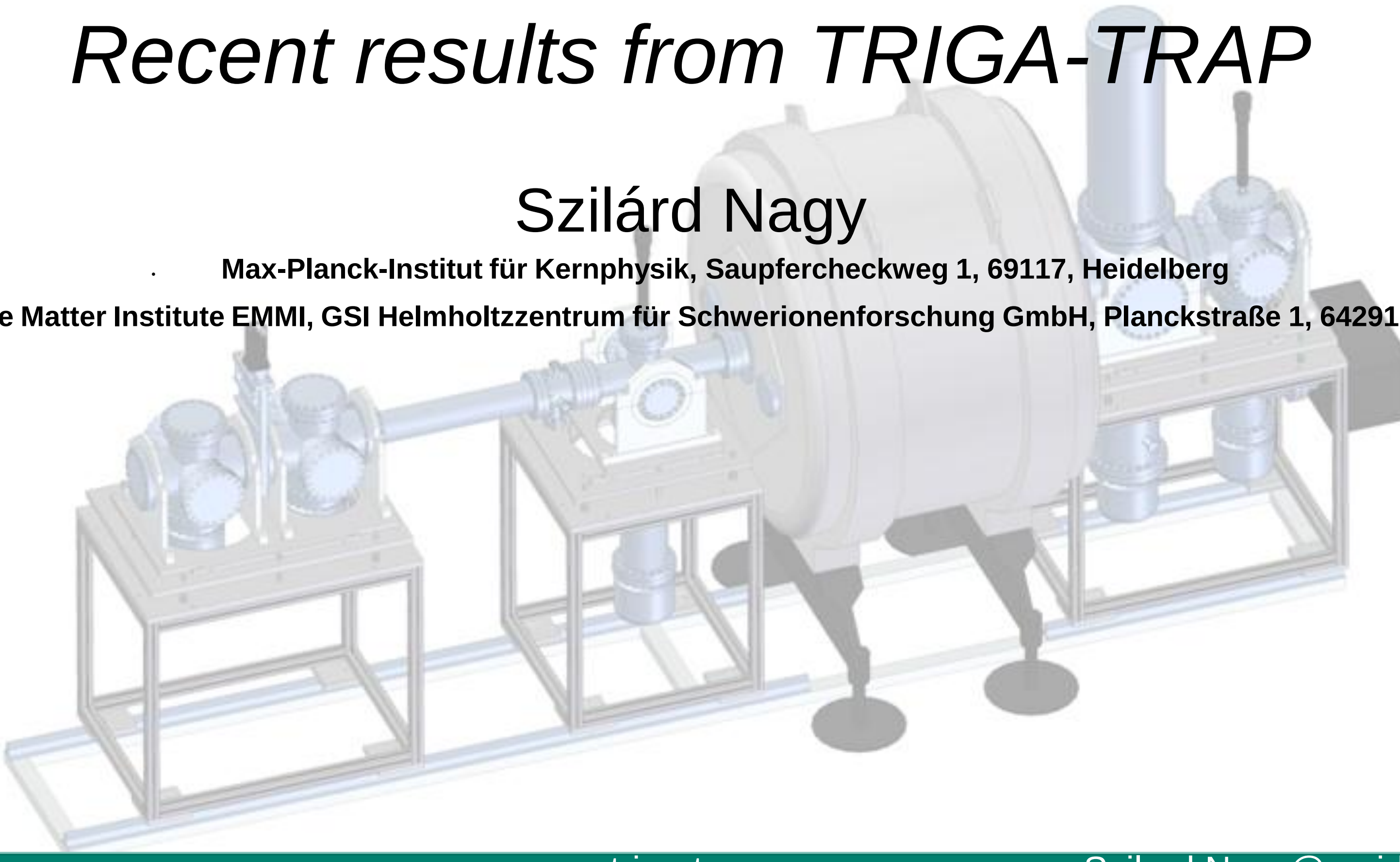
Max Planck Institute for Nuclear Physics

ExtreMe Matter Institute EMMI

EMMI Physics Days 2012

GSI, Darmstadt, Germany
November 13 - 14, 2012

Recent results from TRIGA-TRAP



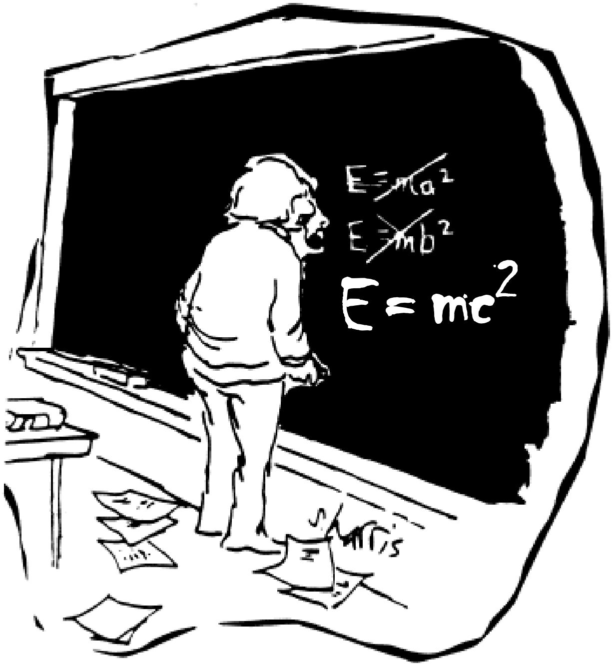
Szilárd Nagy

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117, Heidelberg

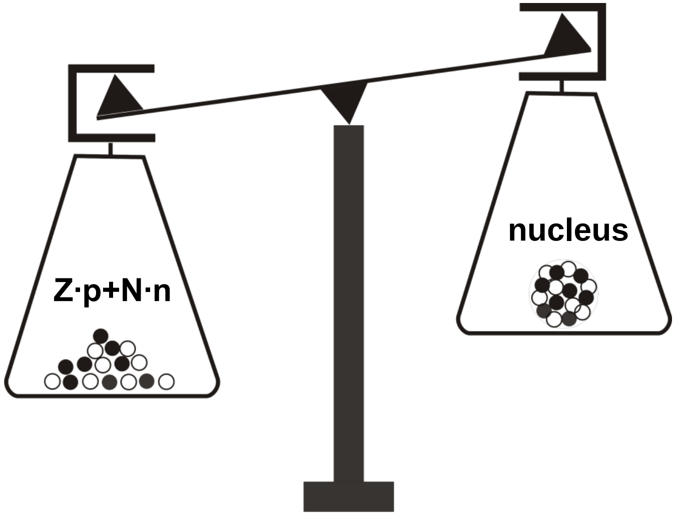
ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt

The mass defect

Macrocosm: mass surplus ☺



Microcosm: mass deficit



$$B(N,Z) = [Nm_n + Zm_p - m(N,Z)]c^2$$

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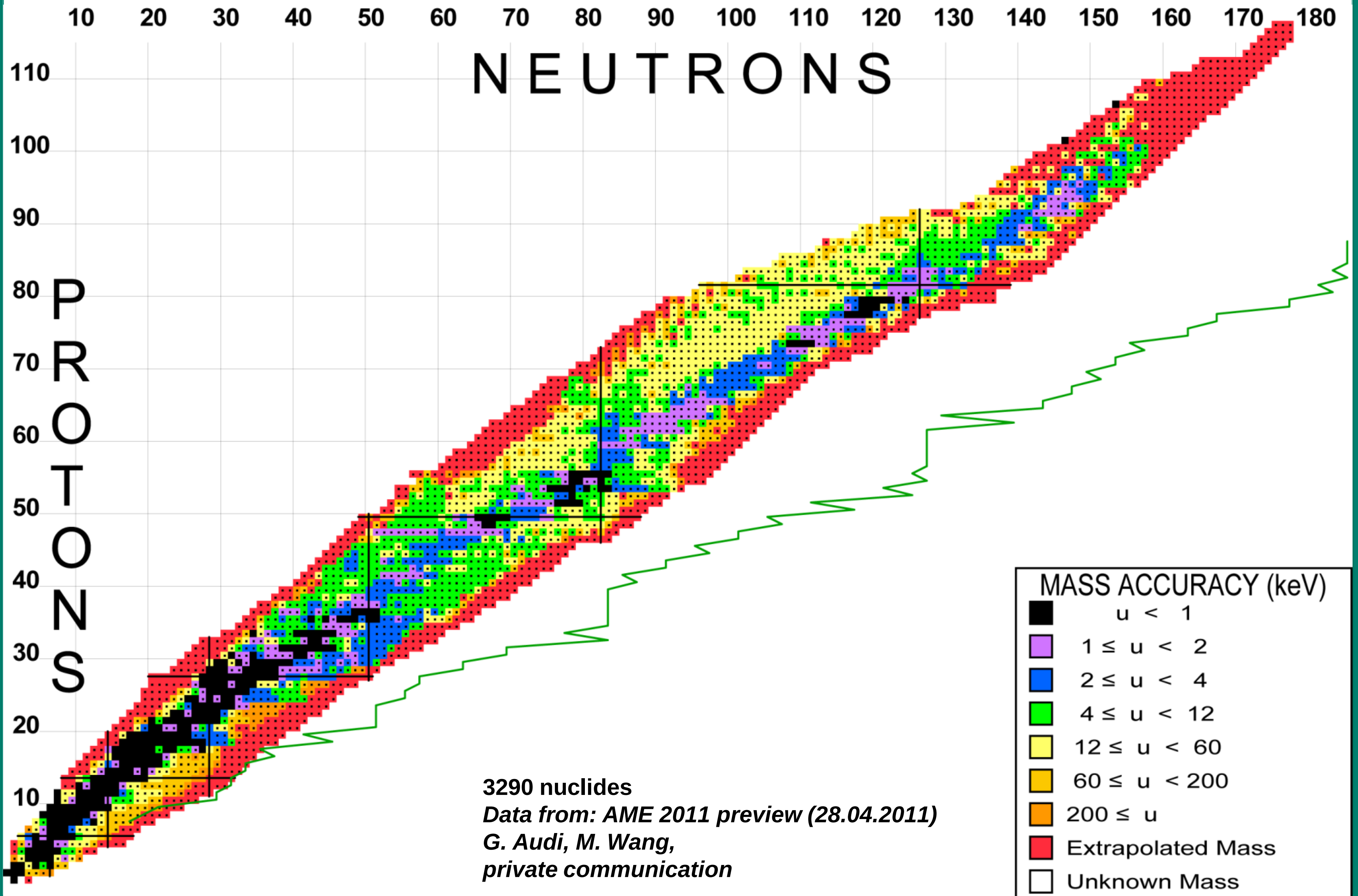
Why do we need high-precision atomic masses?

Field	Examples	δm/m
Nuclear structure physics - separation of isobars	shell closures, shell quenching, OES, regions of deformation, drip lines, halos, S_n, S_p, S_{2n}, S_{2p}, $\delta V_{pn,}$ island of stability	10^{-6} to 10^{-7}
Astrophysics, nuclear models and mass formula - separation of isomers	rp-process and r-process path, waiting-point nuclei, proton threshold energies, astrophysical reaction rates, neutron star, x-ray burst	
Weak interaction studies	CVC hypothesis, CKM matrix unitarity, *Ft* of superallowed ß-emitters	10^{-8}
Metrology, fundamental constants	α $(h/m_{Cs},\ m_{Cs}/m_{p},\ m_p/m_e)$ m_{Si}	10^{-9} to 10^{-10}
Neutrino physics	$m_{mother} - m_{daughter}$: $0\nu\beta\beta$, $0\nu\varepsilon\varepsilon$ β –decay, EC	$\leq 10^{-8}$ $\leq 10^{-10}$
CPT tests QED in highly-charged ions - separation of atomic states	m_p and $m_{\bar{p}}$ m_{e-} and m_{e+} m_{ion}, electron binding energy	10^{-11} 10^{-12}

Mass uncertainty in the latest Atomic Mass Evaluation



3290 nuclides
Data from: AME 2011 preview (28.04.2011)
G. Audi, M. Wang,
private communication

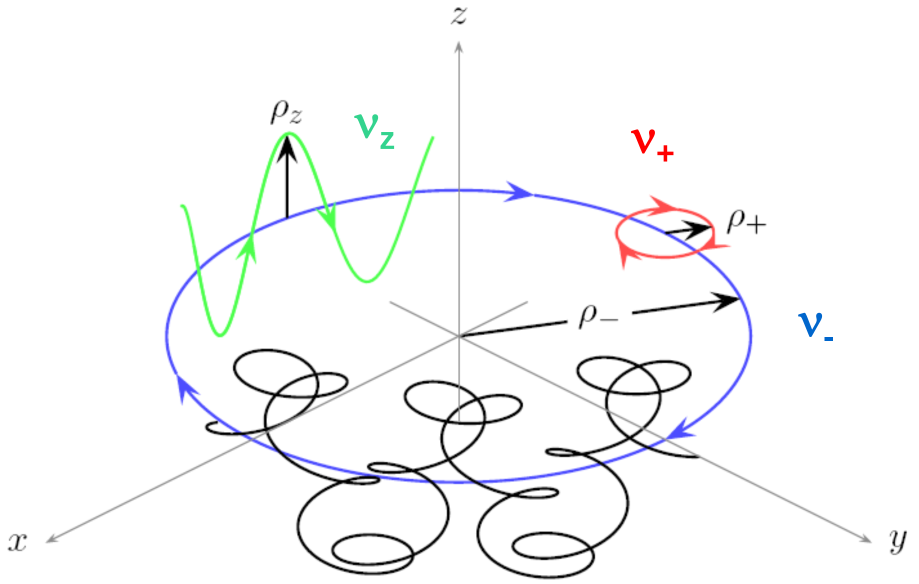
Penning Trap

the most accurate mass spectrometer

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

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

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



typical cyclotron frequency: q = 1+, m = 100 u, B = 7 T
$\Rightarrow \nu_c$ = 1 MHz

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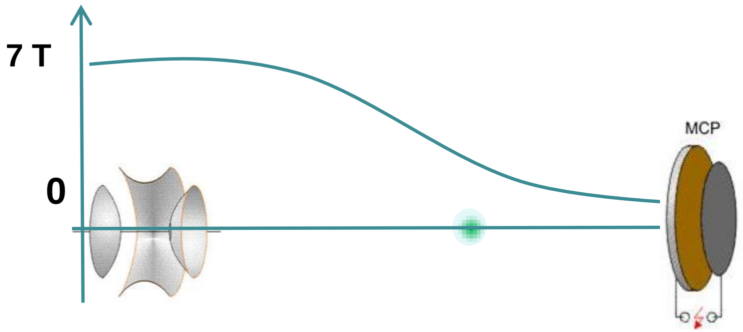
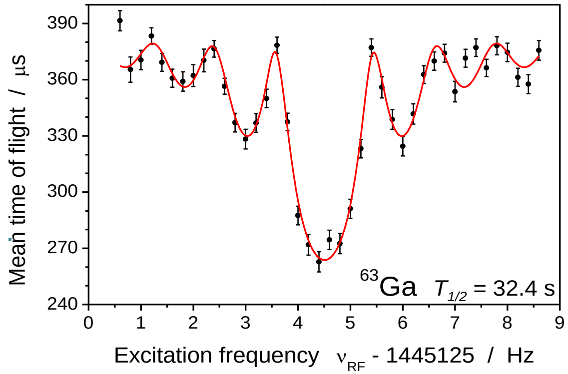
Penning-trap mass measurement in a nutshell

Time-of-flight ion-cyclotron resonance technique

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

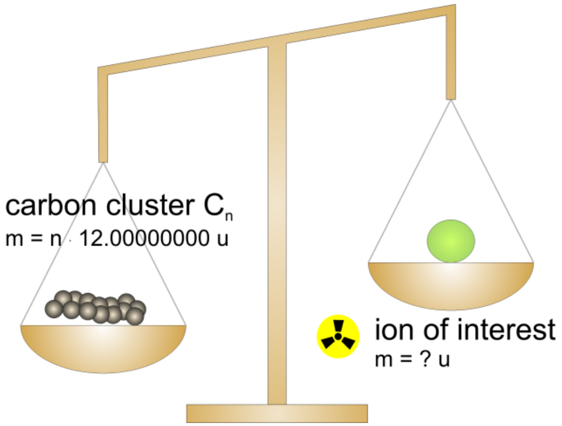
$$\nu_c = \frac{1}{2\pi}\frac{q\,B}{m}$$





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

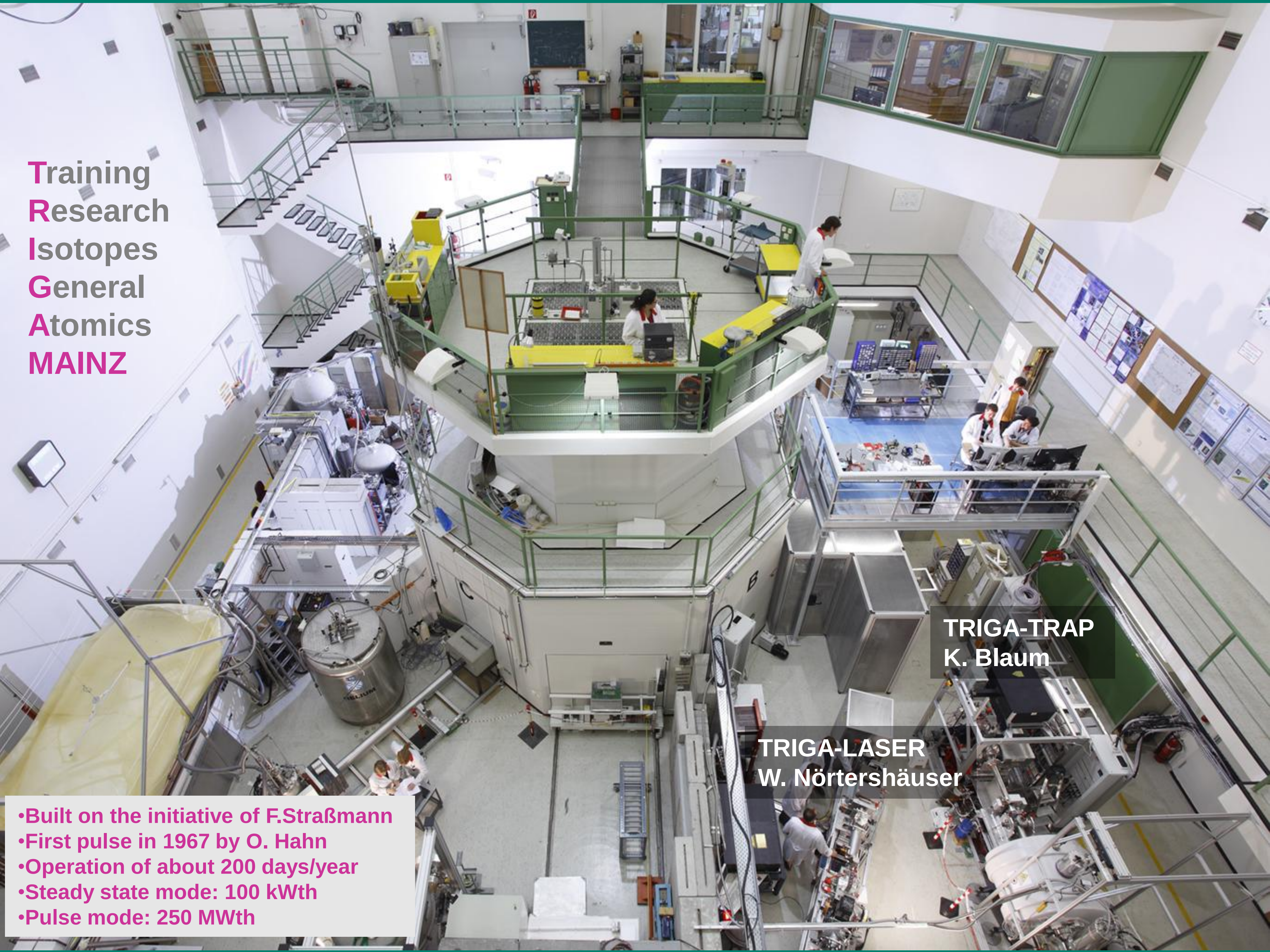
calibration with C-cluster ions @TRIGA-TRAP



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}

Training
Research
Isotopes
General
Atomics
MAINZ



- Built on the initiative of F.Straßmann
- First pulse in 1967 by O. Hahn
- Operation of about 200 days/year
- Steady state mode: 100 kWth
- Pulse mode: 250 MWth

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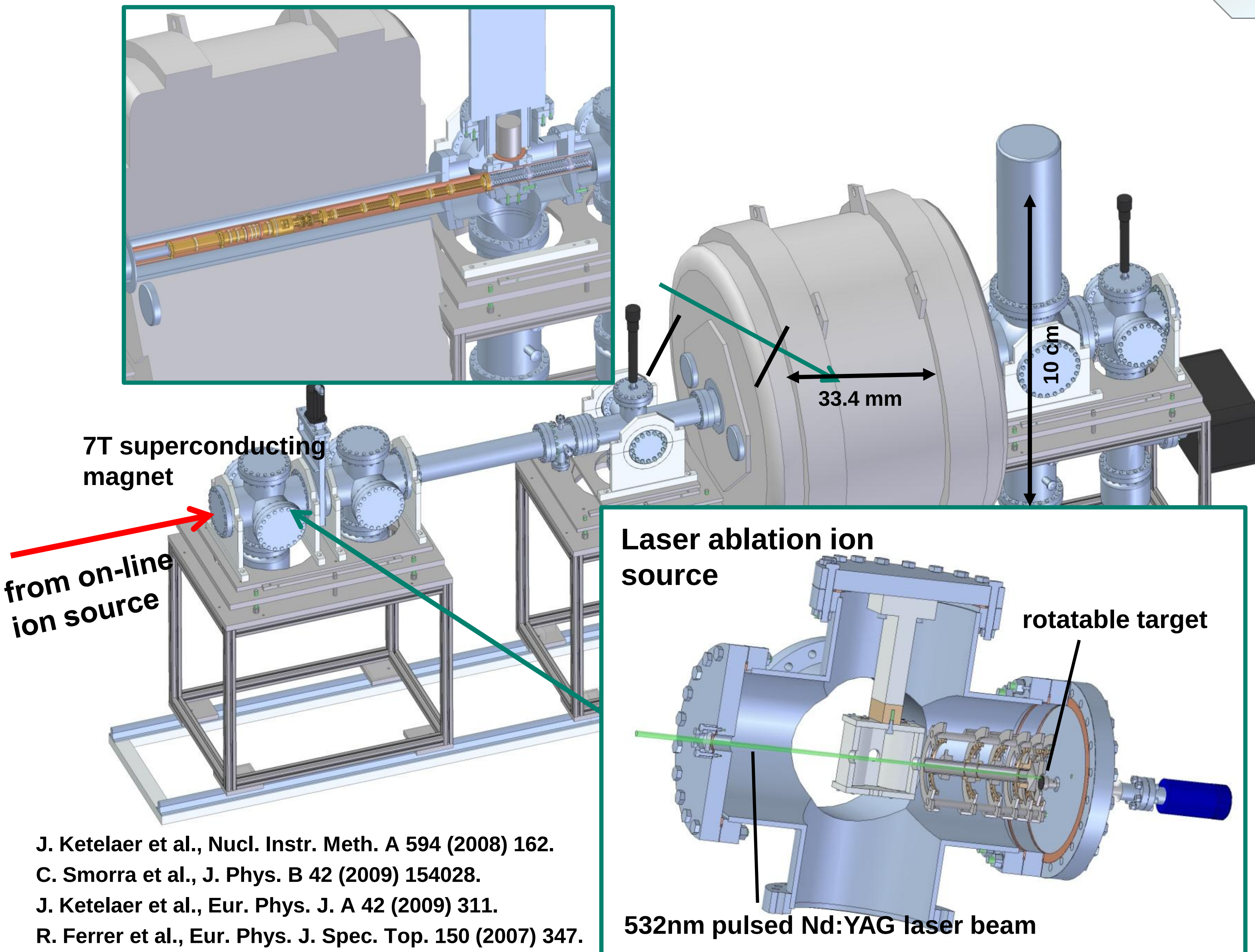
TRIGA-TRAP technical details



J. Ketelaer et al., Nucl. Instr. Meth. A 594 (2008) 162.
C. Smorra et al., J. Phys. B 42 (2009) 154028.
J. Ketelaer et al., Eur. Phys. J. A 42 (2009) 311.
R. Ferrer et al., Eur. Phys. J. Spec. Top. 150 (2007) 347.
G. Eitel et al., Nucl. Instrum. Meth. A 606 (2009) 475.

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

are extremely rare processes and have not been observed yet

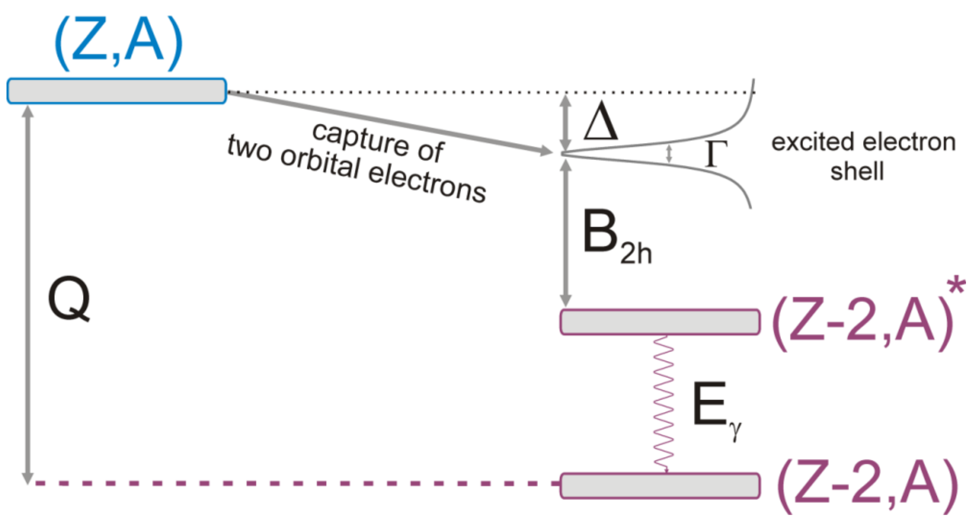
$0\nu\beta\beta$ ($T_{1/2}$>10^{25}y)

$0\nu\varepsilon\varepsilon$ ($T_{1/2}$>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



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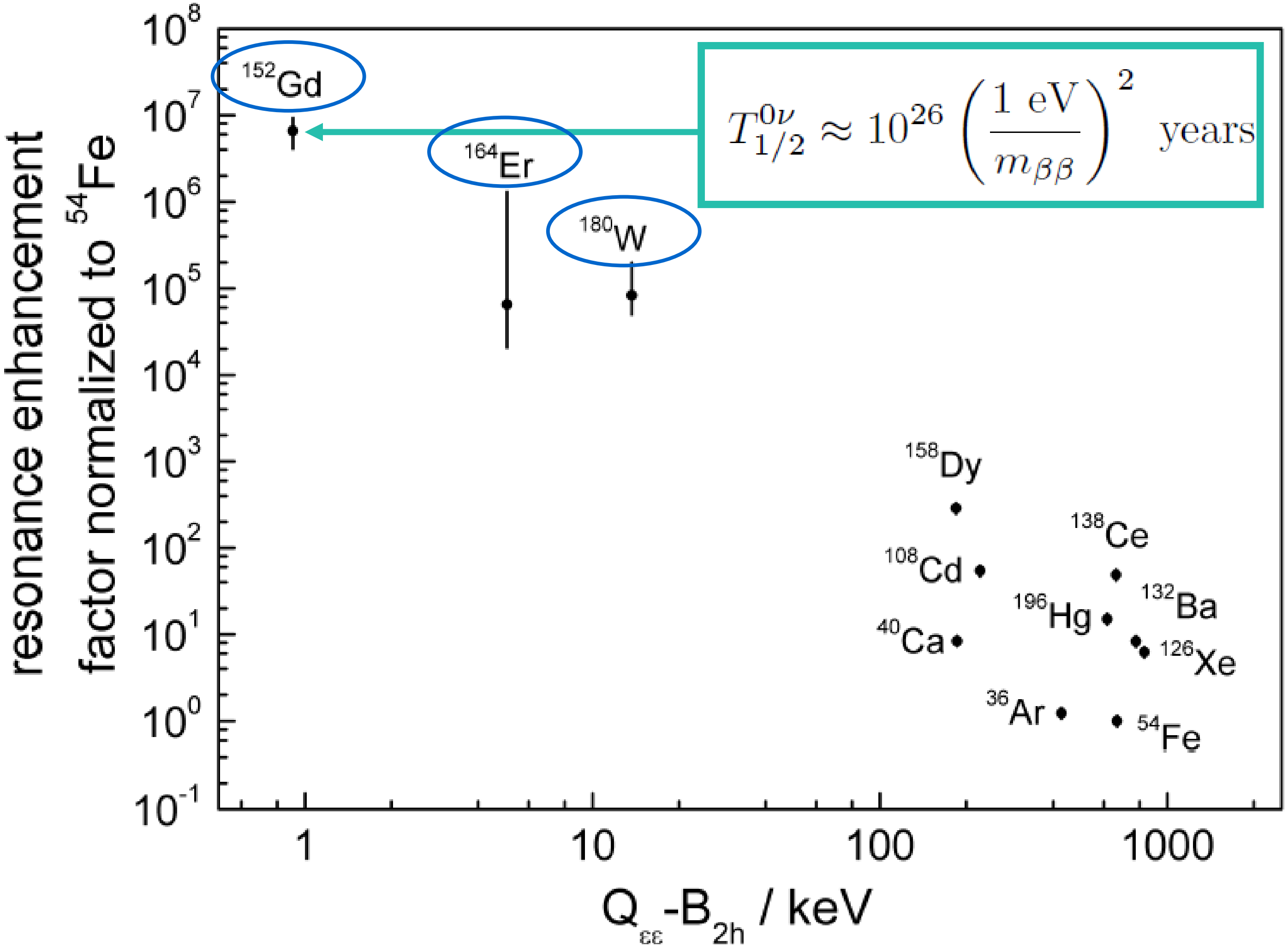
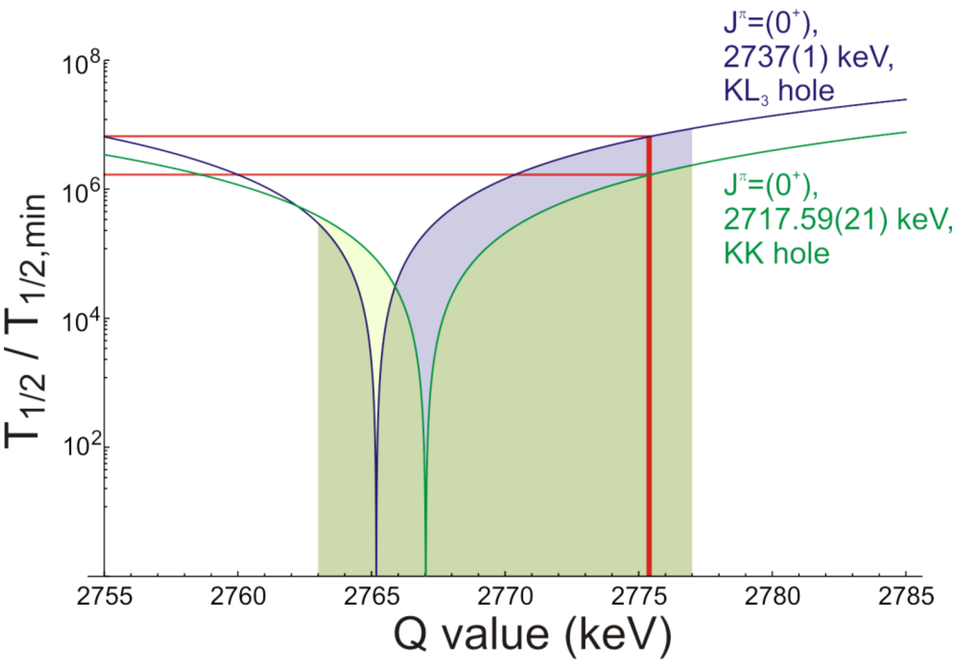
Resonance enhancement factors

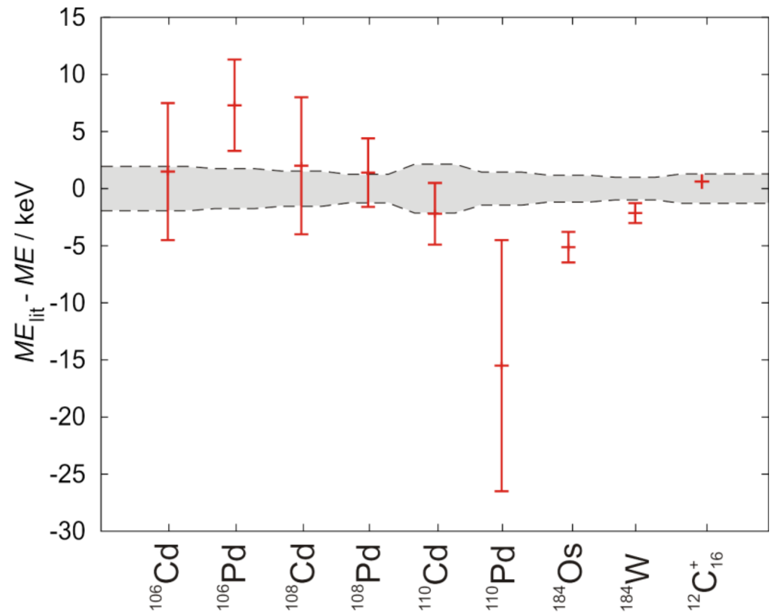
S. Eliseev, Phys. Rev. Lett. 106, 052504 (2011)



Recent TRIGA-TRAP results

- inaccurate or imprecise Q-value is a limiting factor





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

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

- **Factor 3 to 10 smaller uncertainty**
- **Direct Q-value measurements**

C.Smorra. et al., Phys. Rev. C 85, 027601 (2012)
C.Smorra. et al., Phys. Rev. C 86, 044604 (2012)

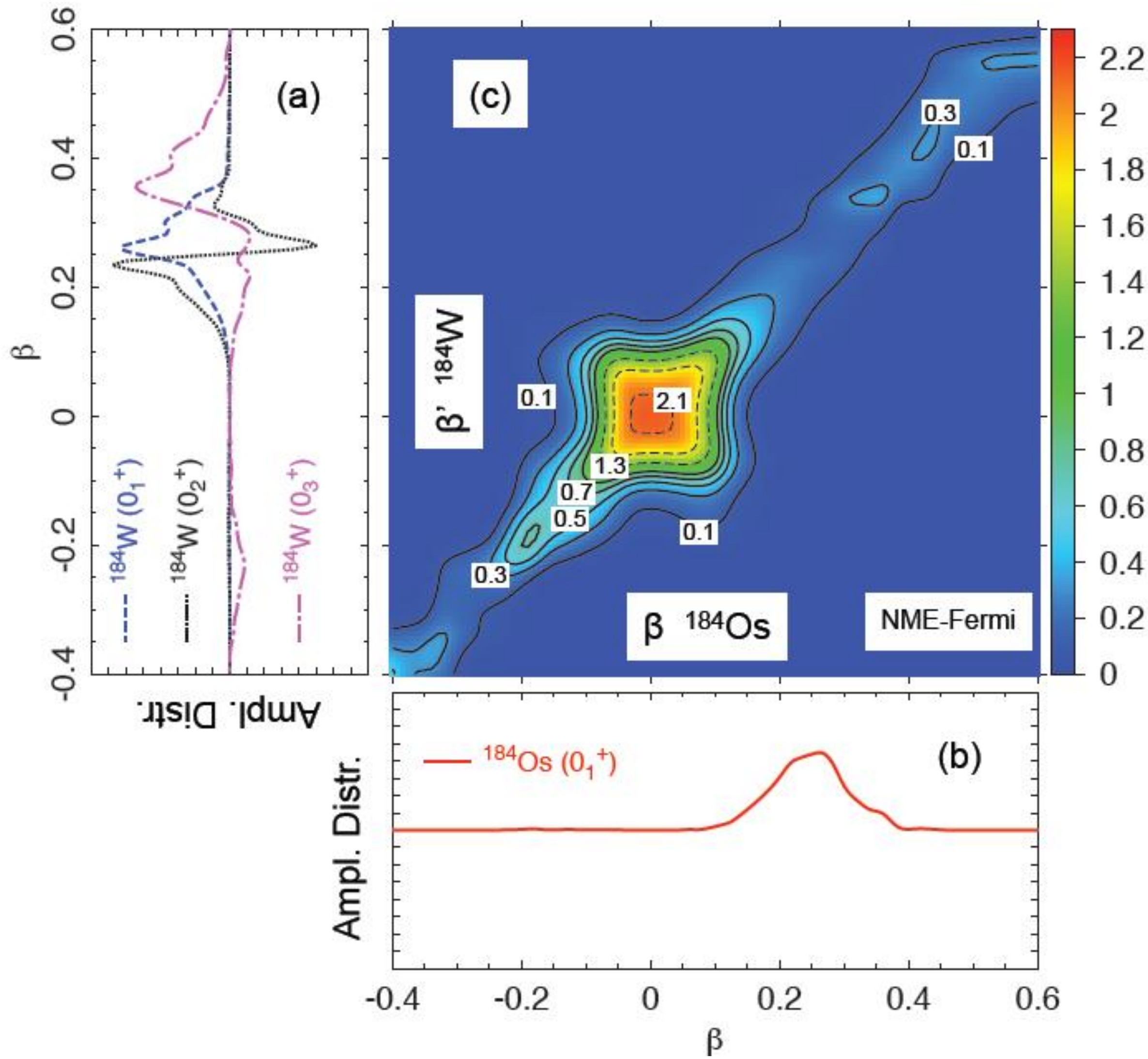
TRIGA-TRAP Q-value results

E_γ / keV	J_f^π	Q_{lit} / keV	Q_{meas} / keV	Δ / keV
$^{106}Cd \xrightarrow{2\varepsilon} {}^{106}Pd$ 2748.2 (0.4)	$(2,3)^-$	2770 (7) SHIPTRAP:	2775.01 (0.56) 2775.39 (0.10)	-0.73(0.69) -0.33(0.41)
$^{108}Cd \xrightarrow{2\varepsilon} {}^{108}Pd$ 0.0 (0) 433.938 (0.005)	0^+ 2^+	272 (6)	272.04 (0.55)	> 200
$^{184}Os \xrightarrow{2\varepsilon} {}^{184}W$ 1322 .152 (0.022)	0^+	1451.2(1.6)	1453.68(0.58)	11.3 (1.6) 8.83(0.58)
$^{110}Pd \xrightarrow{2\beta^-} {}^{110}Cd$		2004 (11) ISOLTRAP:	2017.8 (1.2) 2017.85 (0.64)	

C.Smorra. et al., Phys. Rev. C 85, 027601 (2012)
C.Smorra. et al., Phys. Rev. C 86, 044604 (2012)

M. Goncharov et al., Phys. Rev. C 84, 028501 (2011)
D. Fink et al., Phys. Rev. Lett. 108, 062502 (2012)

NME calculations using EDF



T.R. Rodríguez, G. Pinedo, K. Langanke (2012)

The $0\nu\varepsilon\varepsilon$ half-life of ^{184}Os

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

TRIGA-TRAP Q value
***Q* = 1453.68(0.58) keV**
B_{2h} by V.M. Shabaev *et al.*
Dirac-Fock
Γ, E_γ literature values

EDF calculations
by T. Rodríguez *et al.*

$M(0_1^+) =$ **0.7975**

$M(0_2^+) =$ **0.5405**

$M(0_3^+) =$ **0.1875**

Calculated by
V.M. Shabaev *et al.*

$$T_{1/2}\left(^{184}\mathrm{Os}\ 0_1^+ \rightarrow\ ^{184}\mathrm{W}\ 0_1^+\right) = 1.9 \times 10^{33} \frac{1\ \mathrm{eV}^2}{\langle m_{\epsilon\epsilon}\rangle^2}\ \mathrm{y},$$

$$T_{1/2}\left(^{184}\mathrm{Os}\ 0_1^+ \rightarrow\ ^{184}\mathrm{W}\ 0_2^+\right) = 2.3 \times 10^{32} \frac{1\ \mathrm{eV}^2}{\langle m_{\epsilon\epsilon}\rangle^2}\ \mathrm{y},$$

$$T_{1/2}\left(^{184}\mathrm{Os}\ 0_1^+ \rightarrow\ ^{184}\mathrm{W}\ 0_3^+\right) = 1.6 \times 10^{30} \frac{1\ \mathrm{eV}^2}{\langle m_{\epsilon\epsilon}\rangle^2}\ \mathrm{y}.$$

C. Smorra, T R. Rodríguez et al.
Phys. Rev. C 86, 044604 (2012)

Search for 0νεε nuclides with Penning traps

$^{74}_{34}$Se 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 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?...

Measurements @:

CPT, JYFLTRAP, FSU, SHIPTRAP and TRIGA-TRAP

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?...

$$T_{1/2} = 10^{28} – 10^{29}\ y$$

Left to do:

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

Natural abundance: 0.014%

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Summary

- Penning-trap mass measurements contribute to neutrino physics via precise Q-values
- Q-value measurements of double-beta transitions of ^{106}Cd, ^{108}Cd, ^{110}Pd and ^{184}Os @ TRIGA-TRAP
  - Uncertainties of the Q-values and mass values were improved
  - Resonance condition in ^{106}Cd, ^{108}Cd and ^{184}Os were investigated
  - The $0\nu\varepsilon\varepsilon$ half-life of ^{184}Os was re-evaluated

Outlook

TRIGA-TRAP will focus on:

- measuring actinoides
- online measurement of short-lived radionuclides
- development of non-destructive detection

- TRIGA-SPEC is a development platform for MATS and LaSpec within NUSTAR at FAIR@GSI

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MPI-K Heidelberg

Prof. K. Blaum
S. Eliseev
C. Smorra
M. Eibach
T. Beyer

Inst. f. Physik, UNI-Mainz

Prof. K. Wendt
F. Schneider

GSI Darmstadt

M. Block
F. Herfurth

Inst. f. Kernchemie, UNI-Mainz

Prof. W. Nörtershäuser
C. Geppert
J. Krämer
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THANK YOU!