Spectroscopy of Fl decay chains and plans for Lundium

Daniel Cox

Jun. 23, 2021

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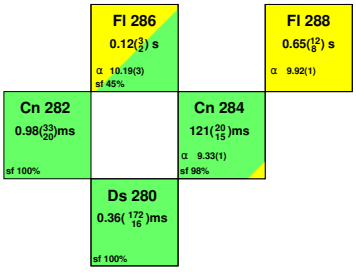
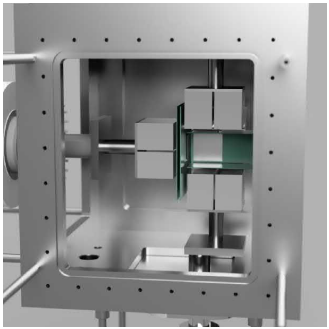
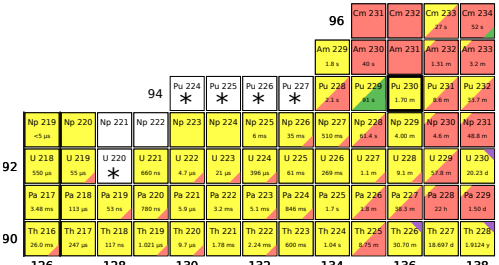
Outline

- Recent Results - Flerovium
- Upgrades - Lundium
- Future - Plutonium







Recent Results

PHYSICAL REVIEW LETTERS **126,** 032503 (2021)

Editors' Suggestion | Featured in Physics

Spectroscopy along Flerovium Decay Chains: Discovery of ^{280}Ds and an Excited State in ^{282}Cn

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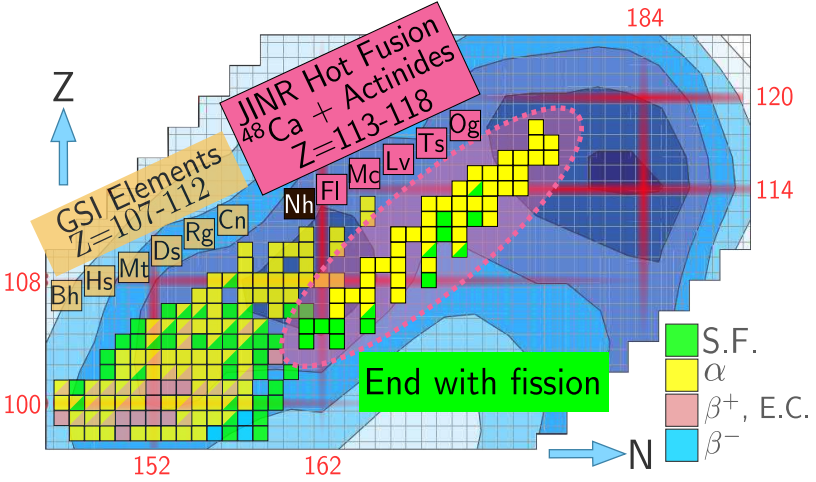
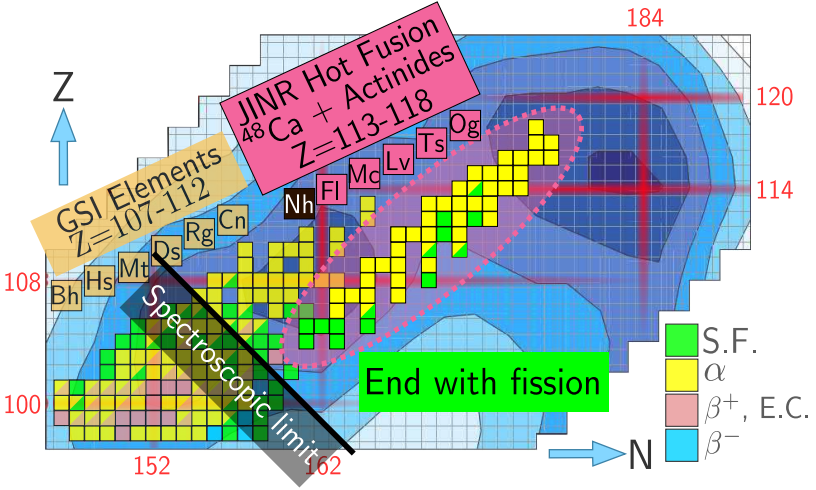
Recent Results

- What we wanted to do
- What we did
- Results - Highlights
- Summary & Outlook

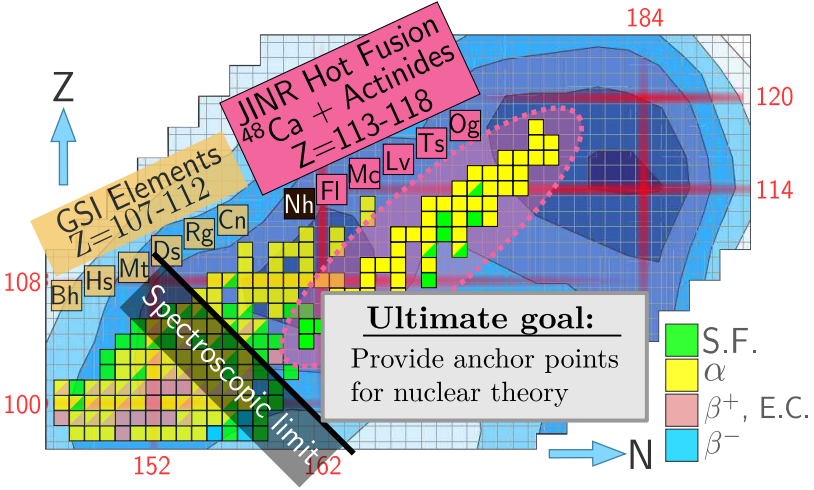
Superheavy Nuclei $Z \geq 104$ (Rf)



Superheavy Nuclei $Z \geq 104$ (Rf)



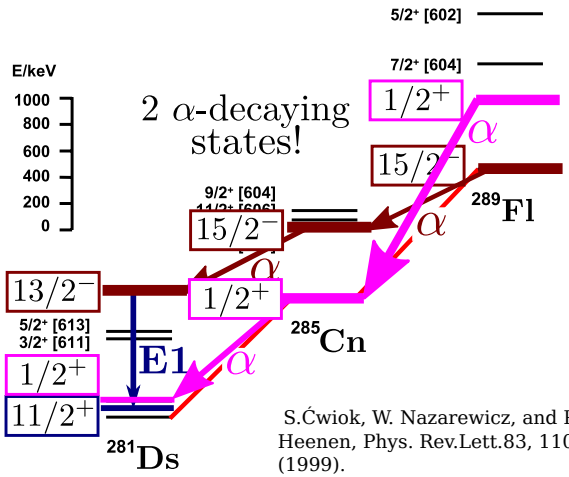
Superheavy Nuclei $Z \geq 104$ (Rf)



Experimental objective

Guide Nuclear Theory at $Z = 114$

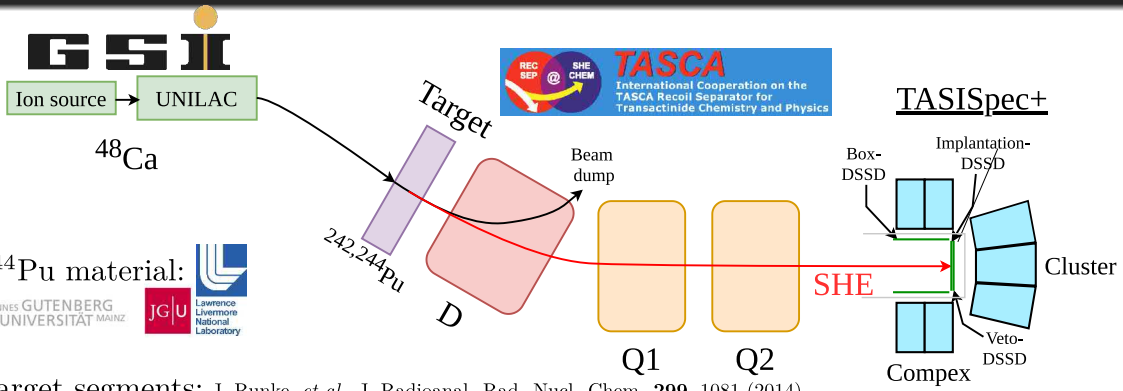
- Search for $E1$ γ transitions and K X rays from highly converted transitions
- Precise Q_α values along Odd-A ^{287,289}Fl-decay chains
- Settle a proposed α-decay branch of ^{281}Ds into ^{277}Hs [2]
- Beam time approved (2016), scheduled for August 2018, finally performed March 2019 and February 2020



S.Ćwiok, W. Nazarewicz, and P.H. Heenen, Phys. Rev.Lett.83, 1108 (1999).
As discussed S. Hofmann et al. Eur. Phys J. A 48, 62 (2012).

[2] Ch.E. Düllmann *et al.*, Phys. Rev. Lett. **104**, 252701 (2010).

Experimental scheme



Target segments: J. Runke, *et al.*, J. Radioanal. Rad. Nucl. Chem. **299**, 1081 (2014).

Target wheel: E. Jäger, *et al.*, J. Radioanal. Nucl. Chem. **299**, 1073 (2014).

Other targets & degrader foils: GSI target laboratory

TASCA: A. Semchenkov, *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 4153 (2008).

TASCA settings

Established from previous experiments:
- Fl (E114)
- Mc (E115)

Experimental scheme

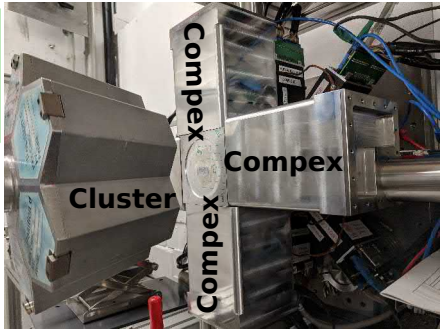
Highly efficient multi-coincidence spectroscopy set-up
for TASCA's very compact focal plane image

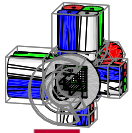
\+ 1 Imp. DSSSD (1024 pixels)
1 Veto DSSSD (1024 pixels)
4 Box DSSSDs (1024 pixels)

$\sim 80\%$ α-detection efficiency

\+ 4 Ge Compex (4 crystals each)
1 Ge Cluster (7 crystals each)

$\sim 50\%$ γ-detection effi. @ 150 keV





L.-L. Andersson et al., NIM A 622, 164 (2010).

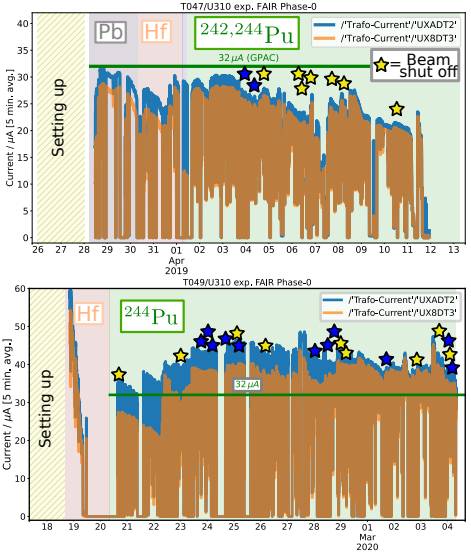
L.G. Sarmiento et al., NIM A 667, 26 (2012).

Fully simulated with Geant4

JOHANNES GUTENBERG UNIVERSITÄT MAINZ · LUND UNIVERSITY · UNIVERSITY OF LIVERPOOL · GSI · HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz · UNIVERSIDAD NACIONAL DE COLOMBIA

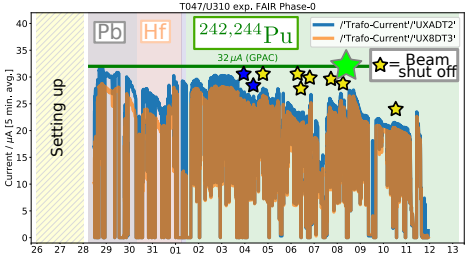
Result - in a nutshell

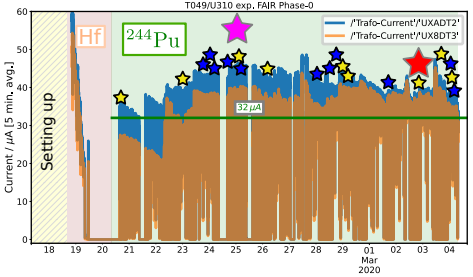
- In total 29 chains of which 16 with beam shutoff
  - $2\times{}^{286}$Fl
  - $12\times{}^{288}$Fl
  - $15\times{}^{289}$Fl
- Beam integral $6.0 \cdot 10^{18}$ particles
- Production cross sections of ^{288,289}Fl: $\sigma \sim 5$ pb each



Highlights:

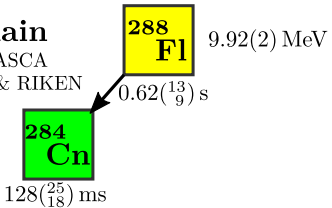
- Discovery of ^{280}Ds ★
  (α-decay branch of ^{284}Cn)
- Excited state in ^{282}Cn ★
  A. Såmark-Roth *et al.*,
  Phys. Rev. Lett. **126**, 032503 (2021).
- Fine structure in ^{289}Fl
  α-decay chains ★
  D.M. Cox *et al.*,
  to be submitted to Phys. Rev. Lett.



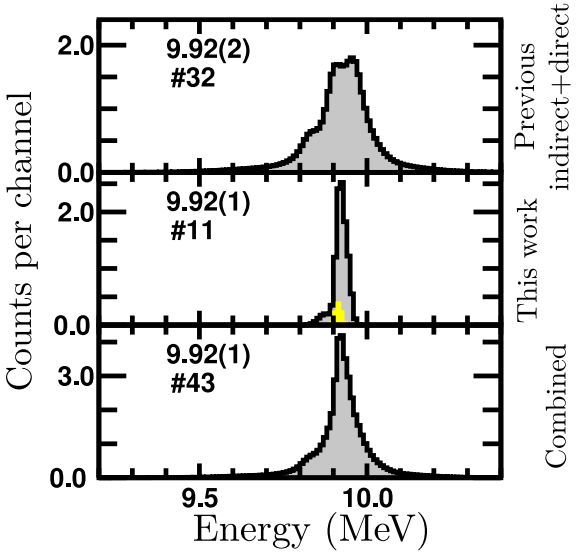


Discovery of ^{280}Ds

Reference chain
24 direct, FLNR & TASCA
12 indirect, FLNR, SHIP & RIKEN



- Two closely lying decay paths ($\Delta E \sim 0.1$ MeV)?
- Superior spectroscopic quality of our 12 new ^{288}Fl-decay chains solves the puzzle

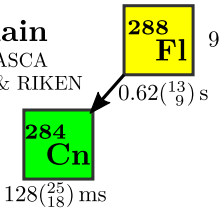


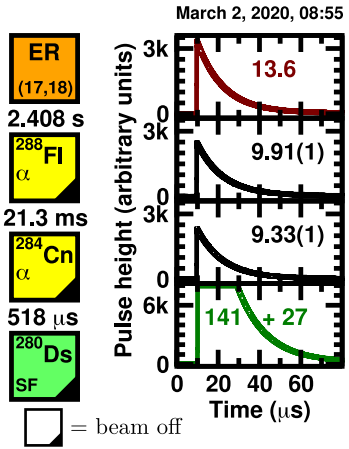
Discovery of ^{280}Ds

Reference chain

24 direct, FLNR & TASCA

12 indirect, FLNR, SHIP & RIKEN



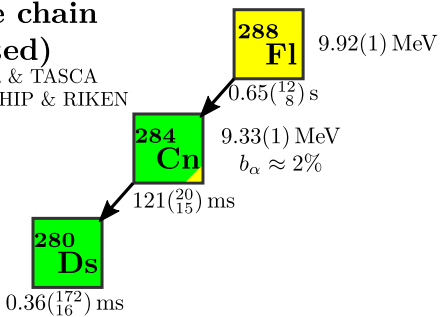


$N_{\text{random}} = 3 \times 10^{-12}$

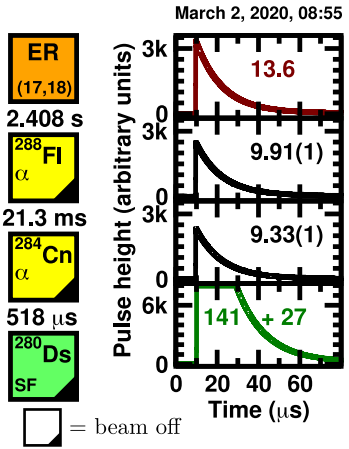
Discovery of ^{280}Ds

Reference chain (updated)

36 direct, FLNR & TASCA
12 indirect, FLNR, SHIP & RIKEN

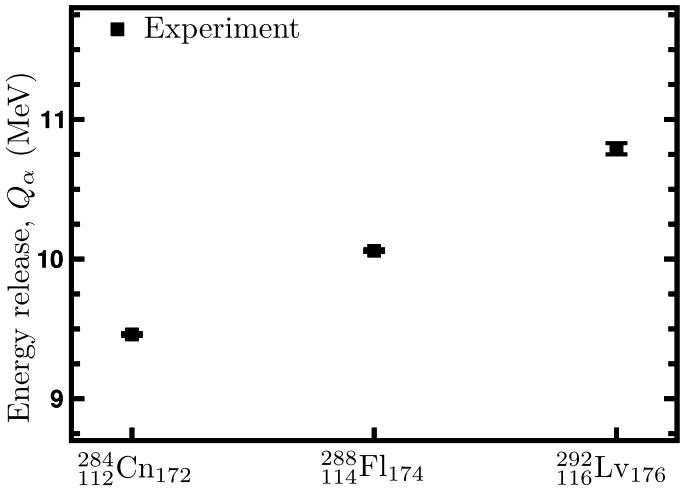


- First α decay of ^{284}Cn (1 out of 51)
- Discovery of ^{280}Ds



$N_{\text{random}} = 3 \times 10^{-12}$

Q_α sequence across $Z = 114$



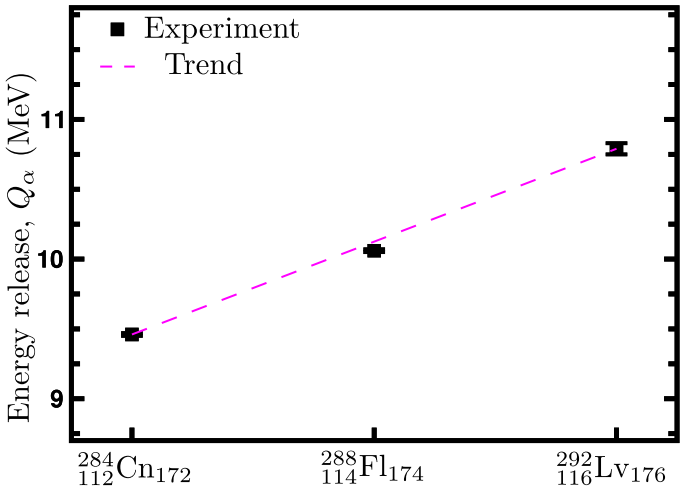
^{292}Lv:

Yu. Ts. Oganessian, *et al.*,
in JINR Preprint, E7-2004-160 (2004), p. 128

S. Hofmann, *et al.*,
Eur. Phys. J. A **48**, 62 (2012).

D. Kaji, *et al.*,
J. Phys. Soc. Jpn. 86, 034201 (2017).

Q_α sequence across $Z = 114$



^{292}Lv:

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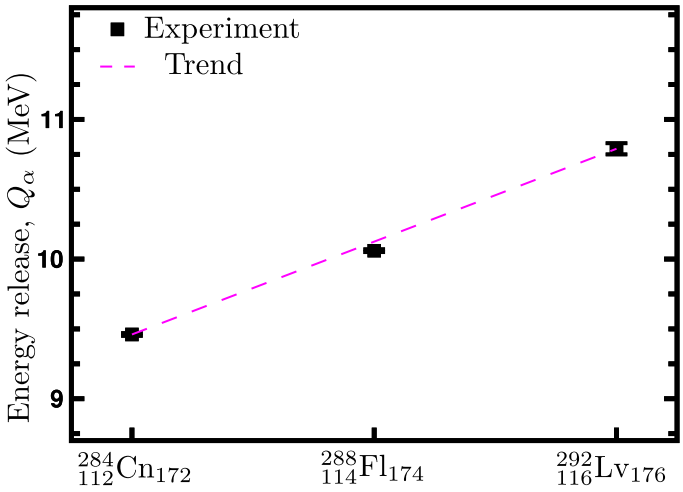
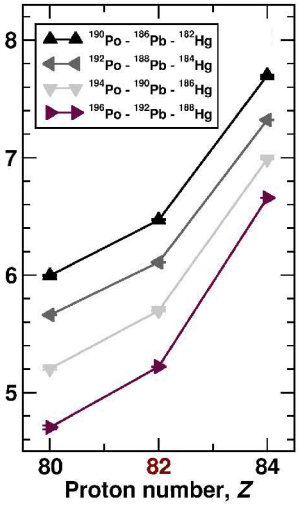
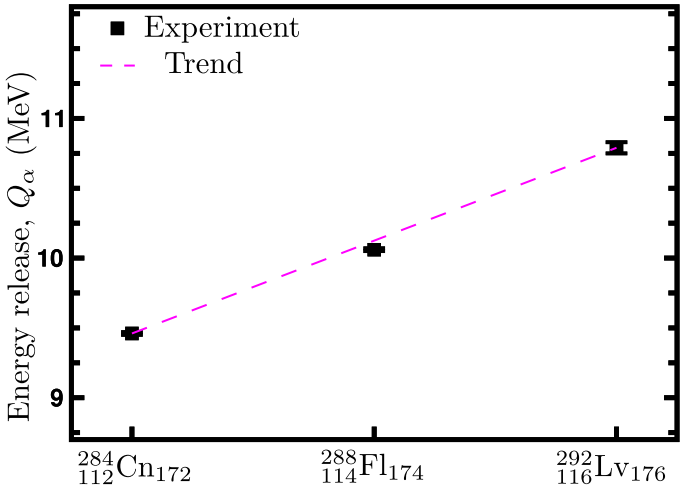
J. Phys. Soc. Jpn. 86, 034201 (2017).

Q_α sequence across $Z = 114$

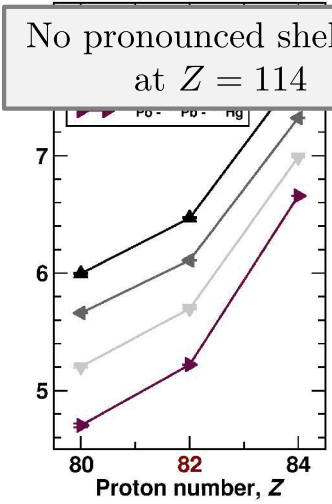




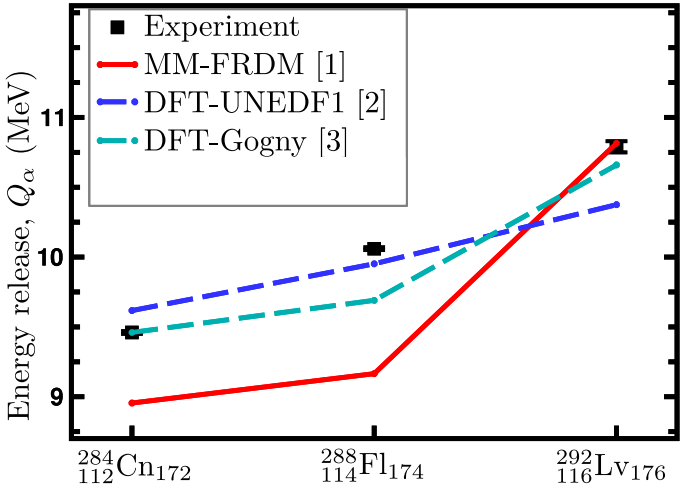
Q_α sequence across $Z = 114$



No pronounced shell gap at $Z = 114$



Q_α sequence across $Z = 114$



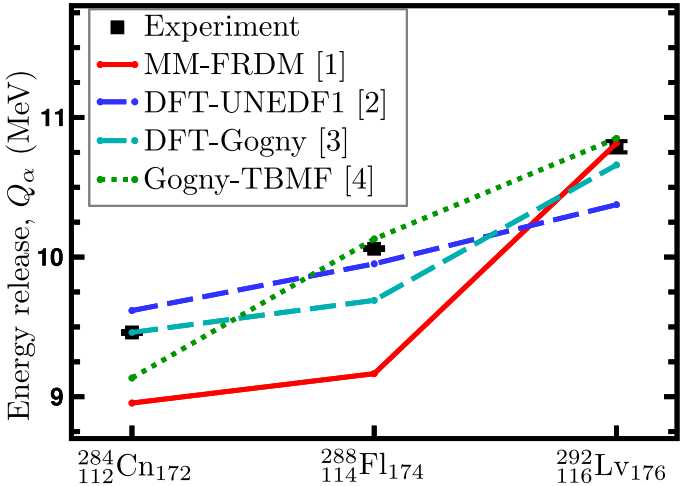
No pronounced shell gap at $Z = 114$

[1] P. Möller, it et al., At. Data. Nucl. Data Sheets **109–110**, 1 (2016).

[2] E. Olsen and W. Nazarewicz, Phys. Rev. C **99**, 014317 (2019).

[3] M. Warda and J. L. Egido, Phys. Rev. C **86**, 014322 (2012).

Q_α sequence across $Z = 114$



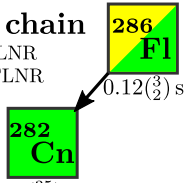
No pronounced shell gap at $Z = 114$

[4] J. L. Egido and A. Jungclaus, Phys. Rev. Lett. **125**, 192504 (2020).

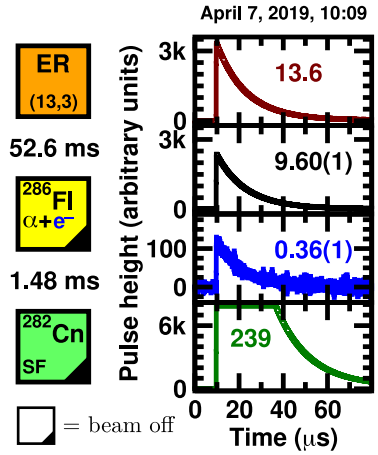
Watch out for triaxial shapes!

Excited state in ^{282}Cn

Reference chain
11 direct, FLNR
16 indirect, FLNR



Binding energies (Cn, $Z = 112$)
$K = 190$ keV
$L = 40$ keV



$N_{\text{random}} = 8 \times 10^{-7}$

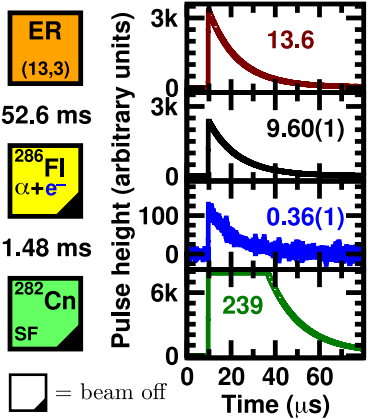
Excited state in ^{282}Cn

Reference chain
11 direct, FLNR
16 indirect, FLNR

Binding energies (Cn, $Z = 112$)

$K = 190$ keV
$L = 40$ keV

- Cannot be a "to-be-reconstructed" α
- $\approx 10^{-3}$ an escaping α
- $< 1\%$ it is a random coincidence
- Consistent correlation times with ^{286}Fl
- 9.6 MeV α-decay branch
- 0.36 MeV internal conversion e$^-$



$N_{\text{random}} = 8 \times 10^{-7}$

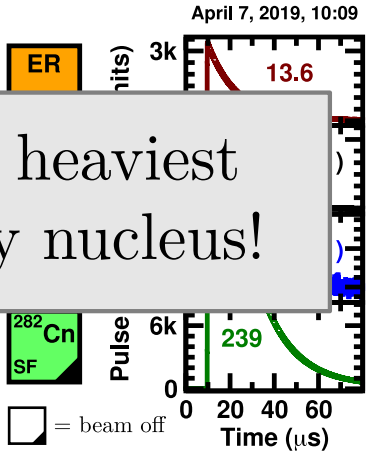
Excited state in ^{282}Cn

Reference chain
11 direct, FLNR
16 indirect, FLNR

10.20(4) MeV

$0.12(^{3}_{2})$ s

Excited state in the heaviest even-even superheavy nucleus!

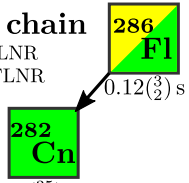


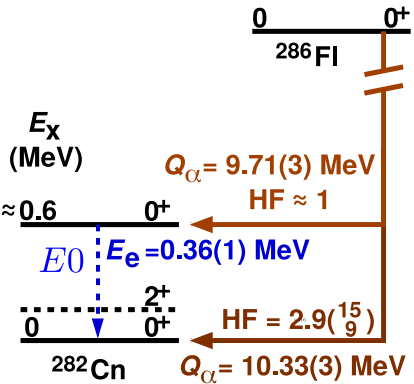
= beam off

$N_{\text{random}} = 8 \times 10^{-7}$

Excited state in ^{282}Cn

Reference chain
11 direct, FLNR
16 indirect, FLNR

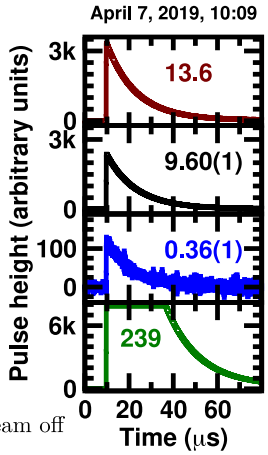




$E0$

Transition strengths
+ GEANT4

A. Såmark-Roth *et al.*,
Phys. Rev. C
(to be published)



= beam off

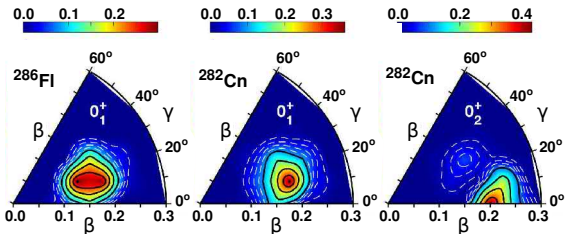
$N_{\text{random}} = 8 \times 10^{-7}$

Excited state in ^{282}Cn

- Triaxial beyond-mean-field [4] predicts low-lying 0_2^+ state at $\sim 1\,\mathrm{MeV}$
- Triaxial ground states common?
- Is this evidence of shape coexistence and transitions?
- ^{186}Pb case comes to mind [5]

[5] A.N. Andreyev *et al.*, Nature **405**, 430 (2000).

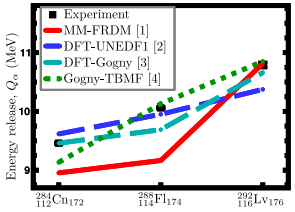
Predicted squared wavefunctions [4]

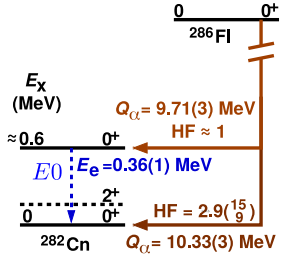


[4] J.L. Egido and A. Jungclaus, Phys. Rev. Lett. **125**, 192504 (2020) & Phys. Rev. Lett. **126**, 192501 (2021)

Summary

Demonstration of benchmarking capability of nuclear spectroscopy experiments in the SHE regime





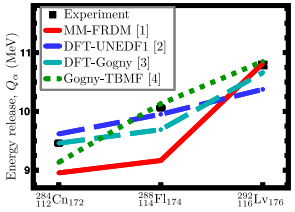
Knut och Alice Wallenbergs Stiftelse

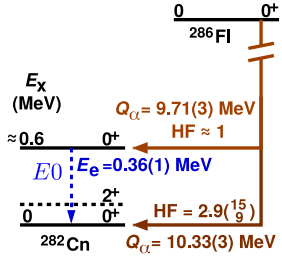
FAIR Phase 0 Research Program

LUND UNIVERSITY

Summary

Demonstration of benchmarking capability of nuclear spectroscopy experiments in the SHE regime





Knut och Alice Wallenbergs Stiftelse

FAIR Phase 0 Research Program

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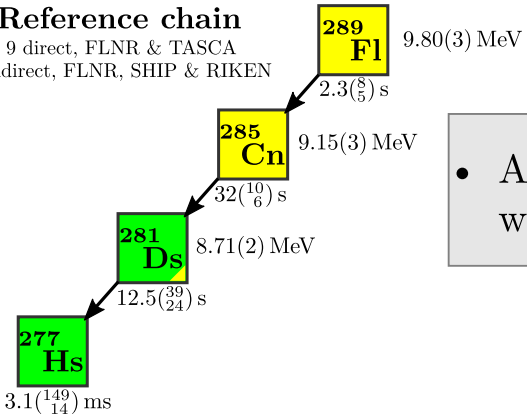
Outlook (short term): ^{289}Fl-decay chains

Reference chain
9 direct, FLNR & TASCA
9 indirect, FLNR, SHIP & RIKEN



D.M. Cox *et al.*, Phys. Rev. Lett. (to be published)

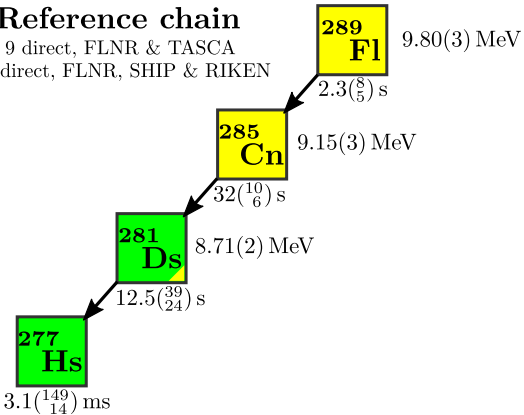
- Almost doubling global data set with 15 new ^{289}Fl-decay chains

Outlook (short term): ^{289}Fl-decay chains

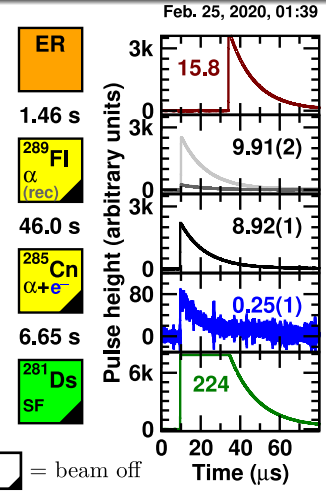
Reference chain

9 direct, FLNR & TASCA

9 indirect, FLNR, SHIP & RIKEN



D.M. Cox *et al.*, Phys. Rev. Lett. (to be published)



$N_{\text{random}} = 7 \times 10^{-7}$

Outlook (short term): ^{289}Fl-decay chains

Reference chain

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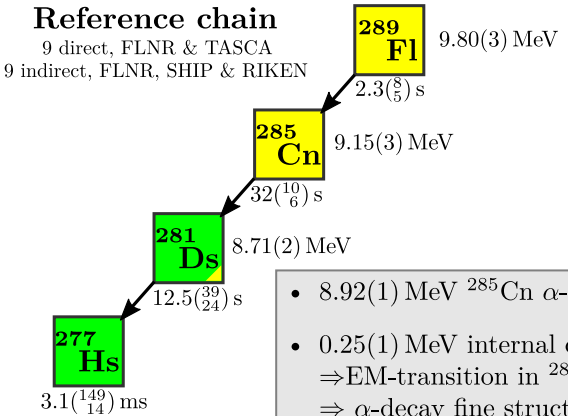
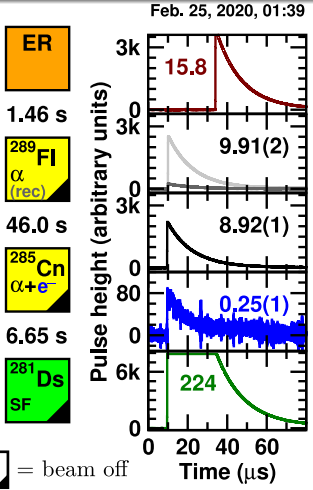


D.M. Cox *et al.*, Phys. Rev. Lett. (to be published)

- 8.92(1) MeV ^{285}Cn α-decay branch
- 0.25(1) MeV internal conversion e$^-$
  $\Rightarrow$EM-transition in ^{281}Ds
  $\Rightarrow$ α-decay fine structure
- 9.91(2) MeV deviates from ^{289}Fl main branch ...



= beam off

$N_{\text{random}} = 7 \times 10^{-7}$

Outlook (short term): ^{289}Fl-decay chains

Reference chain

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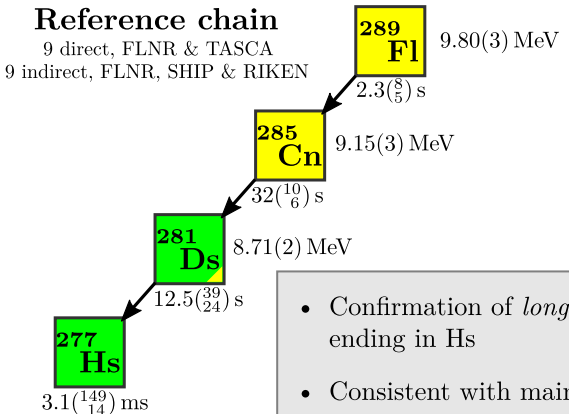
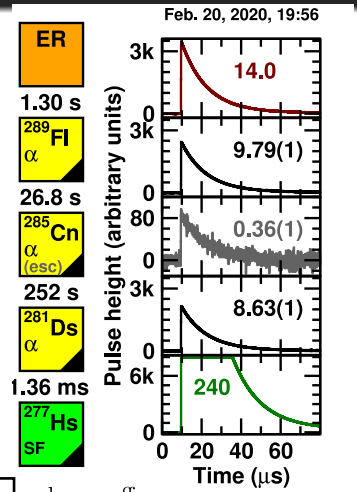


D.M. Cox *et al.*, Phys. Rev. Lett. (to be published)

- Confirmation of *long* chain ending in Hs
- Consistent with main decay path
- Insights into ^{281}Ds α decay and ^{277}Hs fission



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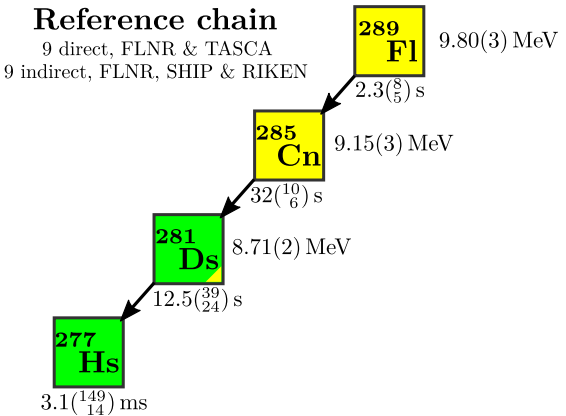
$N_{\text{random}} = 2 \times 10^{-8}$

Outlook (short term): ^{289}Fl-decay chains



D.M. Cox *et al.*, Phys. Rev. Lett. (to be published)

Summary

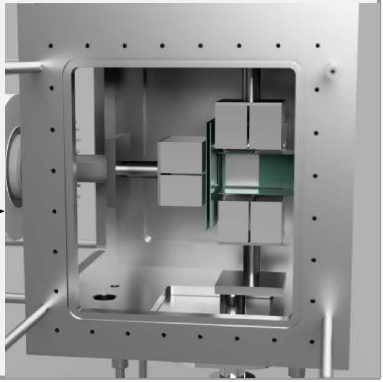
- Experimental challenge (due to long correlation times)
  ⇒ Beam shut-off routine
  ⇒ Key UNILAC pulsed beam
- First decay scheme of ^{289}Fl provides valuable insights
- A shy 2 α-photon coincidences
  ⇒ Further studies
  ⇒ Increased sensitivity

Outlook

Quote referee report:

"Future technical developments should allow to wring out tantalizing physics from compound nucleus production data where cross-sections are in the picobarn range"

Lundium decay station



Knut och Alice Wallenbergs Stiftelse

FAIR Phase 0 Research Program

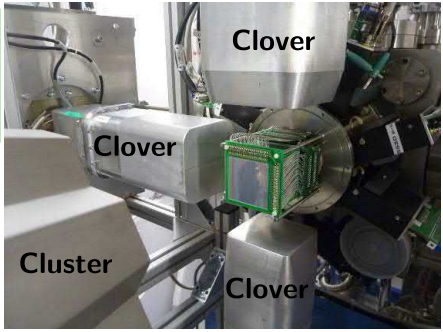
LUND UNIVERSITY

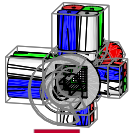
TASISpec++

Highly efficient multi-coincidence spectroscopy set-up
for TASCA's very compact focal plane image

1 Imp. DSSSD (1024 pixels)
+
4 Box DSSSDs (1024 pixels)
$\sim 80\%$ α-detection efficiency

4 Ge Clover (4 crystals each)
+ 1 Ge Cluster (7 crystals each)
$\sim 40\%$ γ-detection effi. @ 150 keV





L.-L. Andersson et al., NIM A 622, 164 (2010).

L.G. Sarmiento et al., NIM A 667, 26 (2012).

Fully simulated with Geant4

TASISpec++

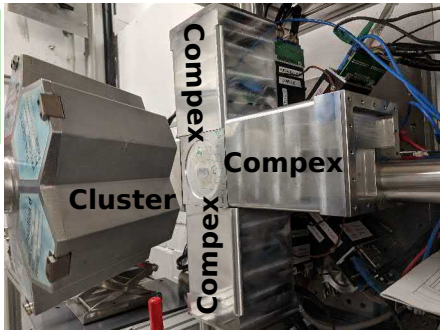
Highly efficient multi-coincidence spectroscopy set-up
for TASCA's very compact focal plane image

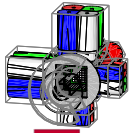
\+ 1 Imp. DSSSD (1024 pixels)
1 Veto DSSSD (1024 pixels)
4 Box DSSSDs (1024 pixels)

$\sim 80\%$ α-detection efficiency

\+ 4 Ge Compex (4 crystals each)
1 Ge Cluster (7 crystals each)

$\sim 50\%$ γ-detection effi. @ 150 keV





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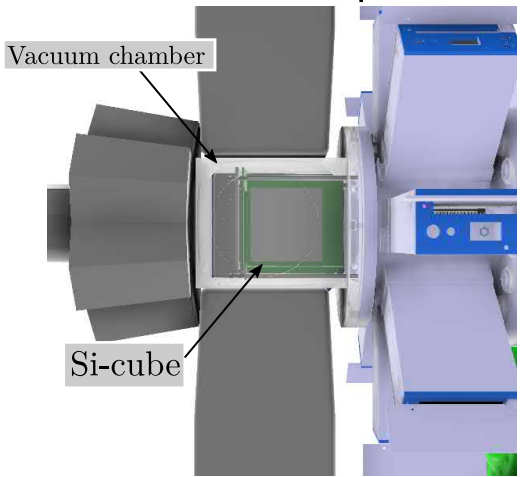
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
LUND UNIVERSITY
UNIVERSITY OF LIVERPOOL
GSI
HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz
UNIVERSIDAD NACIONAL DE COLOMBIA

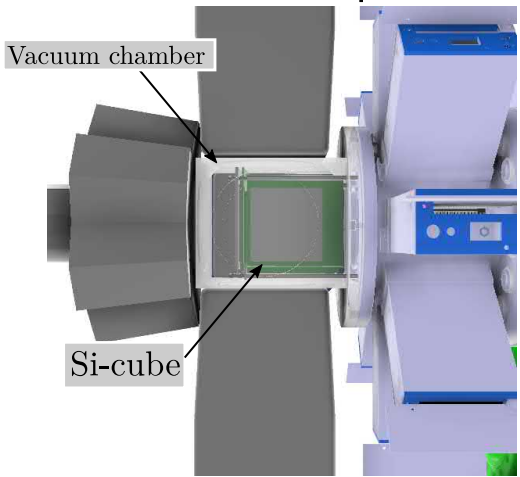
Lundium Upgrade

TASISpec

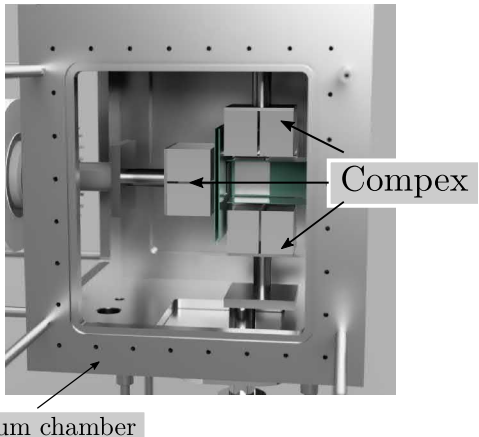


Lundium Upgrade

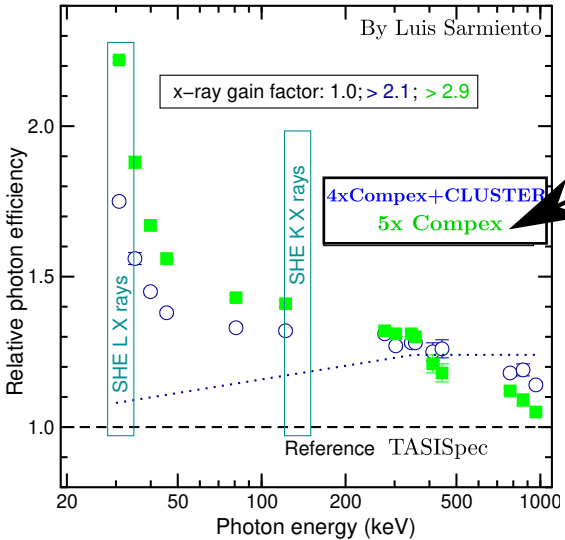
TASISpec

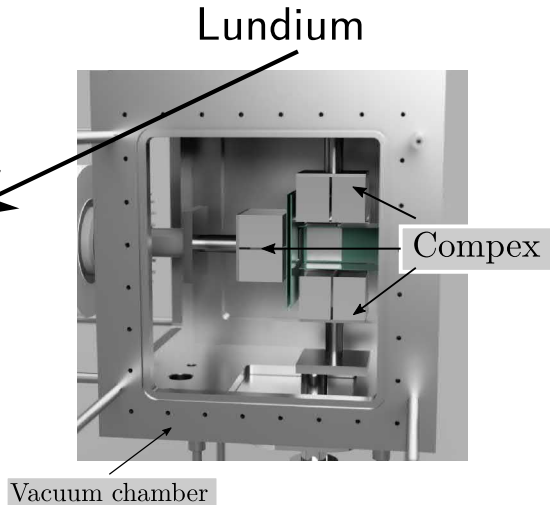


Lundium

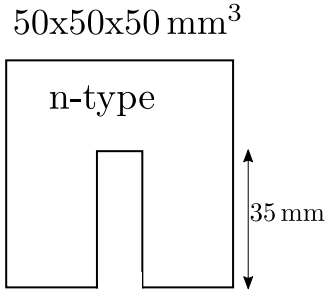


Lundium Upgrade

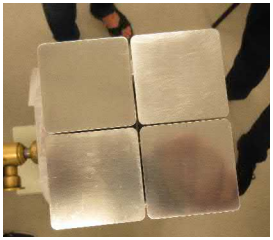




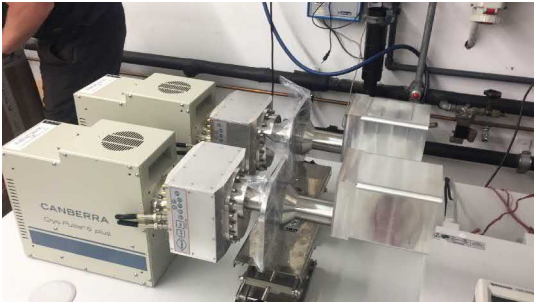
Compex



'Cubic' encapsulated crystals



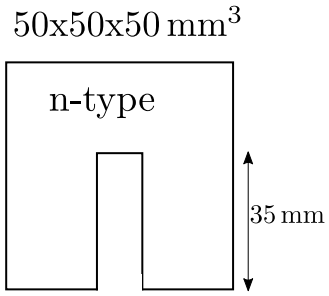
4 crystals in a common cryostat



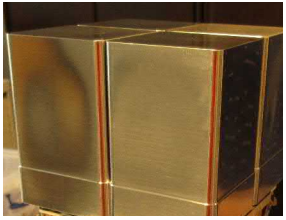
Mechanical cooling, $T \sim$ -160 °C

A. Såmark-Roth, *et al.* EPJA 56 141 (2020)

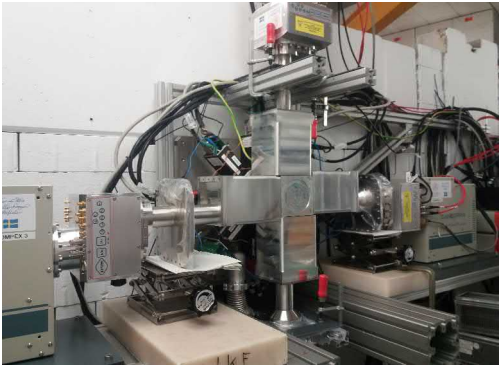
Compex



'Cubic' encapsulated crystals



4 crystals in a common cryostat



Typical resolutions:
1.9 keV @1.33 MeV
0.8 keV @122 keV

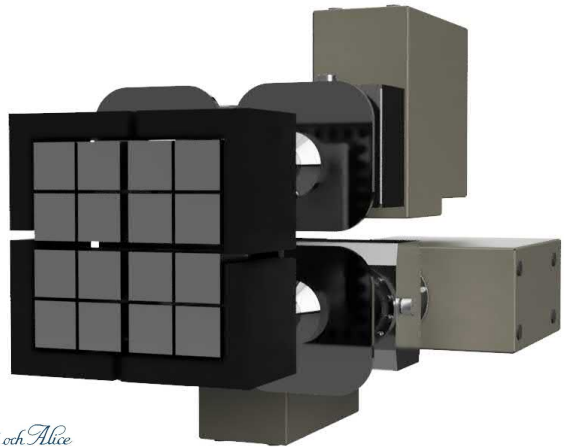
A. Såmark-Roth, *et al.* EPJA 56 141 (2020)

Background Suppression

Anti-compton suppression

- 4 Ge crystals allow running in add-back mode
- Custom made BGO shields
  - Corner cover
  - Full cover

Background Suppression



- Tesselating geometry
- Wall configuration possible
- Travelling setup

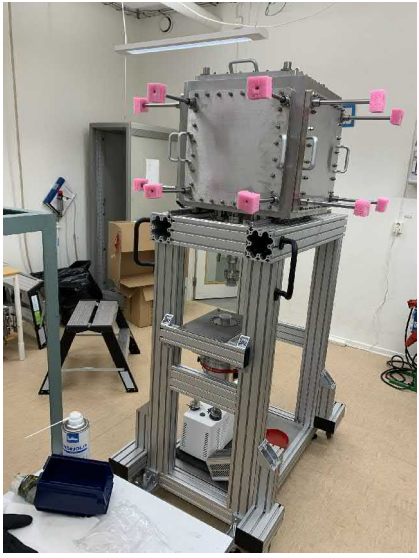
Knut och Alice Wallenbergs Stiftelse

The Crafoord Foundation

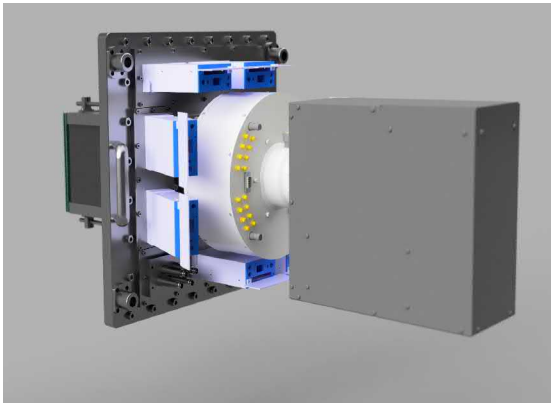
Lundium Upgrade

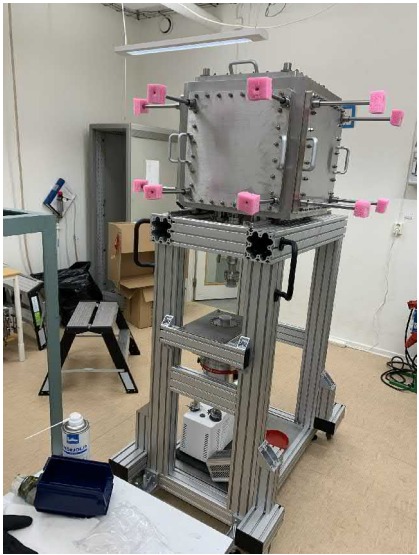
Chamber

- Chamber mounted on trolley
- Pumping scheme finalised (at least for tests)
- Holds vacuum down to 10^{-6} mbar
- Deformation of flanges <1 mm
- Safety is very important!



Lundium Upgrade





Lundium Upgrade

	TASISpec (2010)	TASISpec++ (2019)	Lundium (2022)
Imp DSSD	32x32	32x32	58x58
Veto DSSD	-	32x32	58x58
Box DSSDs	32 (SSSD)	16x16	16x16
Detectors	Cluster + Clover	Compex + Clover	Compex (in vacuum)

Proposal

Discovery and Spectroscopy of Neutron-Deficient Pu Isotopes and their Alpha-Decay Daughters

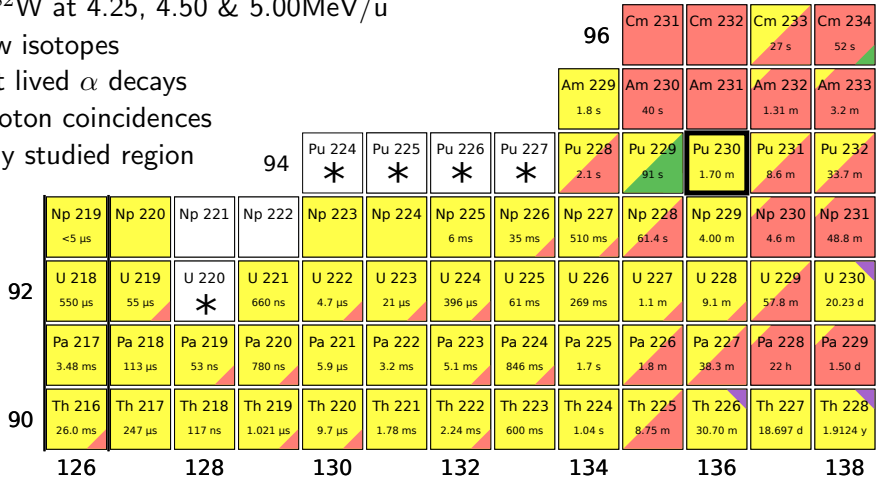
D.M. Cox[A], A.K. Mistry[B,C], E. Parr[B], M. Block[B,D,E], Ch.E. Düllmann[B,D,E], F. Giacoppo[B,D], S. Raeder[B,D], D. Rudolph[A], L.G. Sarmiento[A], H.M. Albers[B], S. Antalic[F], B. Andel[G], R.M. Clark[H], C Fahlander[A], J.M. Gates[H], J. Gerl[B], P. Golubev[A], R.-D. Herzberg[I], Y. Hrabar[A], D.S. Judson[I], B. Kindler[B], I. Kojouharov[B], N. Kurz[B], B. Lommel[B], C.-C. Meyer[D,E], C. Mokry[D,E], P. Mosat[F], P. Papadakis[J], J.L. Pore[H], D. Renisch[D,E], J. Runke[B,E], A. Sämark-Roth[A], H. Schaffner[B], P. Thörle-Pospiech[D,E].

[A] *Lund University, Lund, Sweden.*
[B] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany.*
[C] *Technische Universität Darmstadt, Darmstadt, Germany.*
[D] *Helmholtz Institut Mainz, Mainz, Germany.*
[E] *Johannes Gutenberg-Universität Mainz, Mainz, Germany.*
[H] *Lawrence Berkeley National Laboratory, Berkeley, USA.*
[F] *Comenius University in Bratislava, Bratislava, Slovakia.*
[G] *Instituut voor Kern- en Stralingsfysica, K. U. Leuven, Leuven, Belgium.*
[I] *University of Liverpool, Liverpool, UK.*
[J] *STFC Daresbury Laboratory, Daresbury, Warrington, UK.*

Proposal

$^{48}Ca + {}^{182}W$ at 4.25, 4.50 & 5.00MeV/u

- 5 new isotopes
- Short lived α decays
- α-photon coincidences
- Rarely studied region



Proposal

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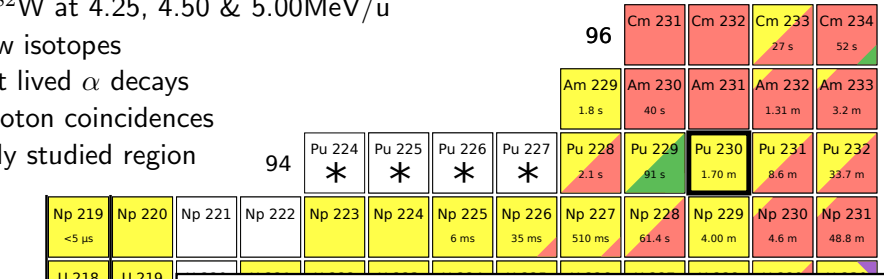

Quadrupole deformation parameters in $^{220,222,224}U$

Ground-state configuration of ^{223}U

Physics-driven commissioning of new experimental setup

Results & Outlook

Many TASISpec successful experiments performed

Intermediate upgrade (with Compex)

U310/T047/T049 - Performed sucessfully

- A. Såmark-Roth, D.M. Cox *et al.* EPJA 56 141 (2020)
- D.M. Cox, A. Såmark-Roth *et al.* IOP. Conf. Proc. Set. 1643 (2020)
- A. Såmark-Roth, D.M. Cox *et al.* PRL 126 032503 (2021)
- D. M. Cox, A. Såmark-Roth *et al.* PRL in preparation (2021)
- A. Såmark-Roth, D.M. Cox *et al.* PRC in preparation (2021)

Lundium upgrade ongoing

Accepted Proposal

Knut och Alice Wallenbergs Stiftelse

LUND UNIVERSITY