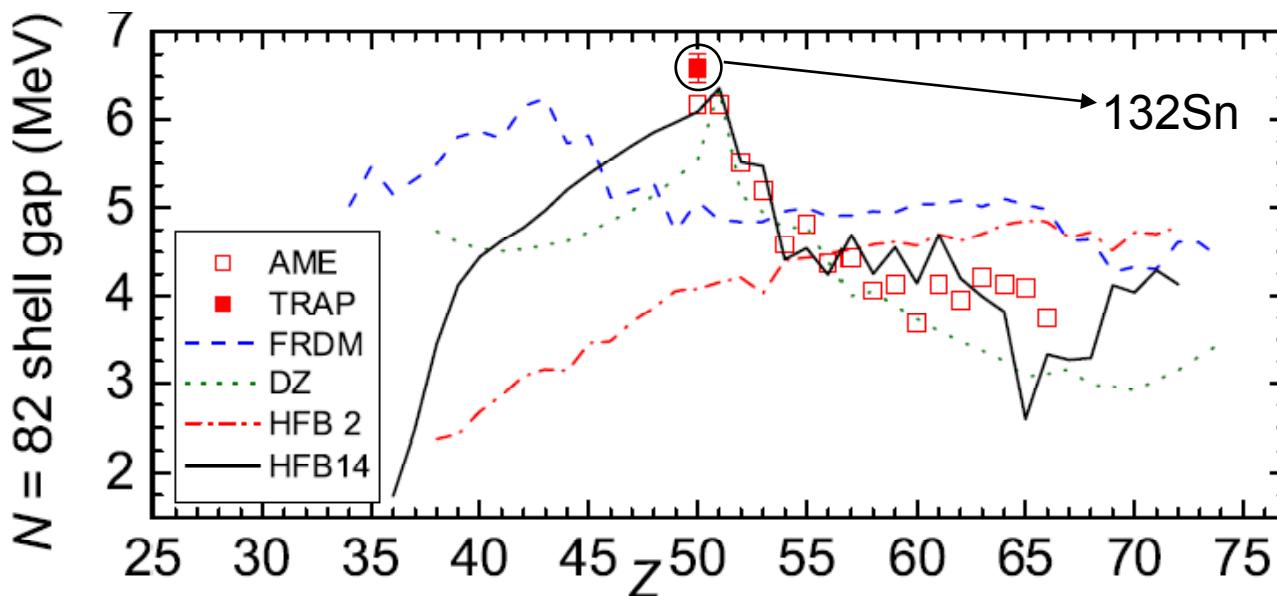
+ refined astrophysical calculations possible

$^{132,134}\text{Sn}$

Motivation: ^{132}Sn as r process ‘waiting-point’,
previous experimental evidence for N=82 shell quenching

Method: ‘classical’ ToF resonance
To suppress isobars: measured as molecule X+34S

$$\text{neutron shell gap} \quad \Delta_n(N_0, Z) = S_{2n}(N_0, Z) - S_{2n}(N_0 + 2, Z)$$



Restoration of N=82 gap

Summary

Precise mass measurements cover a range of physics interests:

- Nuclear structure: halos, magic numbers, residual interaction
- Nucleosynthesis waiting points
- Weak interaction, neutrino-mass determination

Novel techniques used and planned at ISOLTRAP:

- Ramsey excitation: to improve precision
- Purification of isobars with quartz line, molecular sidebands
- Trap-assisted decay spectroscopy

Measured in 2008:

- $^{126,128}\text{Cd}$, $^{220,223-229}\text{Rn}$, – p-n residual interaction, δV_{pn}
- $^{194}\text{Hg}/\text{Au}$, $^{202}\text{Pb}/\text{Tl}$ – candidates for neutrino-mass determination

Published in 2008:

- ^{17}Ne , ^{26}Al and ^{38}Ca , $^{80,81}\text{Zn}$, $^{132,134}\text{Sn}$, masses around A=208

Thanks to my collaborators:

**G. Audi, D. Beck, K. Blaum, C. Boehm, M. Breitenfeldt, S. George, F. Herfurth,
A. Kellerbauer, H.-J. Kluge, D. Lunney, S. Naimi, D. Neidherr, M.
Rosenbusch, S. Schwarz, L. Schweikhard, C. Yazidjian**

**Funding: BMBF, GSI, CERN, ISOLDE, EU networks EUROTRAPS, EXOTRAPS,
NIPNET,
EU Marie Curie EIF programme**

Thanks for your attention

^{26}Al and ^{38}Ca

Motivation: Q_β value of the superallowed $0^+ \rightarrow 0^+$ β -decay of ^{38}Ca and ^{26m}Al ;

Test of the conserved-vector-current (CVC) hypothesis of the electroweak interaction and of the Cabibbo–Kobayashi–Maskawa (CKM) matrix unitarity (V_{ud})

Method: Ramsey technique

for Ca: used molecular beam CaF^+ to separate isobaric contamination ^{38}K

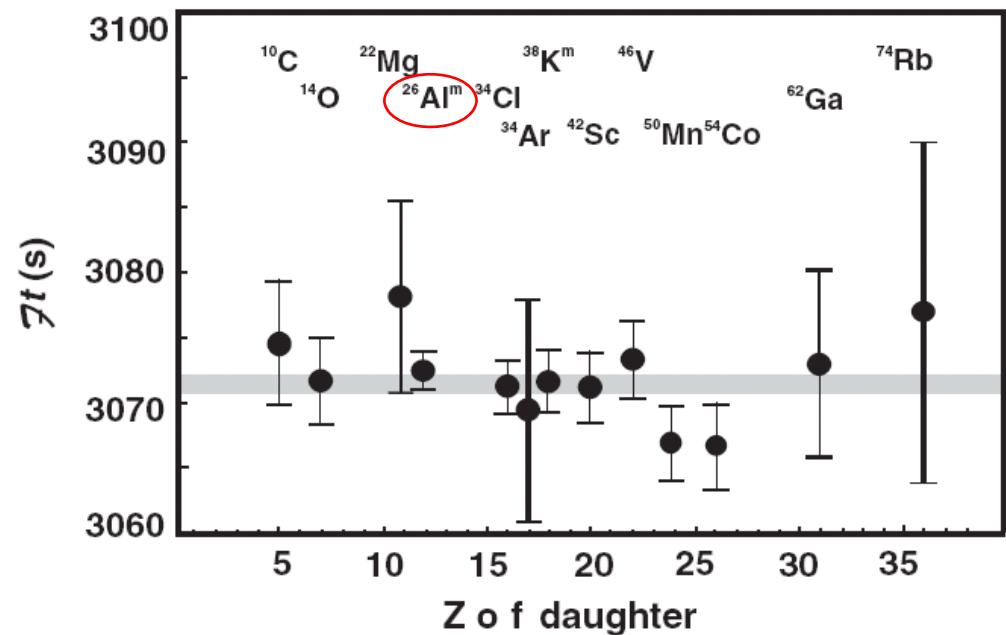
Status for 13 best-known superallowed β -emitters in 2007

$$\overline{\mathcal{F}t} = 3071.4(8) \text{ s}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000 \pm 0.0011.$$

Not included here:

- LEBIT value for ^{38}Ca
- JYFLTRAP value for ^{26m}Al
- Our data on ^{38}Ca and ^{26}Al

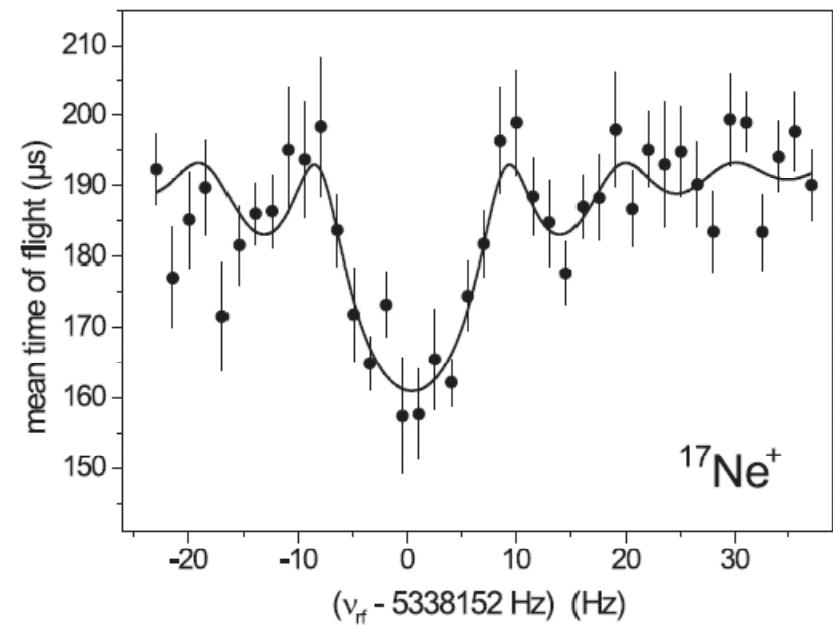


26,27Al, 39Ca: S. George et al., EPL 82, 50005 ('08)
38Ca+Ramsey: S. George et al., PRL 98, 162501 ('07)
Ramsey: S. George et al., IJMS 264, 110 ('07)

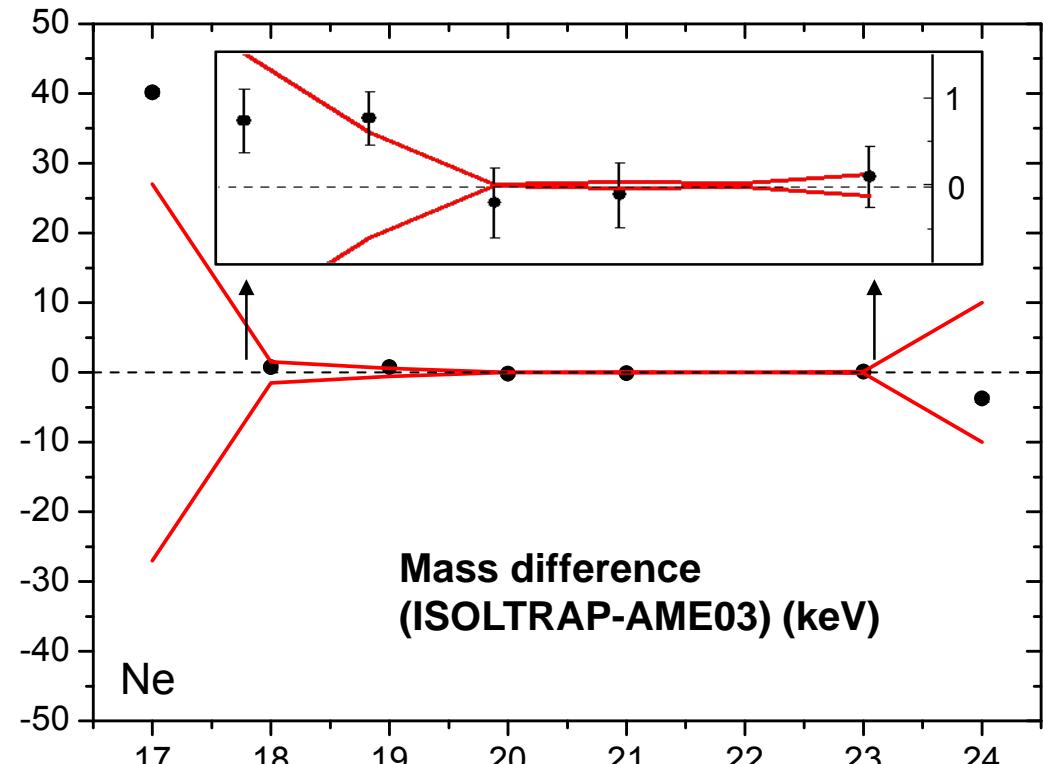
^{17}Ne

Motivation: investigate 2-proton halo behaviour of ^{17}Ne

Method: precise mass measurement used to derive charge radius from isotope-shift investigation



$^{17}\text{Ne}^+$



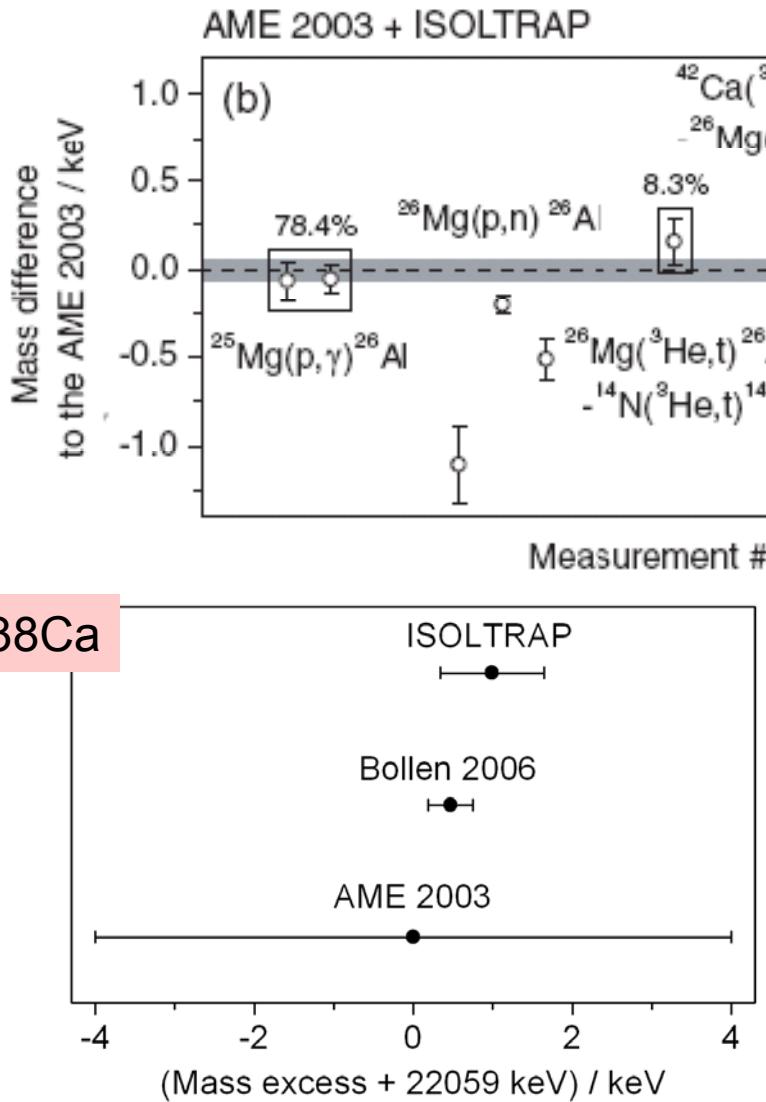
Mass difference
(ISOLTRAP-AME03) (keV)

^{17}Ne mass 50x more precise, and revealing 50-keV shift

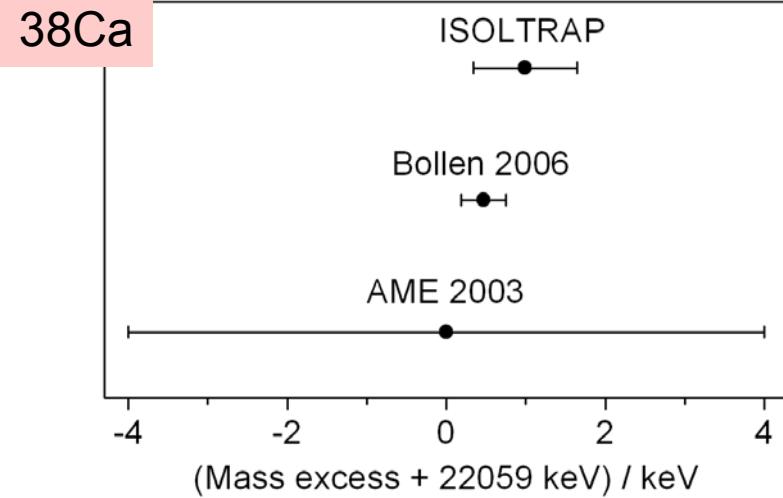
Mass number A

^{26}Al and ^{38}Ca

Mass (AME) reevaluation after our measurements:



Not included in the
AME reevaluation yet
Eronen et al., PRL 97 232501 ('06)



New AME values (JYFLTRAP result not in)

Nuclide	Mass excess/keV present	Mass excess/keV 2003
^{26}Al	-12210.20(06)	-12210.31(06)
^{38}Ca	-22058.46(25)	-22059(5)

Influence on CVC and CKM:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9996(7)$$

S. George et al.,
EPL 82, 50005 ('08),
PRL 98, 162501 ('07),
IJMS 264, 110 ('07)

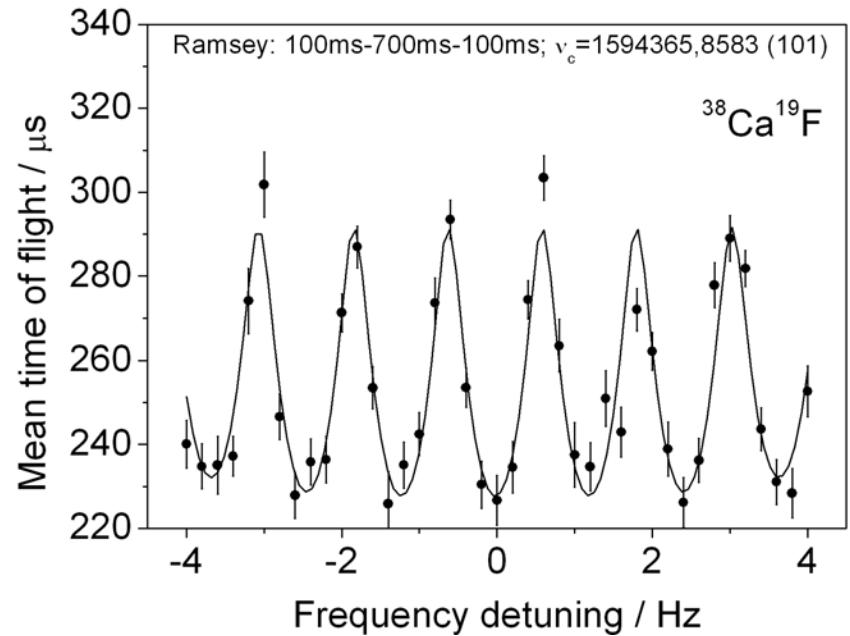
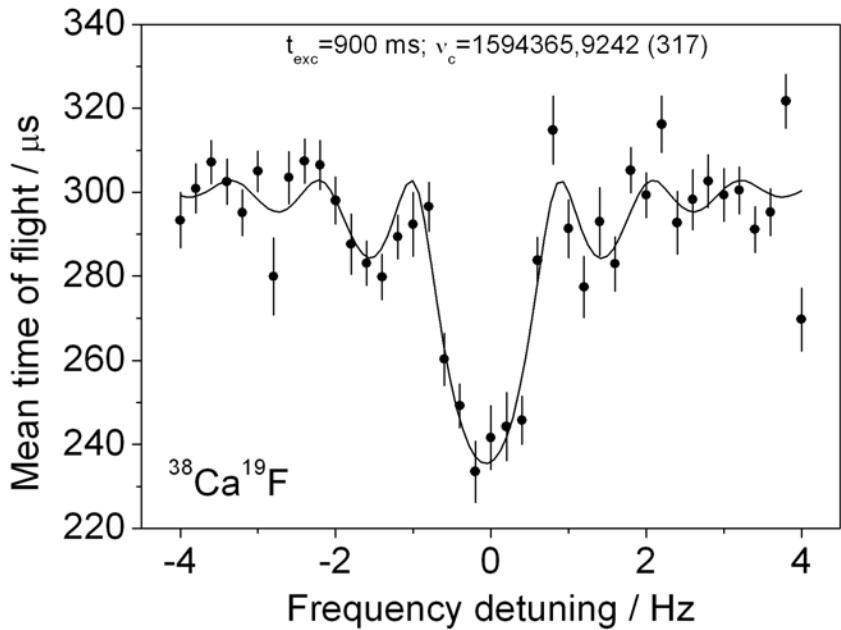
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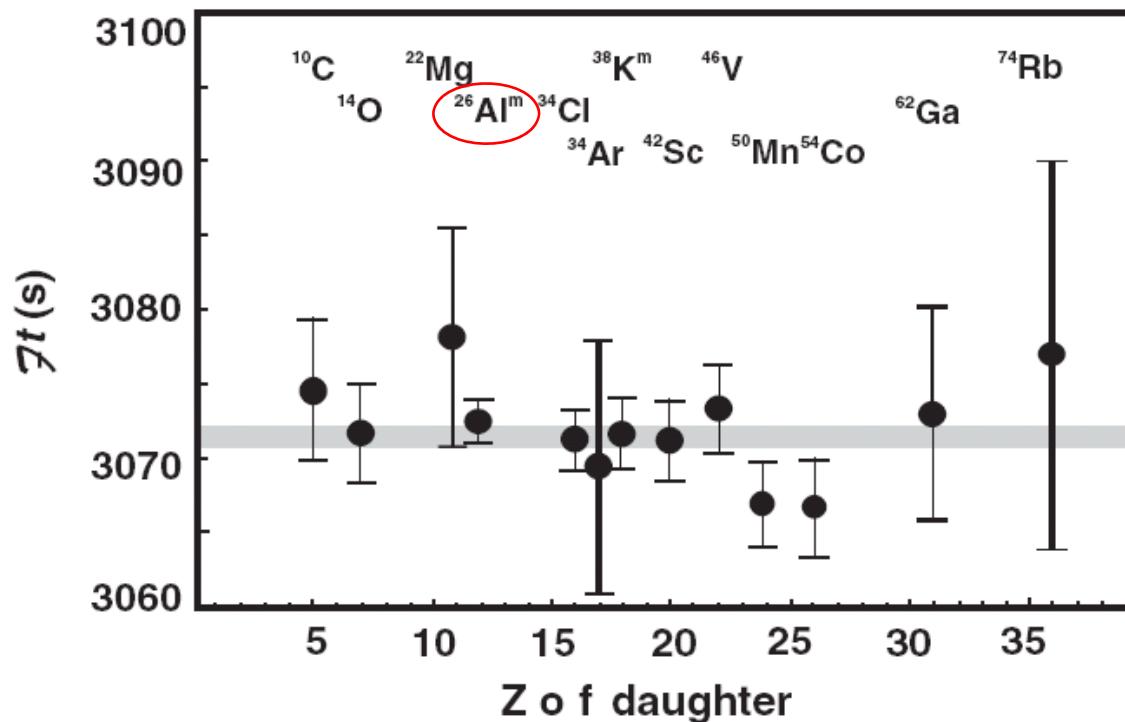
^{26}Al and ^{38}Ca

Status for 13 best-known superallowed β -emitters

I.S. Towner and J.C. Hardy, PRC 77, 025501 ('08)

$$\overline{\mathcal{F}t} = 3071.4(8) \text{ s}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000 \pm 0.0011.$$



Not included yet:

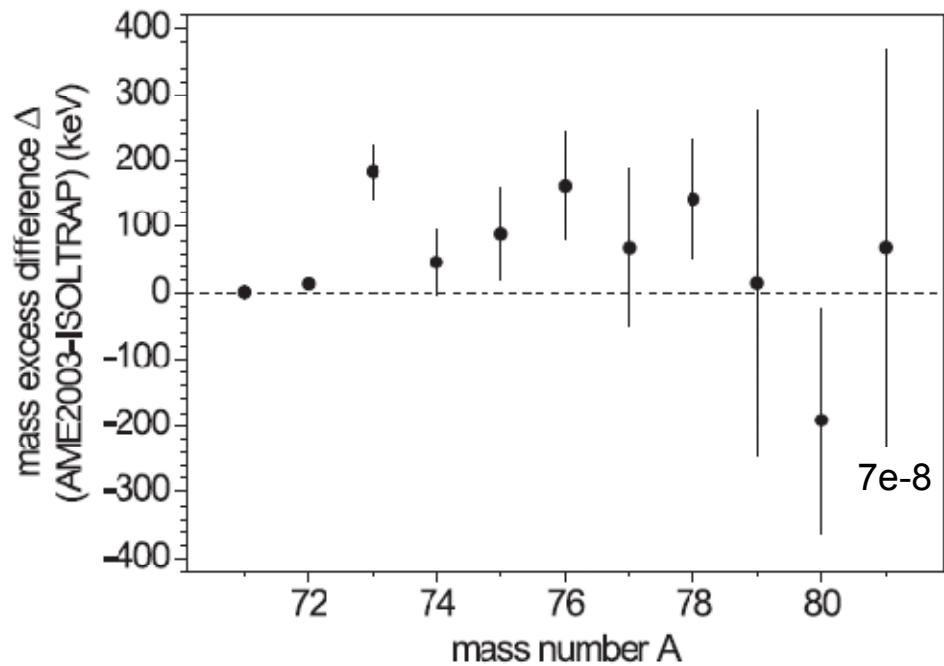
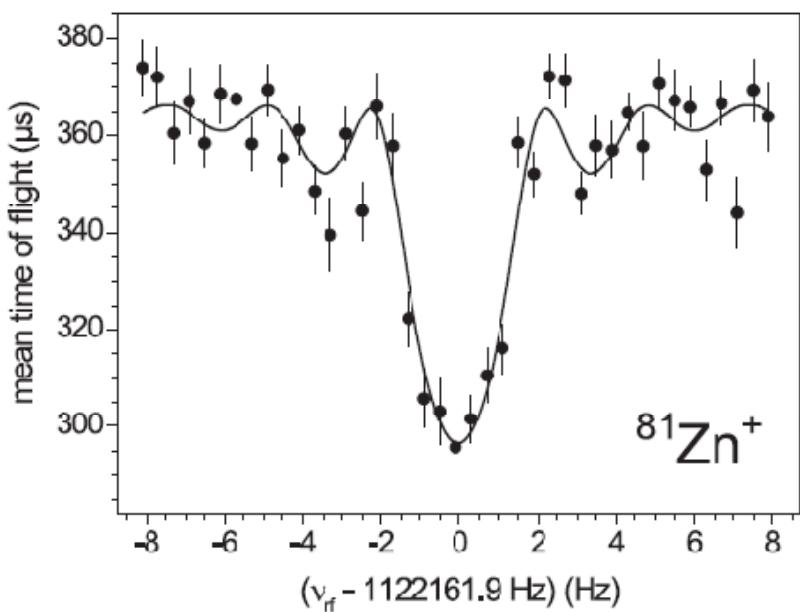
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- JYFLTRAP value for ^{26}mAl
- Our data on ^{38}Ca and ^{26}Al

$^{80,81}\text{Zn}$

Motivation: ^{80}Zn as r process ‘waiting-point’, N=50 shell

Method: ‘classical’ ToF resonance

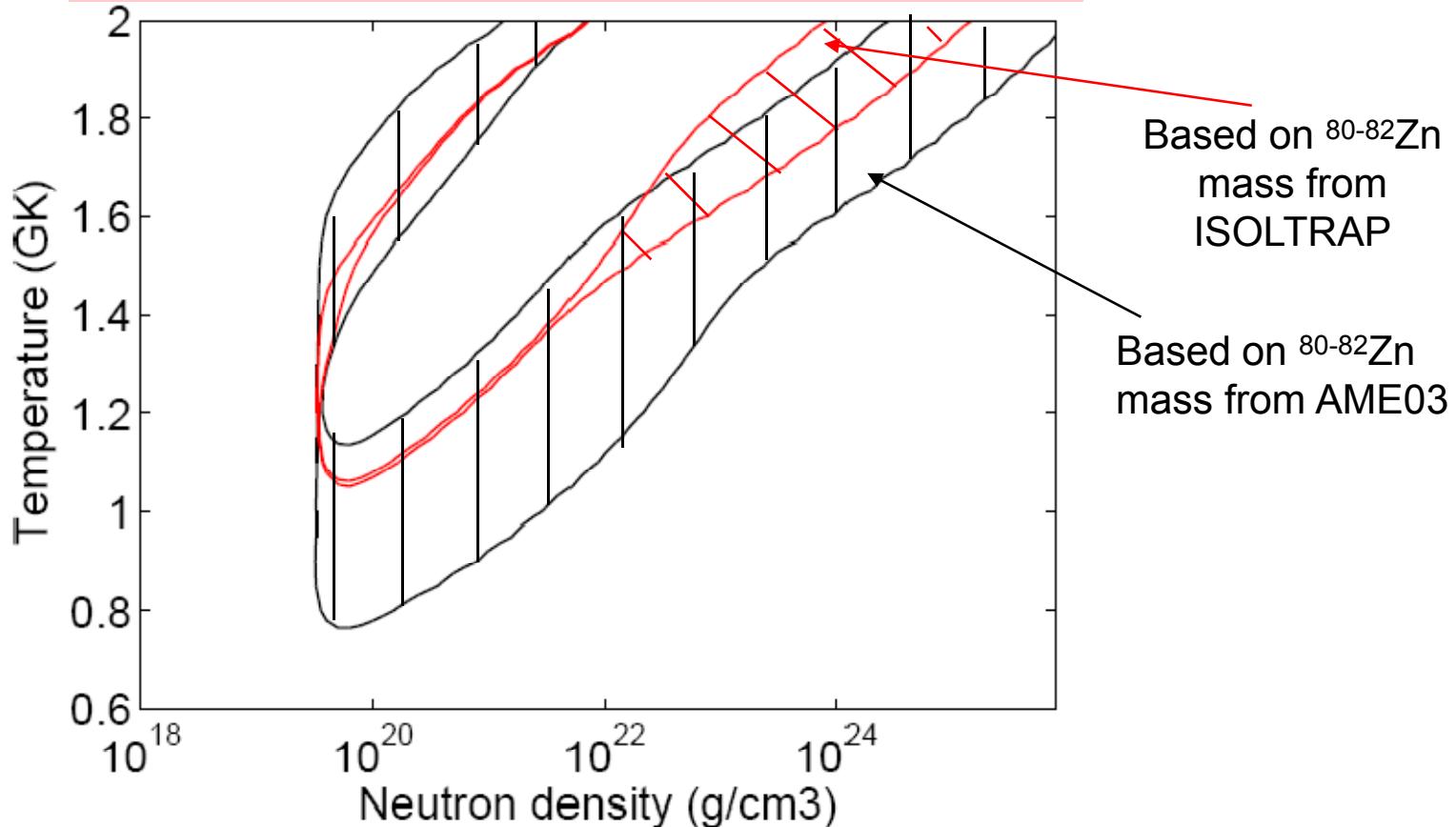
to clean Rb contamination: laser ionization, n-converter, quartz-transfer line



mass of ^{82}Zn : derived from the systematic trends

$^{80,81}\text{Zn}$

Conditions for ^{80}Zn to be r-process waiting point



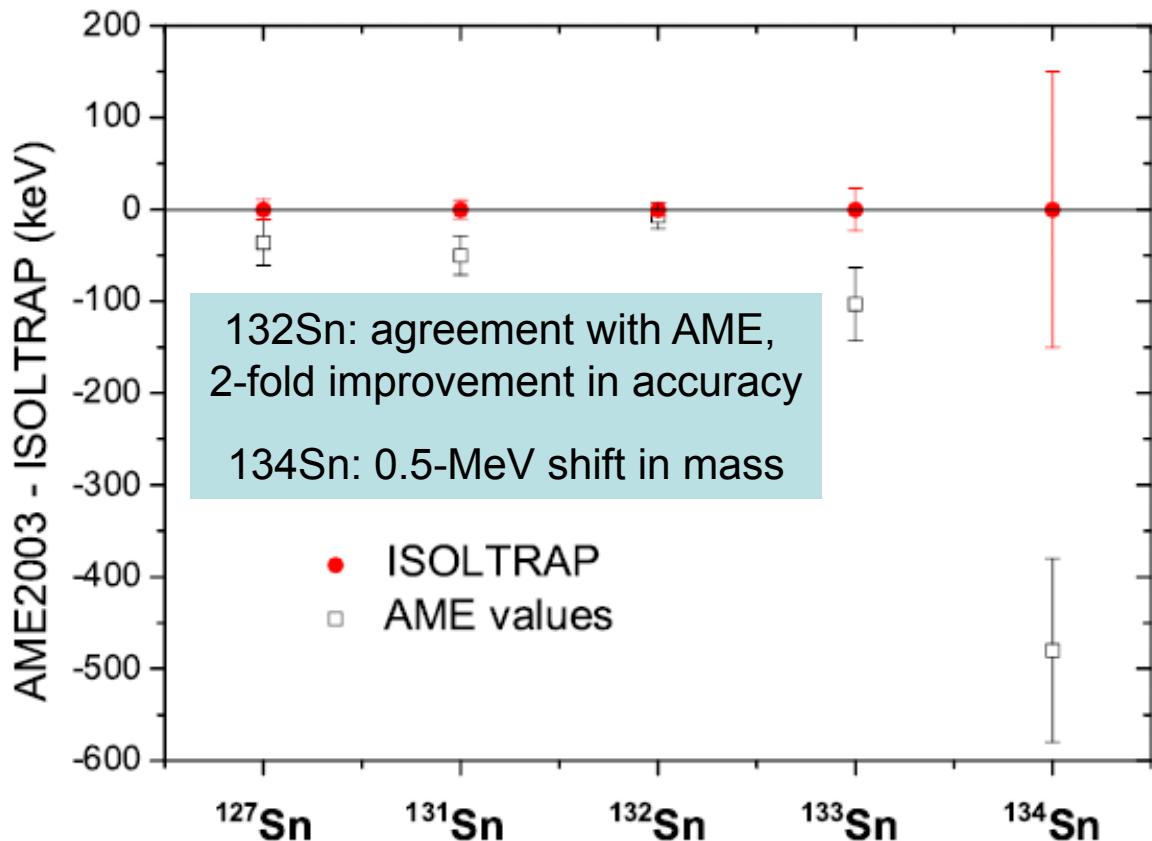
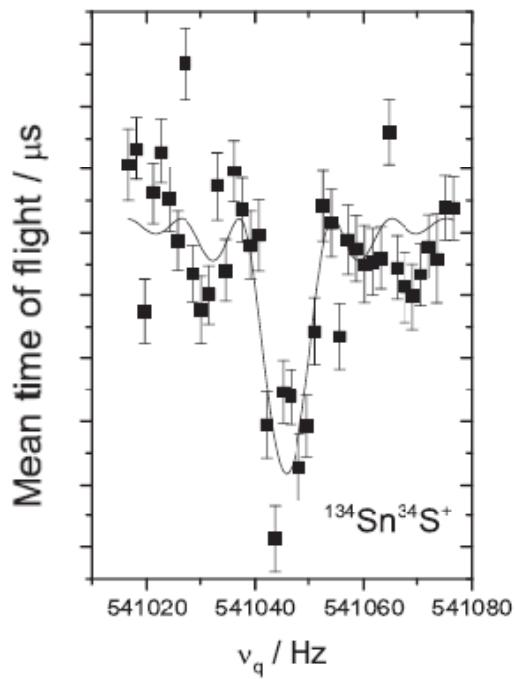
^{80}Zn : - 1st major r-process waiting point with masses (S_n and n-capture Q-value) and half-life are determined experimentally
- refined astrophysical calculations possible

$^{132,134}\text{Sn}$

Motivation: ^{132}Sn as r process ‘waiting-point’,
previous experimental evidence for N=82 shell quenching

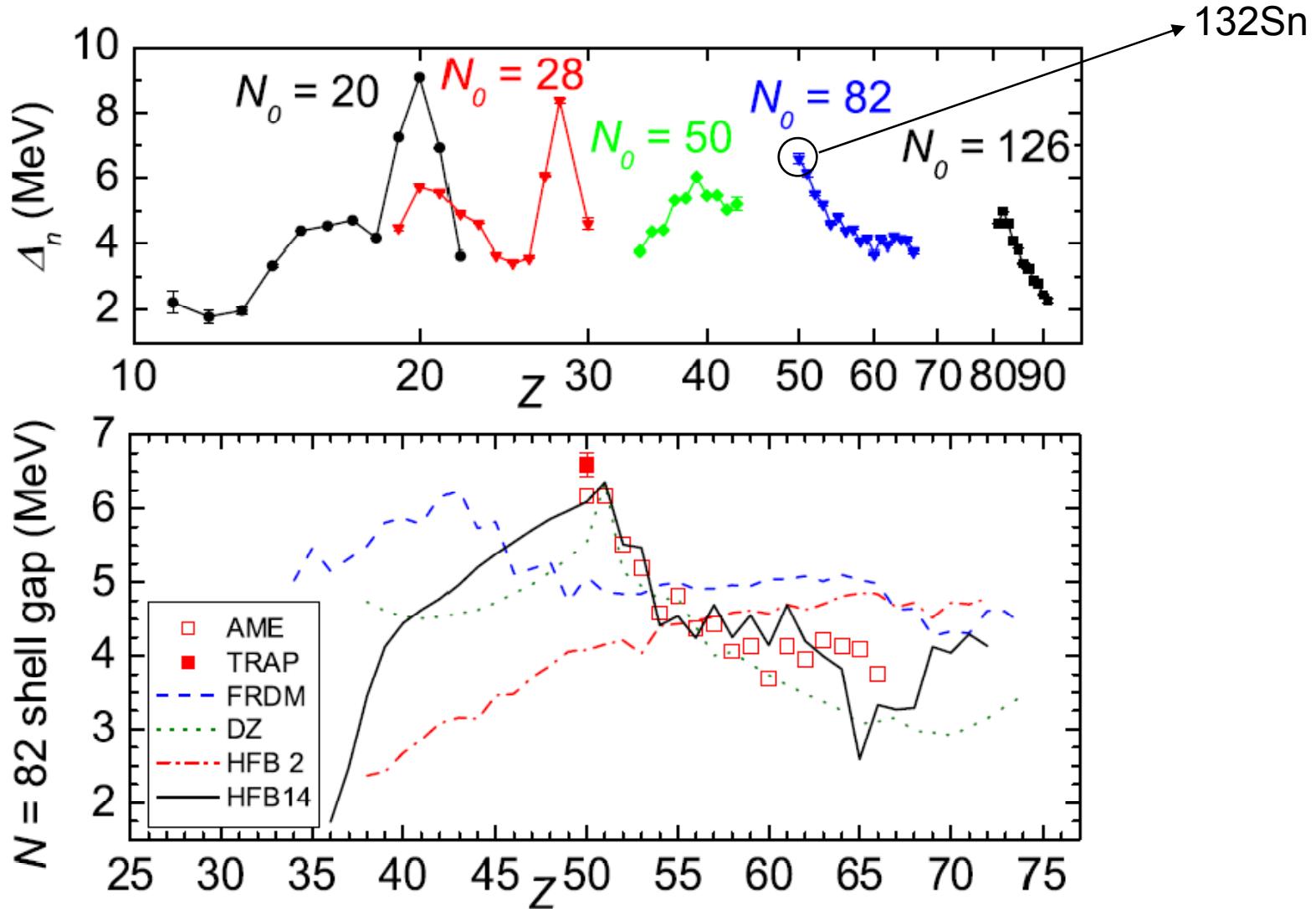
Method: ‘classical’ ToF resonance

To suppress isobars: measured as molecule X+ ^{34}S



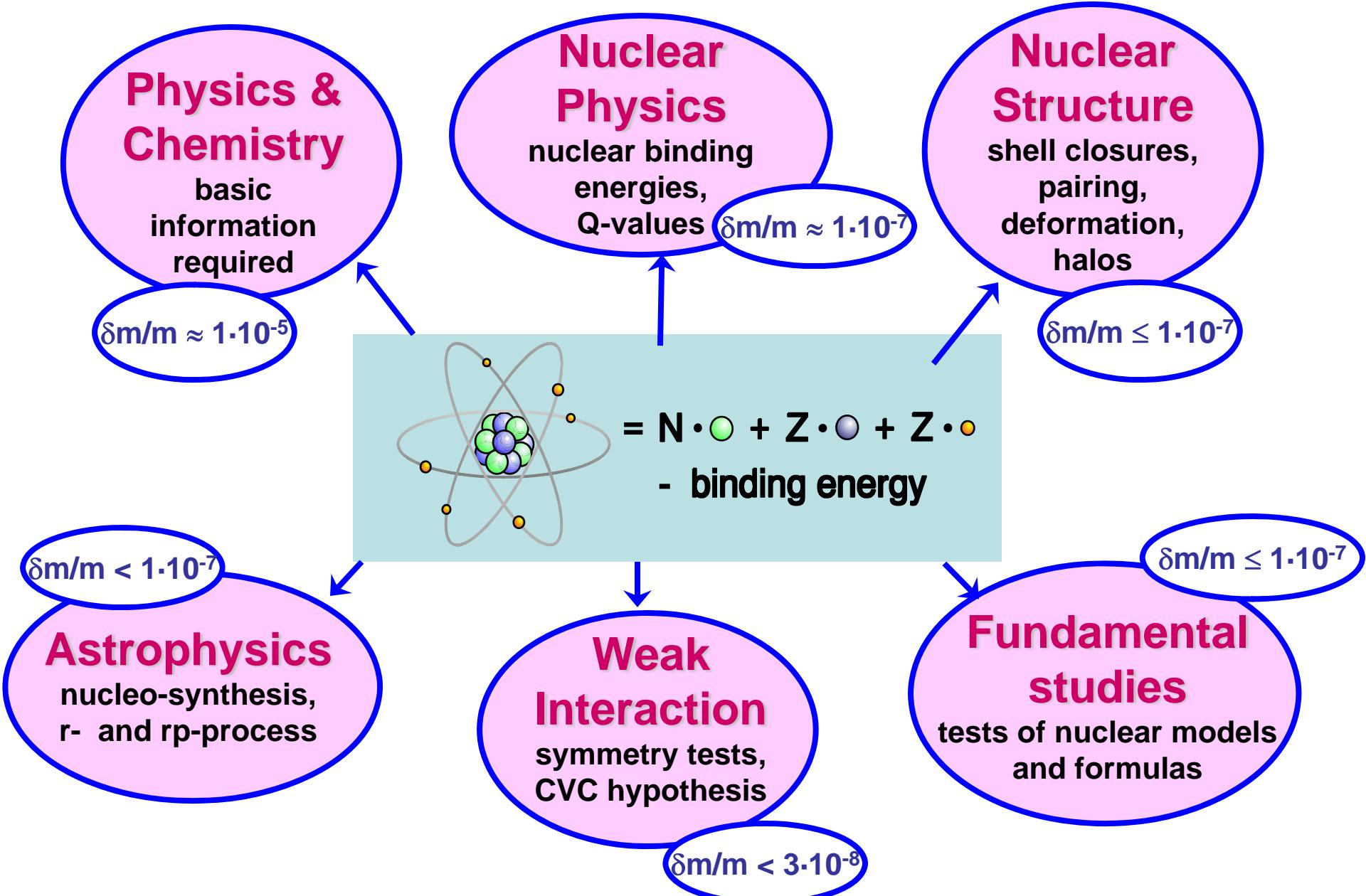
132,134Sn

neutron shell gap $\Delta_n(N_0, Z) = S_{2n}(N_0, Z) - S_{2n}(N_0 + 2, Z)$.



Restoration of $N=82$ gap

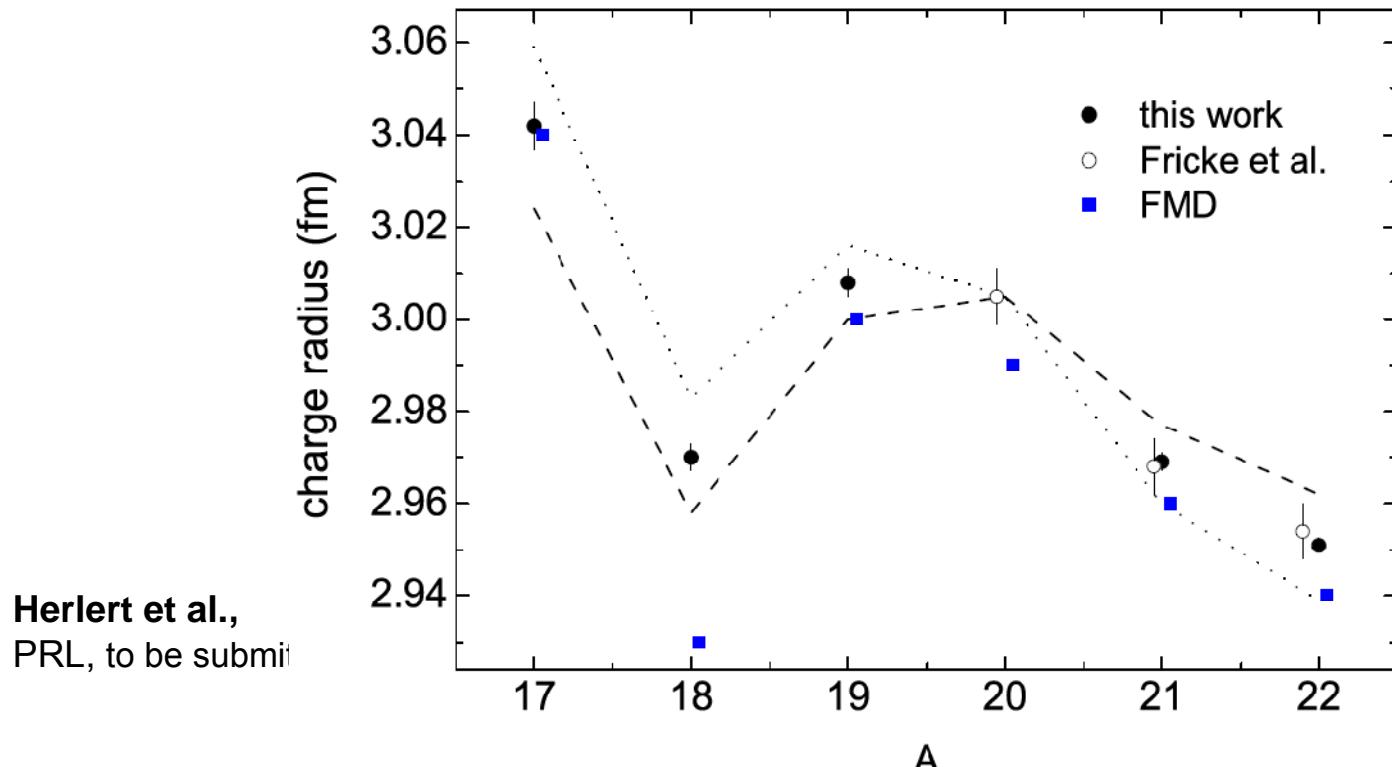
Why do we need nuclear masses?



17Ne

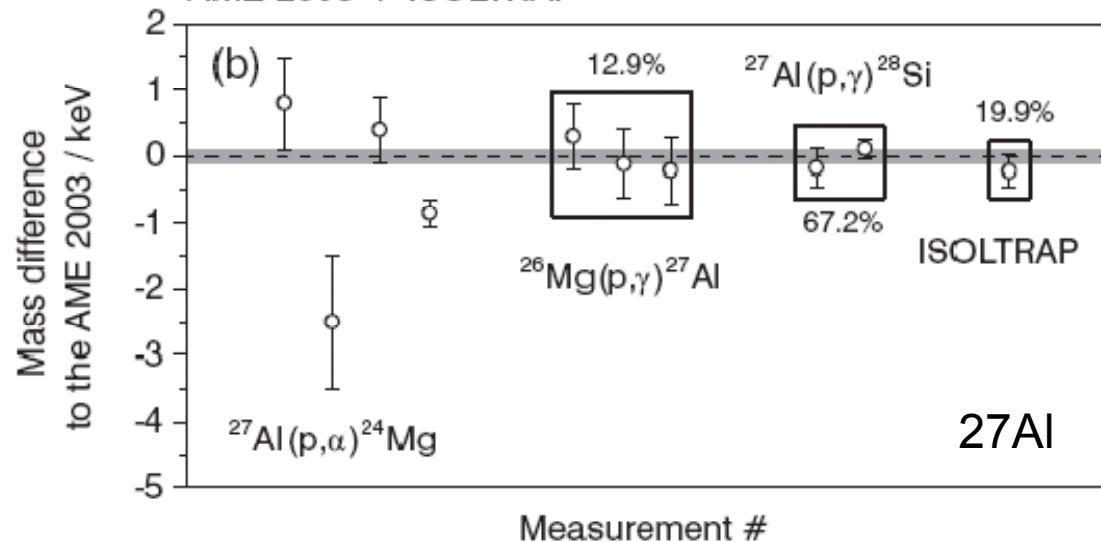
TABLE I: Frequency ratios r of $^{17,19-21}\text{Ne}$ (compared to ^{22}Ne) and masses of $^{17-22}\text{Ne}$ from the present study, compared to literature [16] which already includes data from [15].

A	frequency ratio r	AME'03 (μu)	new mass (μu)
17	0.773 829 869 8 (261)	17017672(29)	17017714.75(57)
18		18005708.2(3)	18005708.70(39)
19	0.864 056 826 3 (89)	19001880.2(3)	19001880.76(16)
20	0.909 101 007 3 (89)	19992440.175(2)	19992440.1842(19)
21	0.954 638 456 4 (116)	20993846.68(4)	20993846.684(41)
22	reference	21991385.11(2)	21991385.113(18)

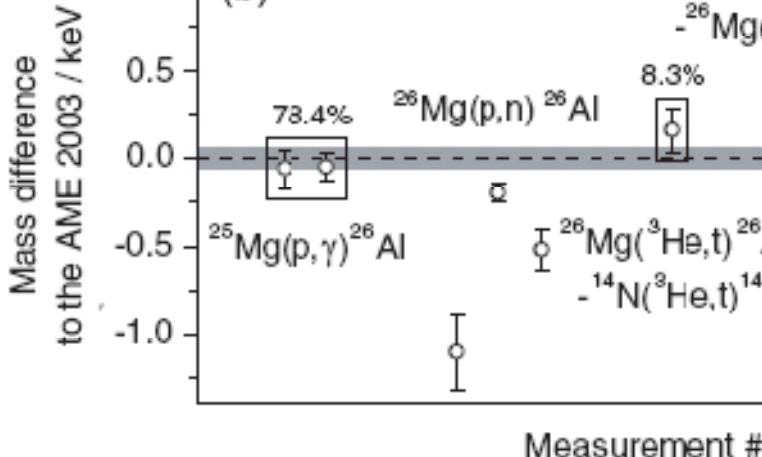


$^{26,27}\text{Al}$ and $^{38,39}\text{Ca}$

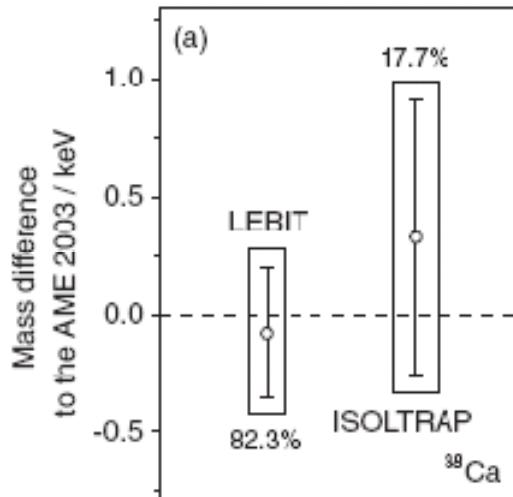
AME 2003 + ISOLTRAP



AME 2003 + ISOLTRAP

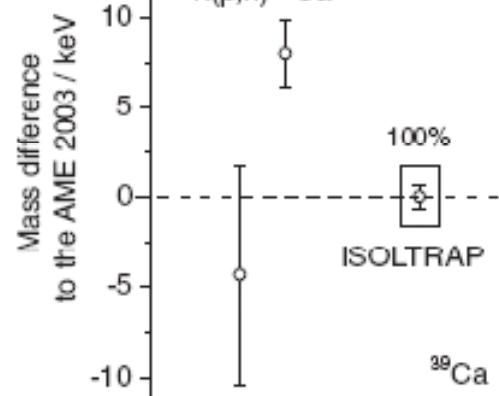


^{39}Ca



(b)

$^{39}\text{K}(\text{p},\text{n})^{38}\text{Ca}$



CVC

TABLE VII. Corrected $\mathcal{F}t$ values for the 13 best-known superallowed decays, obtained with the new correction terms presented in this work. The experimental ft values were taken from results in our 2005 survey [1] updated with more recent published data [6,7,9–16]. The average $\overline{\mathcal{F}t}$ value and the normalized χ^2 of the fit to a constant appear at the bottom.

Parent nucleus	ft (s)	δ'_R (%)	δ_{NS} (%)	δ_C (%)	$\mathcal{F}t$ (s)
$T_z = -1:$					
^{10}C	3039.5(47)	1.679(4)	-0.345(35)	0.175(18)	3074.5(49)
^{14}O	3042.5(27)	1.543(8)	-0.245(50)	0.330(25)	3071.6(33)
^{22}Mg	3052.2(72)	1.466(17)	-0.225(20)	0.380(22)	3078.3(74)
^{34}Ar	3052.5(82)	1.412(35)	-0.180(15)	0.665(56)	3069.4(85)
$T_z = 0:$					
$^{26}\text{Al}^m$	3037.0(11)	1.478(20)	0.005(20)	0.310(18)	3072.5(15)
^{34}Cl	3050.0(11)	1.443(32)	-0.085(15)	0.650(46)	3071.3(21)
$^{38}\text{K}^m$	3051.1(10)	1.440(39)	-0.100(15)	0.655(59)	3071.7(24)
^{42}Sc	3046.4(14)	1.453(47)	0.035(20)	0.665(56)	3071.2(27)
^{46}V	3049.6(16)	1.445(54)	-0.035(10)	0.620(63)	3073.4(30)
^{50}Mn	3044.4(12)	1.445(62)	-0.040(10)	0.655(54)	3066.9(28)
^{54}Co	3047.6(15)	1.443(71)	-0.035(10)	0.770(67)	3066.7(33)
^{62}Ga	3075.5(14)	1.459(87)	-0.045(20)	1.48(21)	3073.0(72)
^{74}Rb	3084.3(80)	1.50(12)	-0.075(30)	1.63(31)	3077(13)
Average $\overline{\mathcal{F}t}$					3071.4(8)
χ^2/ν					0.6

26,27Al and 38,39Ca

Superallowed Fermi β decay between 0^+ states depends uniquely on the vector part of the hadronic weak interaction. When it occurs between isospin $T = 1$ analog states, the conserved vector current (CVC) hypothesis indicates that the ft values should be the same irrespective of the nucleus,

Ion	$T_{1/2}$	Reference	$\frac{\nu_{ion}}{\nu_{ref}}$
$^{26}\text{Al}^+$	717 (24) ky	$^{23}\text{Na}^+$	1.1303707761(104)
$^{27}\text{Al}^+$	stable	$^{23}\text{Na}^+$	1.1736365541(108)
$^{38}\text{Ca}^{19}\text{F}^+$	440 (8) ms	$^{39}\text{K}^+$	1.4622576087(162) ^(a)
$^{39}\text{Ca}^{19}\text{F}^+$	859.6 (1.4) ms	$^{39}\text{K}^+$	1.4877789303(165)

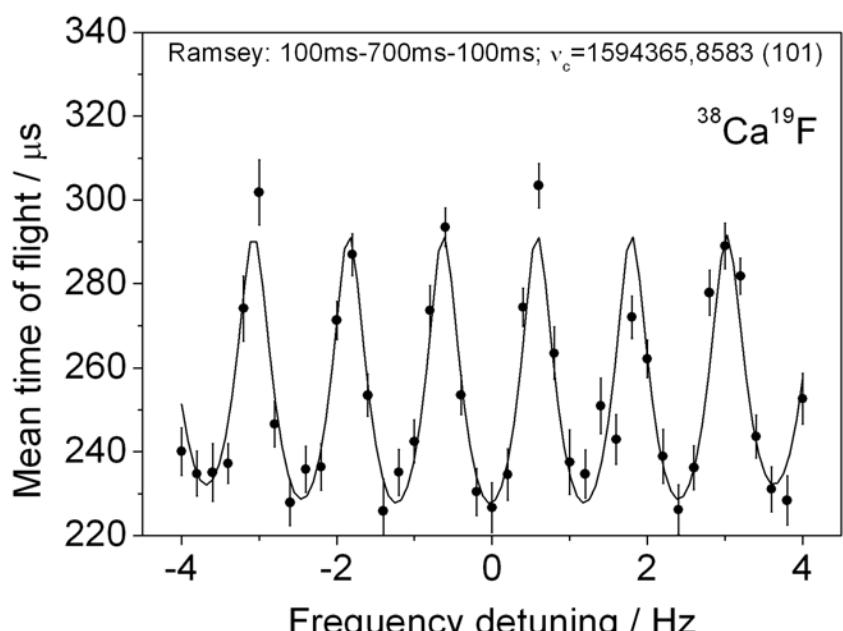
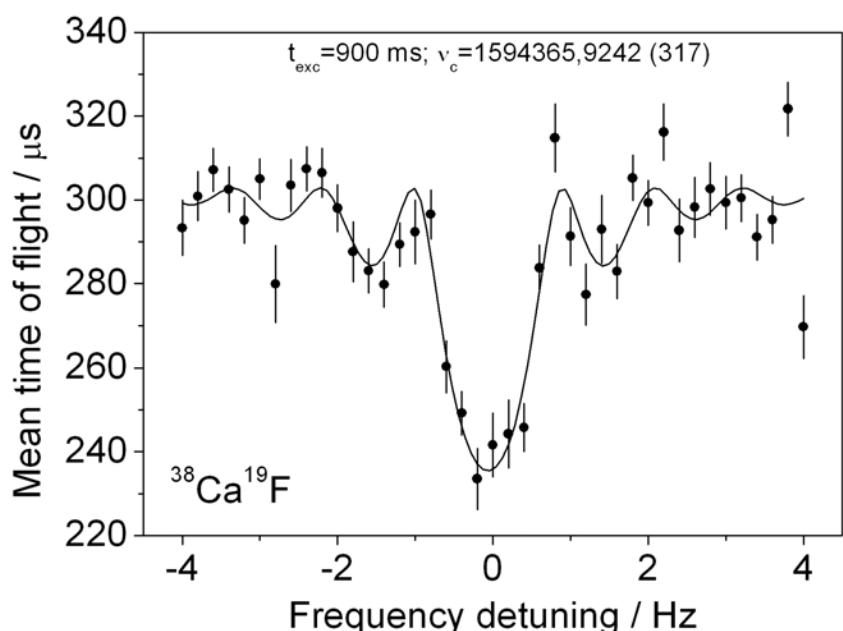
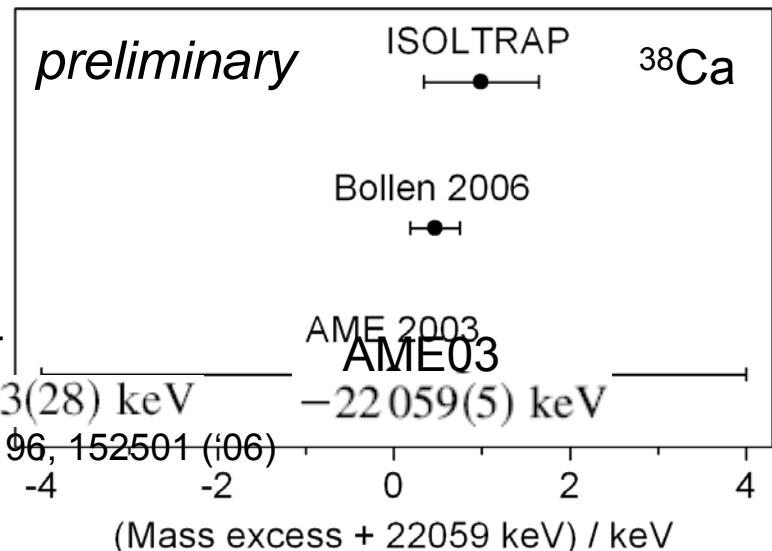
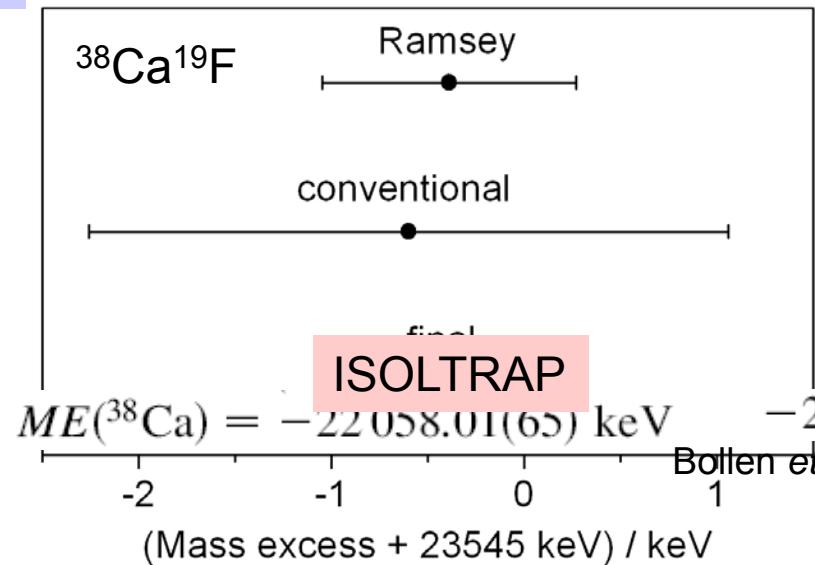
$$ft = \frac{K}{G_V^2 |M_F|^2} = \text{const}, \quad (1)$$

where $K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2 / (m_e c^2)^5 = (8120.278 \pm 0.004) \times 10^{-10} \text{ GeV}^{-4} \text{ s}$; G_V is the vector coupling constant for semileptonic weak interactions; and M_F is the Fermi matrix element. The CVC hypothesis asserts that the vector coupling

The conserved-vector-current (CVC) hypothesis states that the vector-current part of the weak interaction is independent of the strong interaction, i.e. G_V is a true constant and not renormalized in the nuclear medium and thus $ft = \text{const.}$

$$V_{ud}^2 = \frac{K}{2G_F^2 (1 + \Delta_R^V) \overline{Ft}}$$

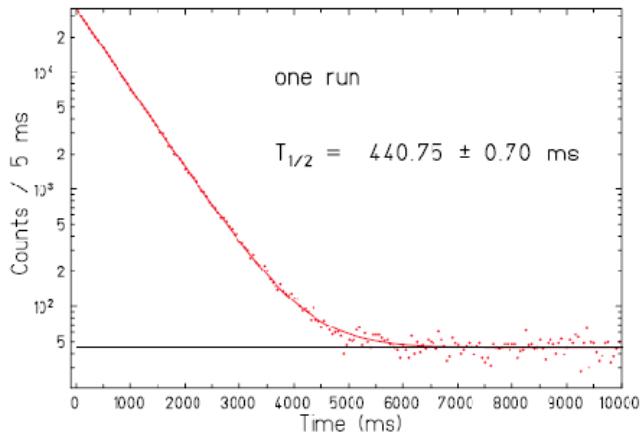
Mass of ^{38}Ca



Mass and half-life of ^{38}Ca

Experiment IS437: Precision measurement of the half-life and the β -decay Q value of the superallowed $0^+ \rightarrow 0^+$ β decay of ^{38}Ca

- fluorination of ^{38}Ca at target and removal of daughter $^{38\text{m}}\text{K}$ with REXTRAP
- half-life measurement with tape-station system mounted behind REXTRAP
- mass measurement (in parallel) with ISOLTRAP



simulation for ^{38}Ca

81Zn

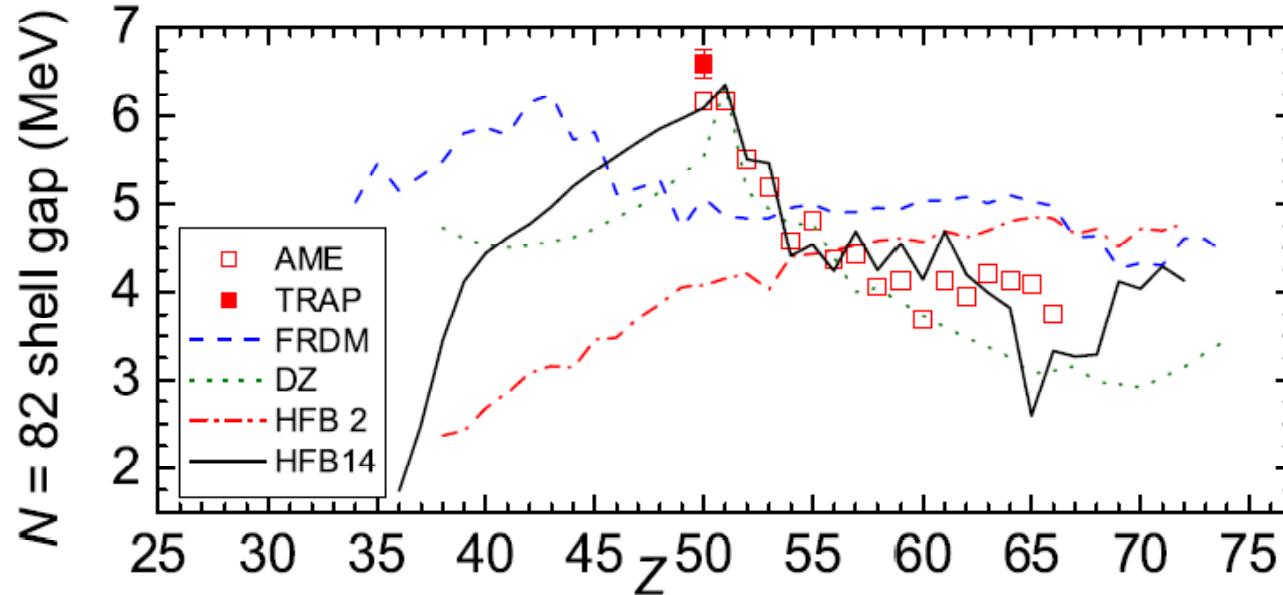
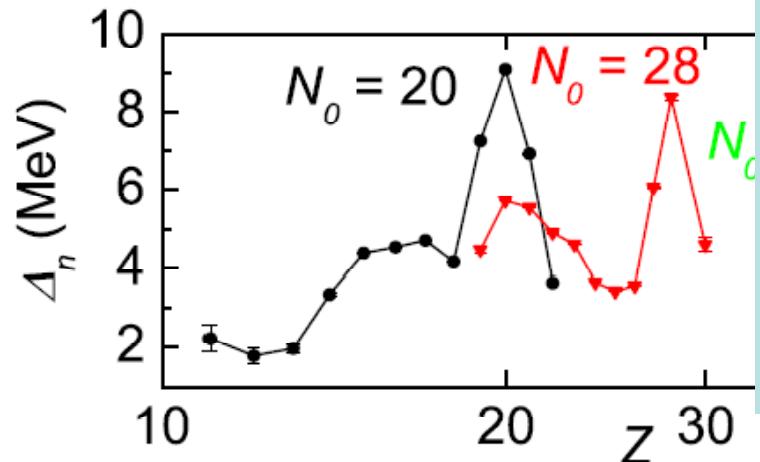
Jyfyltrap: measured 79Zn - agreement

to constrain the path of the r-process neutron separation energies and neutron capture Q-values are needed, requiring mass measurements beyond the waiting point nucleus of interest

$^{132,134}\text{Sn}$

neutron shell gap

$$\Delta_n(N_0, Z) = S_{2n}(N_0, Z)$$



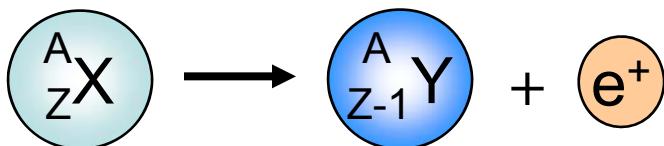
The $N=82$ shell gap has considerable impact on fission recycling during the r process. More generally, the new finding has important consequences for microscopic mean-field theories which systematically deviate from the measured binding energies of closed-shell nuclides

Restoration of $N=82$ gap

Mn and Fe masses

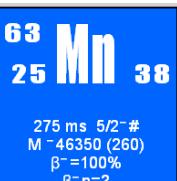
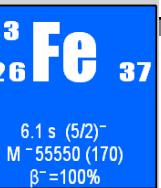
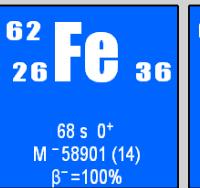
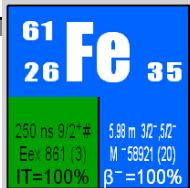
in-trap decay

produced
at ISOLDE

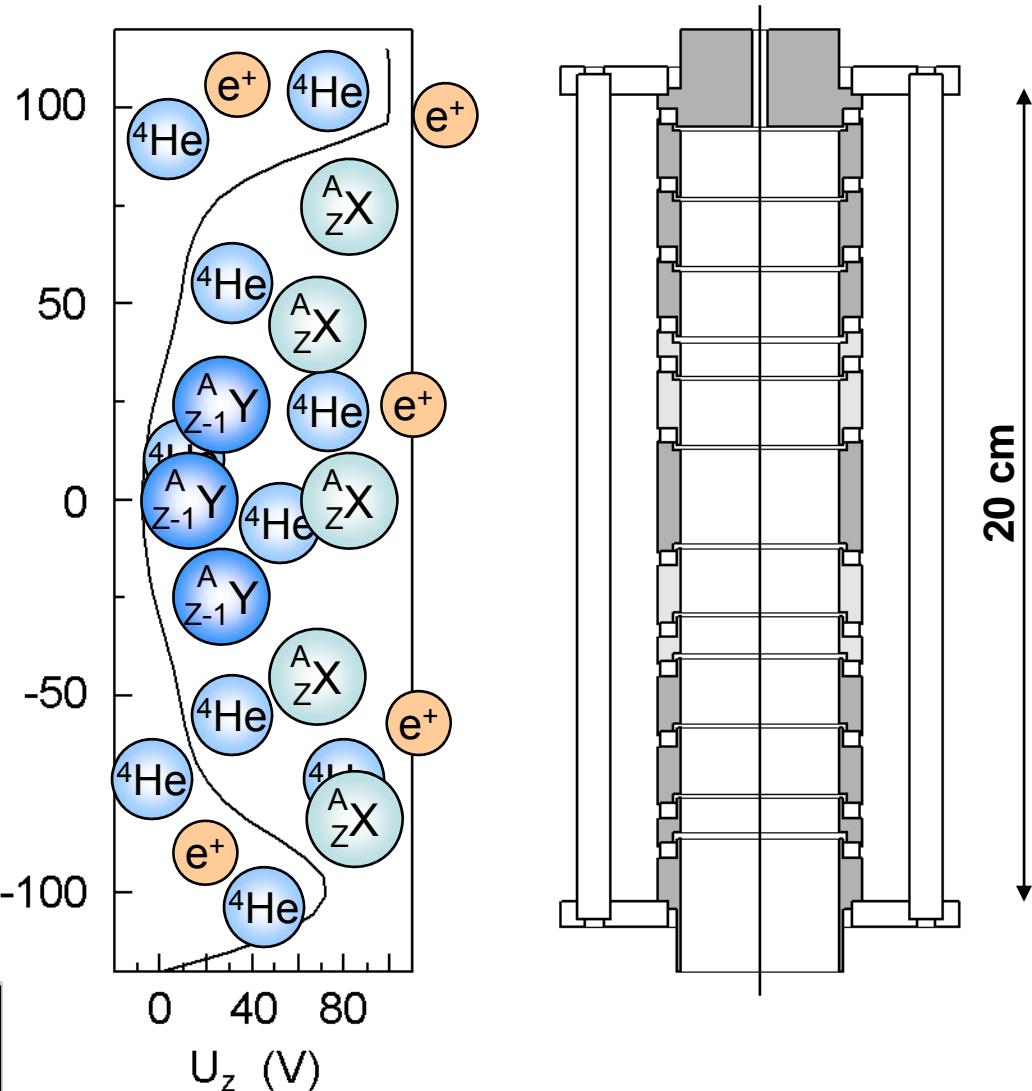


not produced
at ISOLDE

- Make more radioactive species available
- Nearly simultaneous ω_c measurement of mother and daughter nuclei



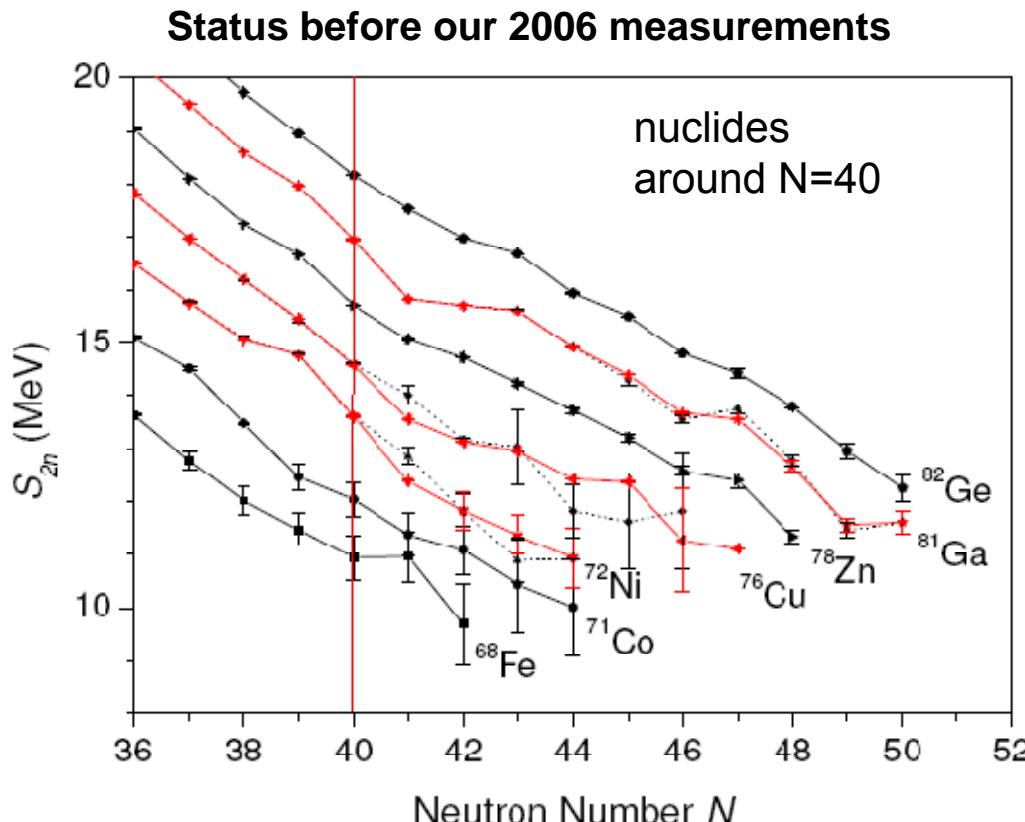
Decay in the buffer-gas-filled preparation trap



Mn and Fe masses

Motivation: suspicion of shell effects at N=40; Fe unavailable at ISOLDE directly

Method: in-trap decay (one of tasks of EURONS TRAPSPEC JRA)

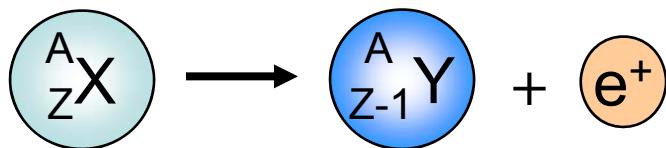


Mn and Fe masses – in-trap decay

In-trap decay:

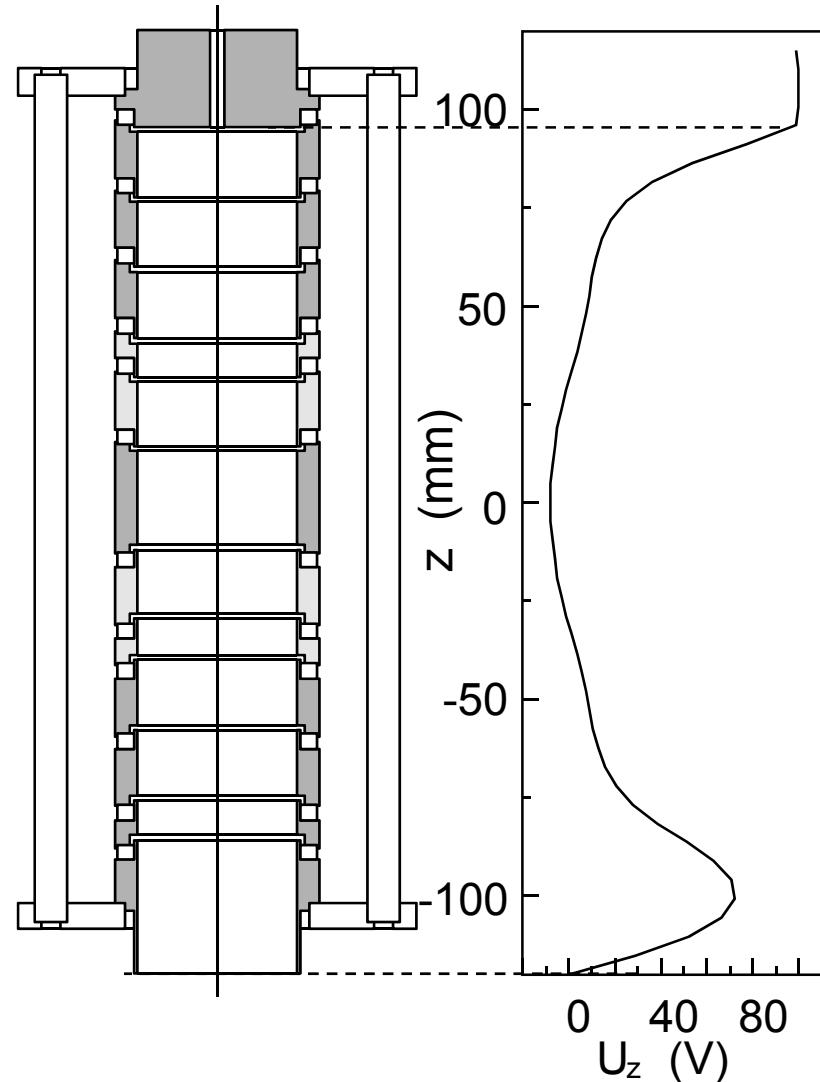
more radioactive species available

nearly simultaneous ω_c measurement of mother and daughter nuclei

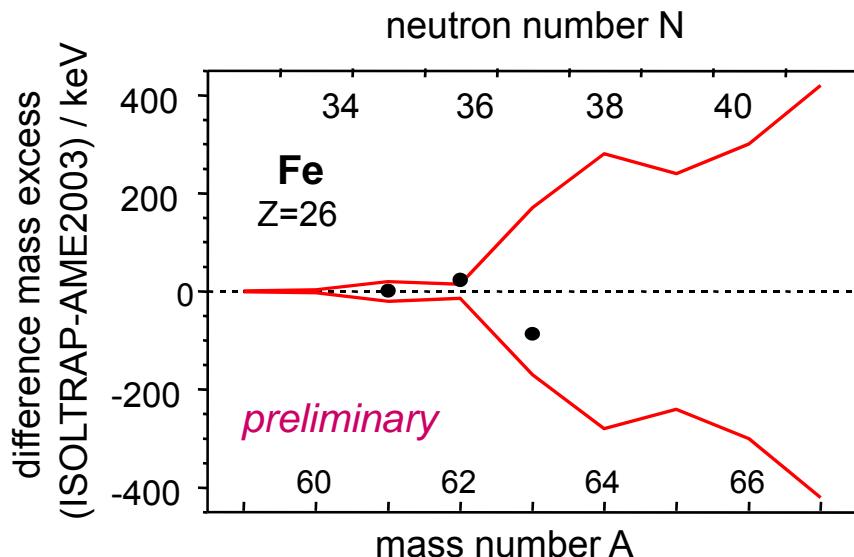
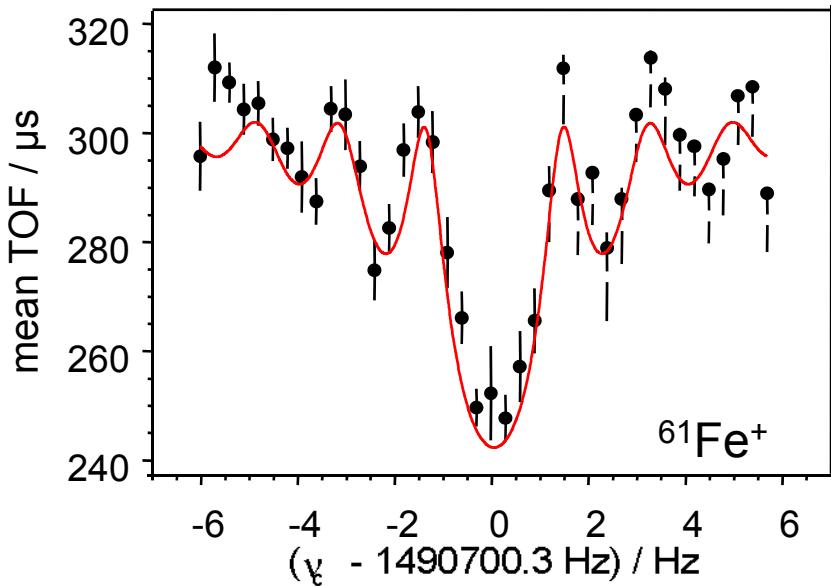
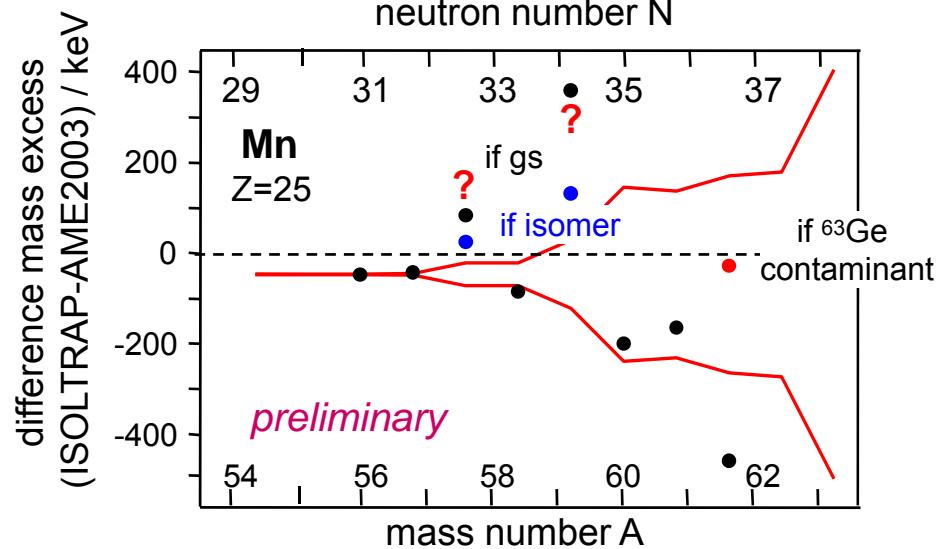


produced not produced
at ISOLDE at ISOLDE

Decay in the buffer-gas-filled
preparation trap



Mn and Fe results



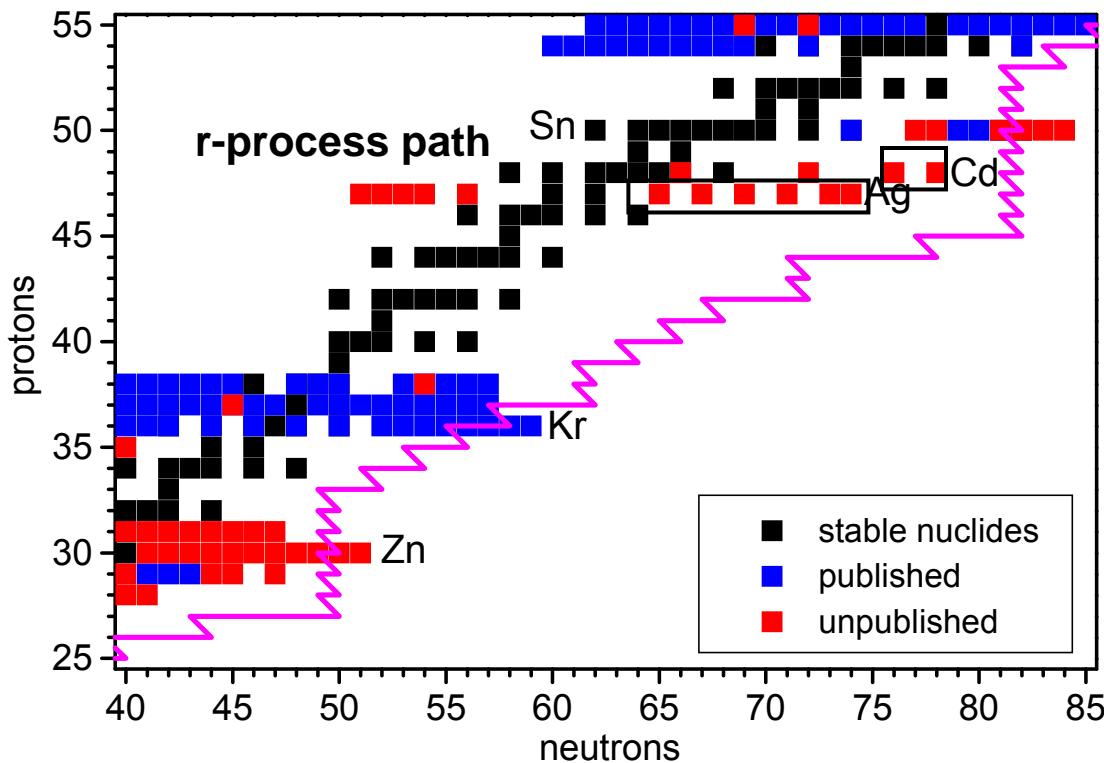
further measurements required ...
planned for 2007

$^{112,114,116,118,120,121}\text{Ag}$ and $^{124,126}\text{Cd}$

Motivation: astrophysics; Ag masses with $A > 117$ known with uncertainty $> 10^{-7}$

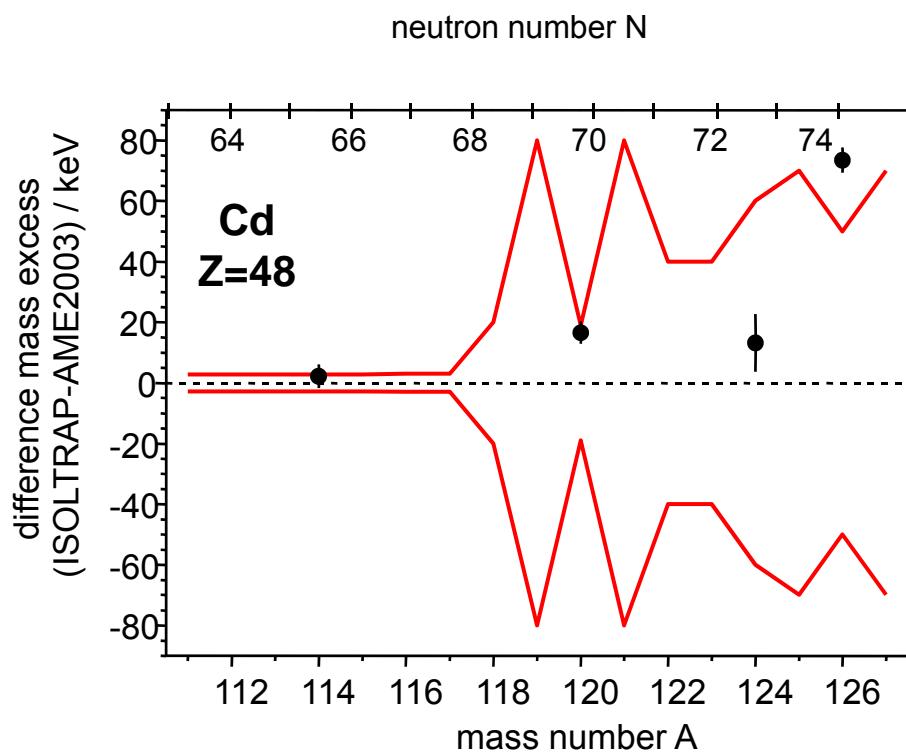
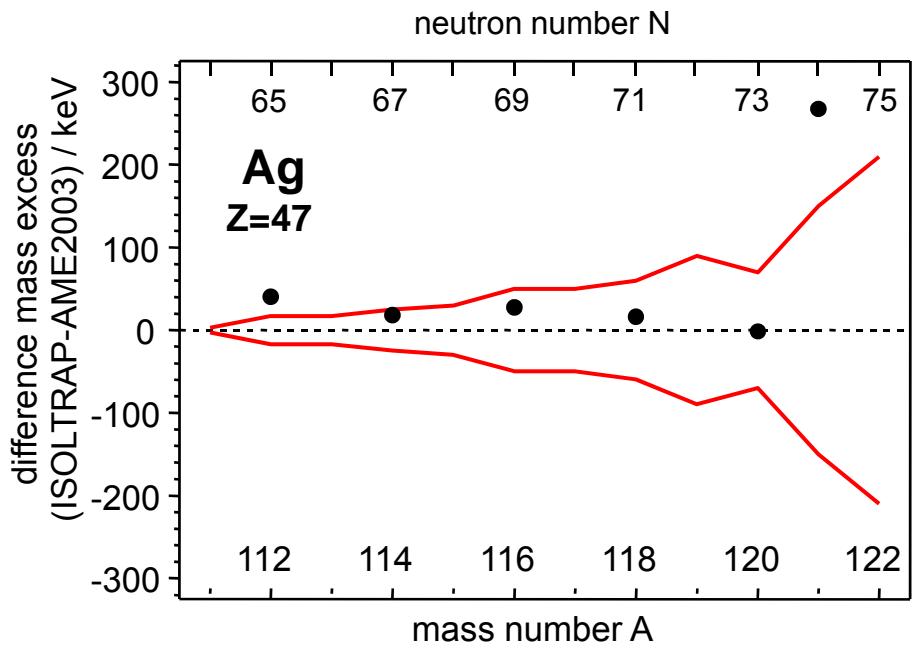
Ultimate goal:

- neutron binding energy of $^{131}\text{Cd} \Rightarrow$ determine waiting-point behaviour of ^{130}Cd
- improve predictions for the waiting-point nucleus ^{129}Ag
- improve theoretical mass-predictions in this region



Run stopped by power cuts

Ag and Cd - results

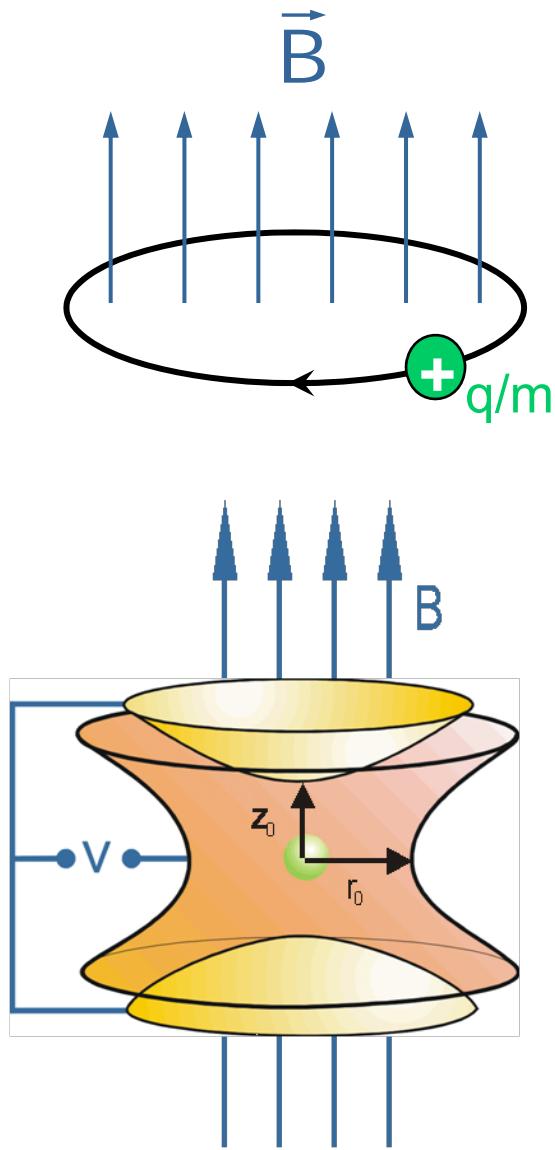


Run stopped by power cuts

new on-line measurements scheduled in May 2007

Measured 2003-2006

Principle of a penning trap



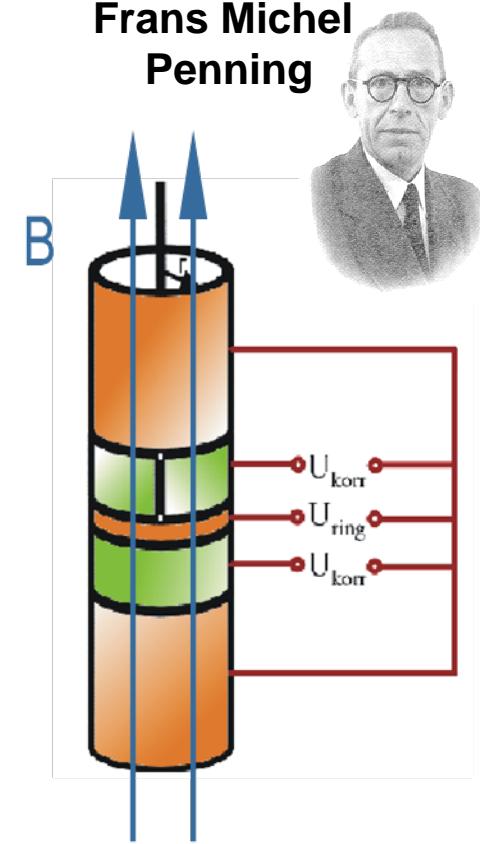
$$\text{Cyclotron frequency: } \nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

Superposition

- strong homogeneous magnetic field
- weak electrostatic quadrupole field

PENNING trap

Frans Michel Penning



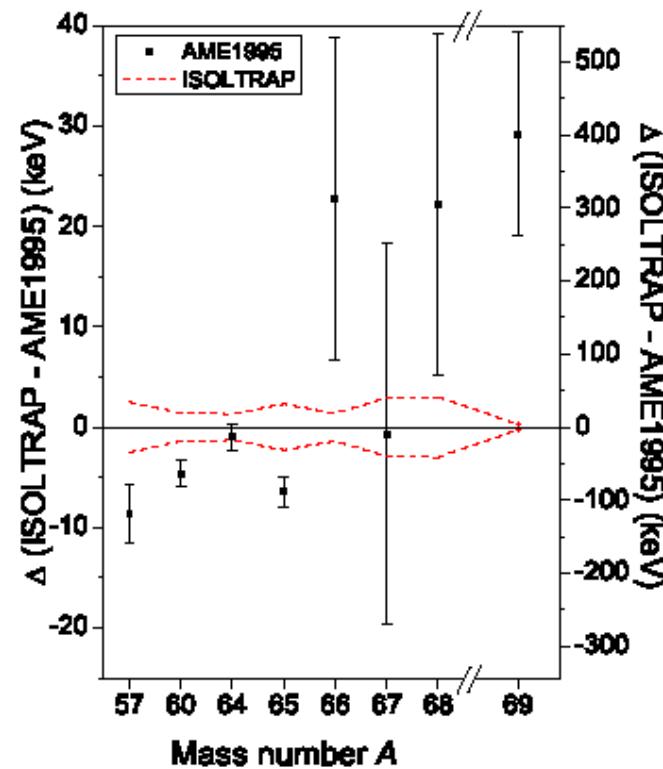
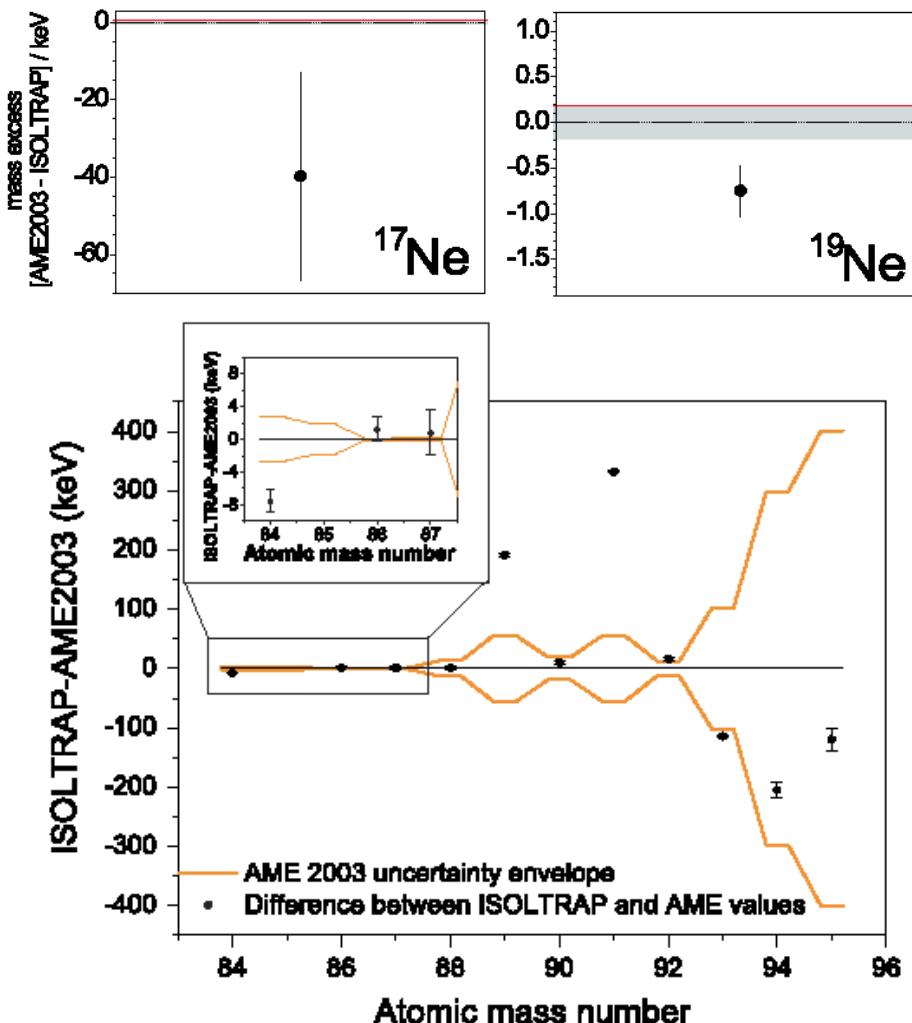
Other results published since last meeting

57,60,64-69Ni, 65-74,76Cu, 63-65,68-78Ga: C. Guénaut, *et al.*, Phys. Rev. C, accepted

72-78,80,82,86Kr: D. Rodríguez, Nucl. Phys. A 769, 1-15 (2006)

84,86-95Kr: P. Delahaye *et al.*, Phys. Rev. C 74, 034331 (2006)

17,19Ne: A. Herlert *et al.*, AIP Conf. Proc. 831, 152-156 (2006)



Ion motion in the Penning trap

Three harmonic eigenmotions

1. Axial oscillation

$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

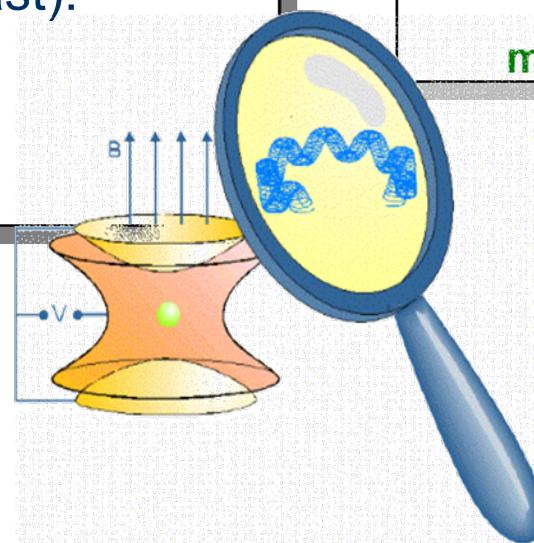
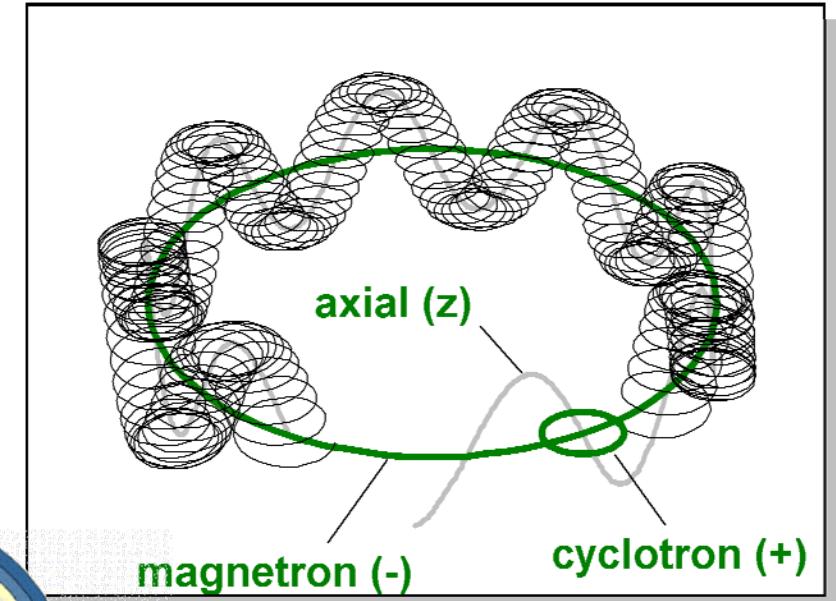
2. Magnetron motion (slow):

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

3. Cyclotron motion (fast):

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

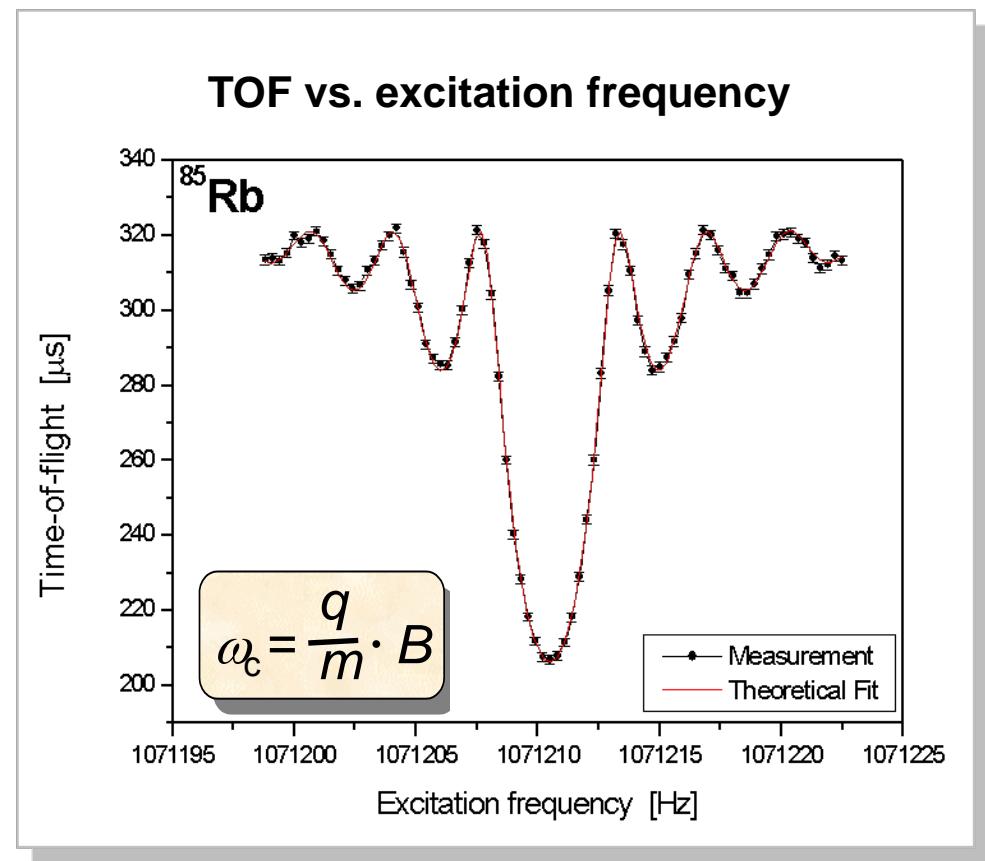
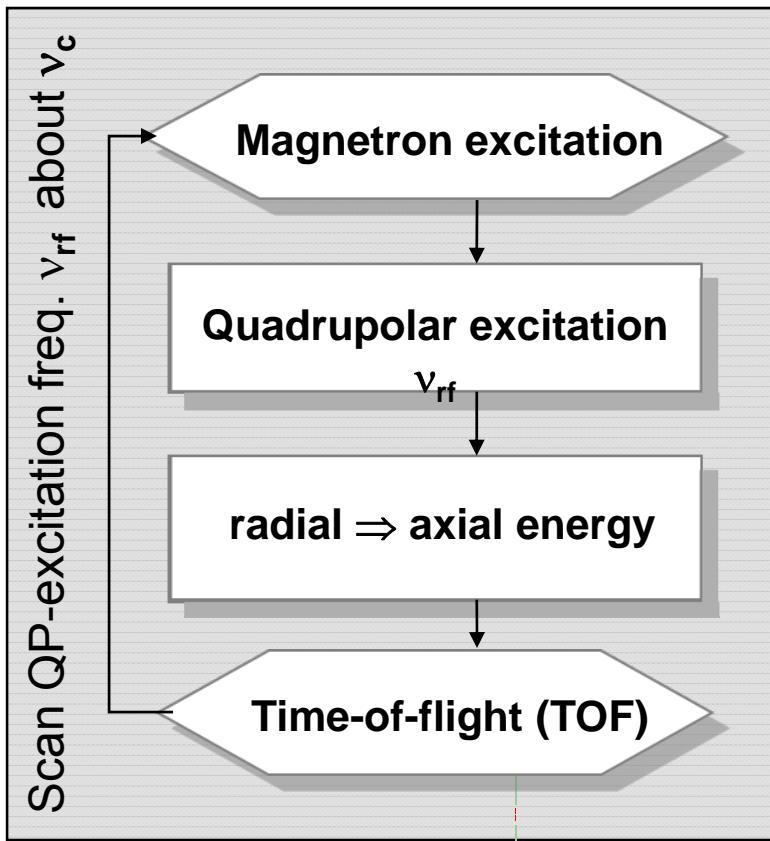
$$\omega_+ + \omega_- = \omega_c$$



$$A=100, B=6T$$

- $v_+ \approx 1 \text{ MHz}$
- $v_- \approx 1 \text{ kHz}$
- $v_z \approx 44 \text{ kHz}$

Mass measurement procedure



Determine atom mass from frequency ratio with a well known reference

Remark: The time-of-flight cyclotron resonance detection has the

Advantage: very high resolving power (up to 10^8)

Disadvantage: destructive! \rightarrow FT-ICR detection method