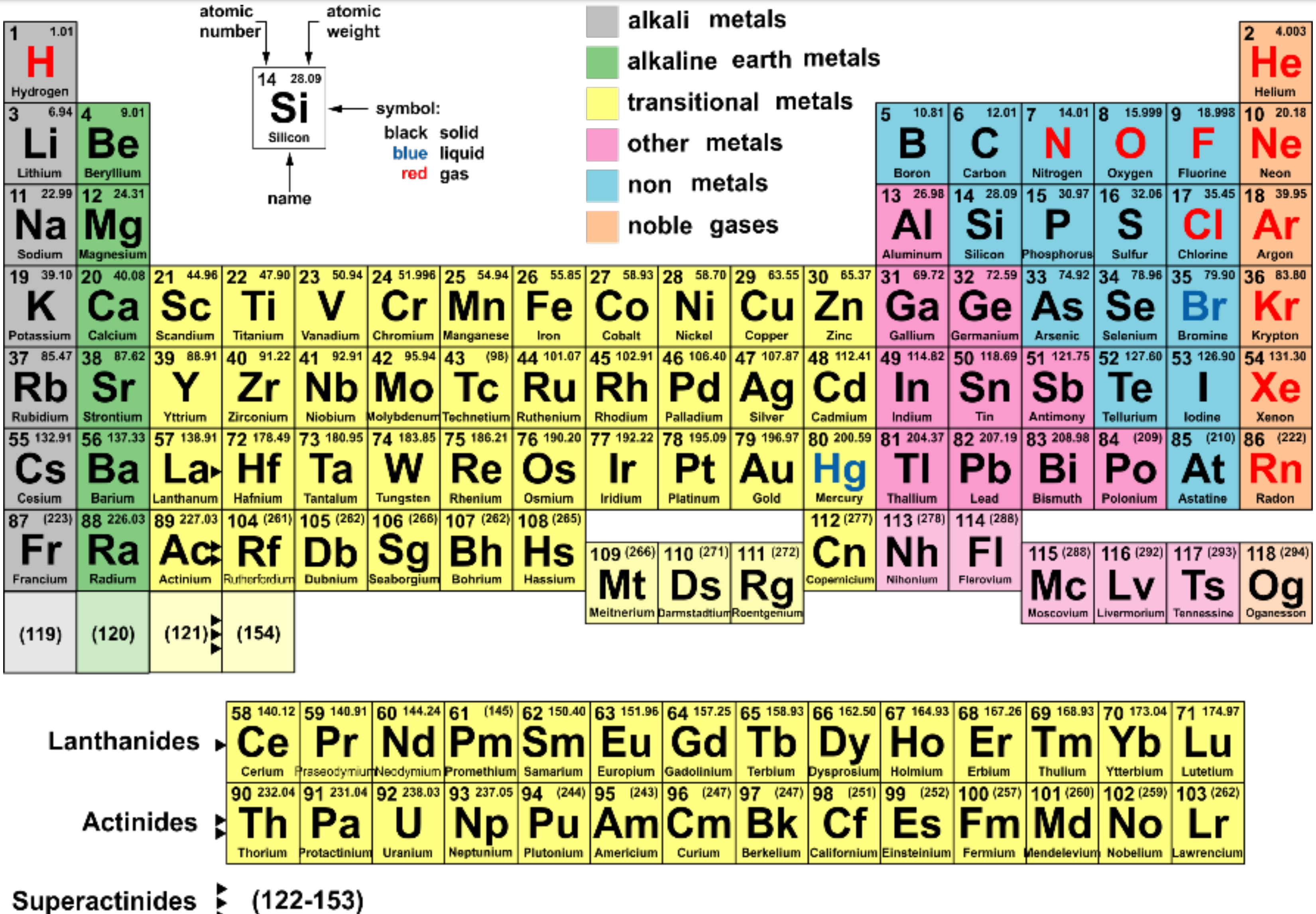
The Heaviest Elements: Latest Results from Berkeley

Rod Clark

Outline

- The Science of the Heaviest Elements
- Structure of Deformed Trans-fermium Nuclei
- Directly making the Heaviest Elements
- Looking to the Future
- Summary

The Periodic Table



Heavy Element Science Questions

Where does the Periodic Table End?

How does electronic structure change because of relativistic effects?

When does it no longer make sense to talk of electronic shell structure?
(One scenario –
The electrons form a Fermi gas;
no discernable valence properties;
the end of Chemistry)

What combinations of protons and neutrons form a nucleus?

How do we describe the forces between nucleons?

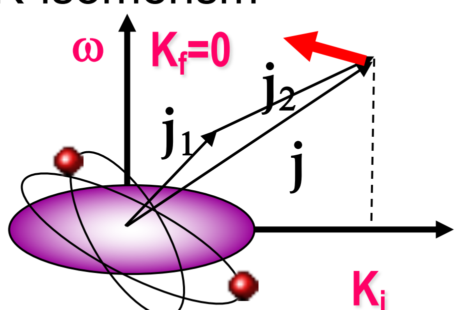
What shapes (high order?), topologies (bubbles?), structures (isomerism?) can the nucleus display?

How does a nucleus decay and what are the timescales?

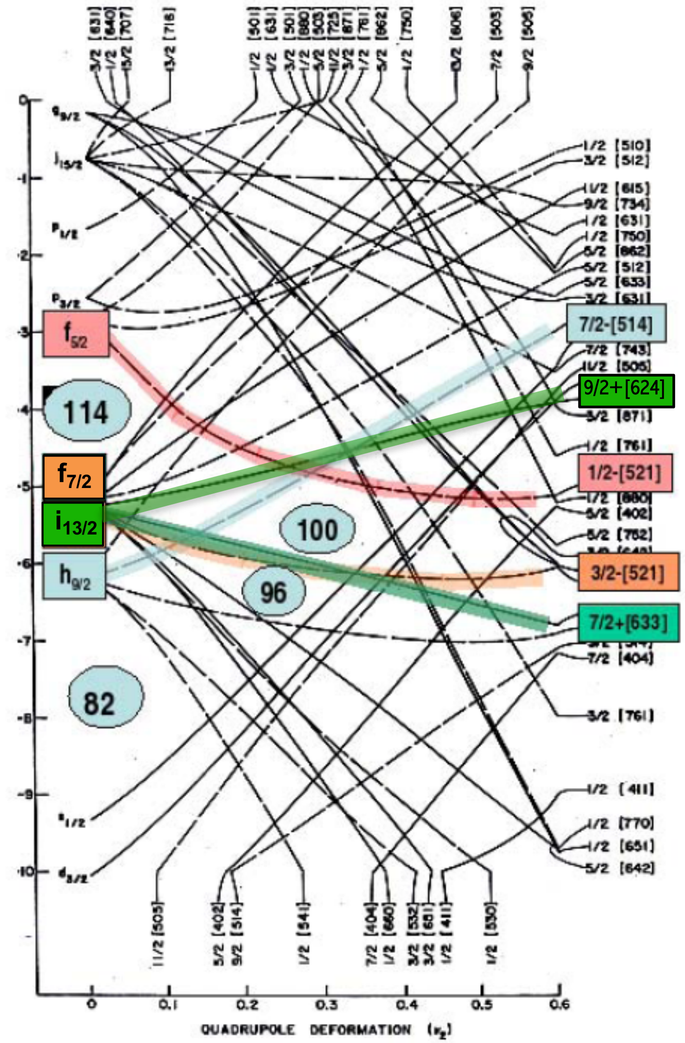
Structure of Deformed Trans-fermium Nuclei

Shapes and Shells

- Single-particle levels → shell structure
  - Next major spherical gaps
  - Deformed gaps
- Deformation and collectivity
  - K-isomerism



  - Rotational structures
  - Low-lying vibrations
- Pairing properties
  - Multi-quasiparticle states
  - Rotation, α-decay, fission



R. R. Chasman et al.,
Rev. Mod. Phys. 49 833 (1977)

Spectroscopy Experiments

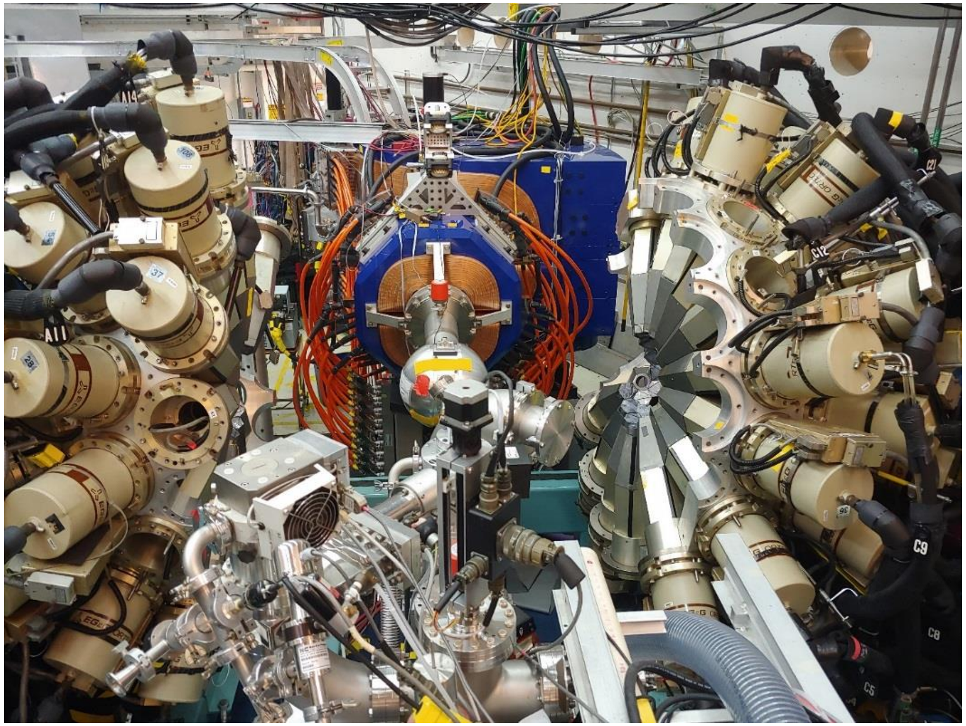
Experiments at Argonne National Lab

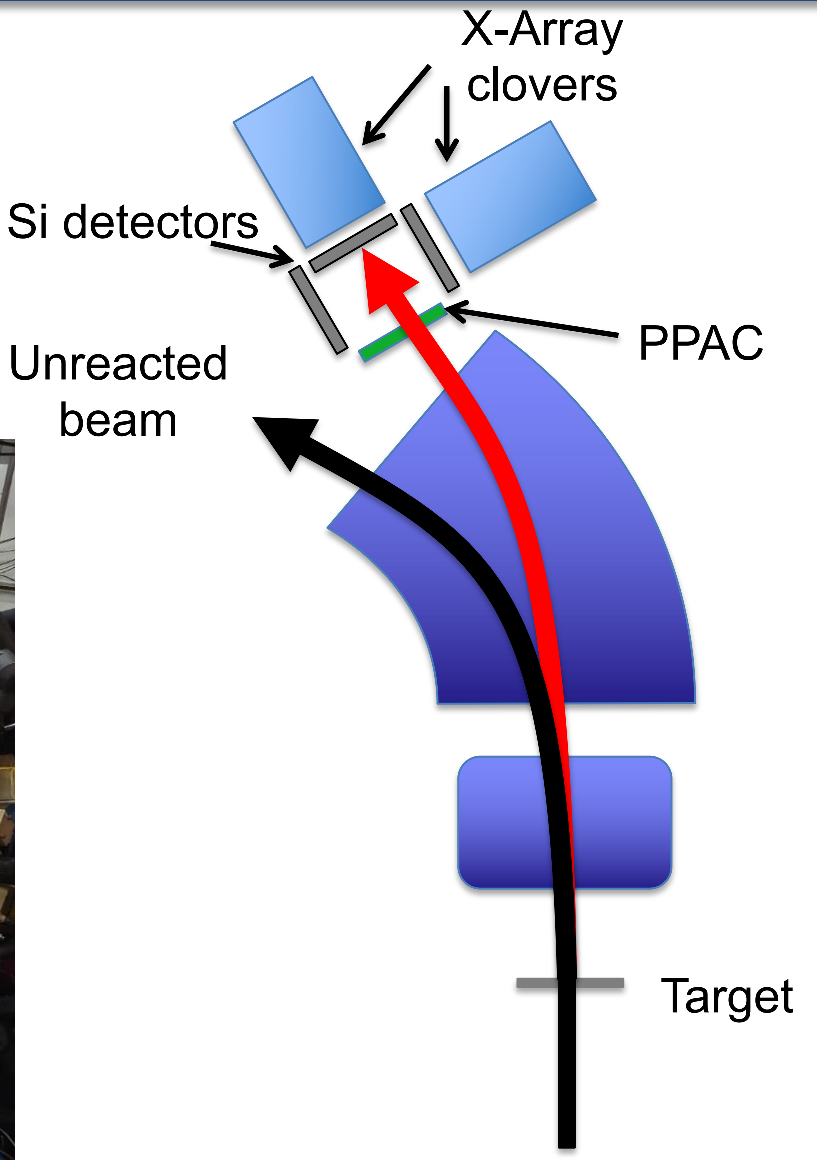
- AGFA : gas-filled separator for recoils
- Gammasphere around target

(prompt gamma-ray spectroscopy)

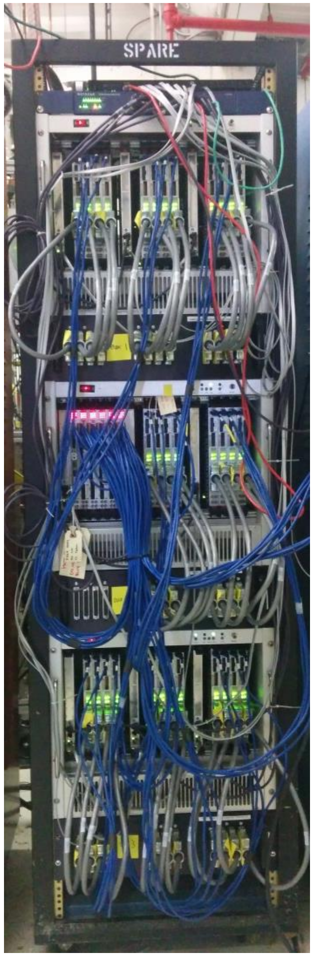
- X-Array at the focal plane

(delayed spectroscopy of decays)



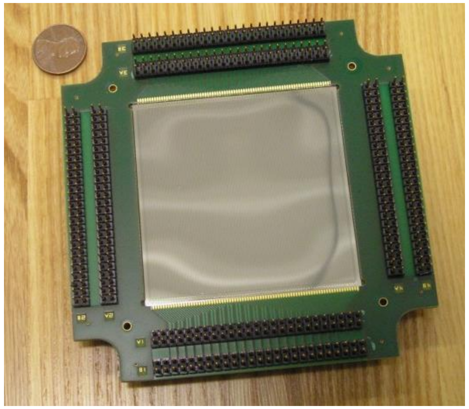


Isomer Spectroscopy

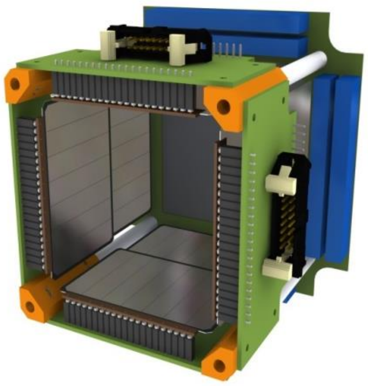


Digital DAQ

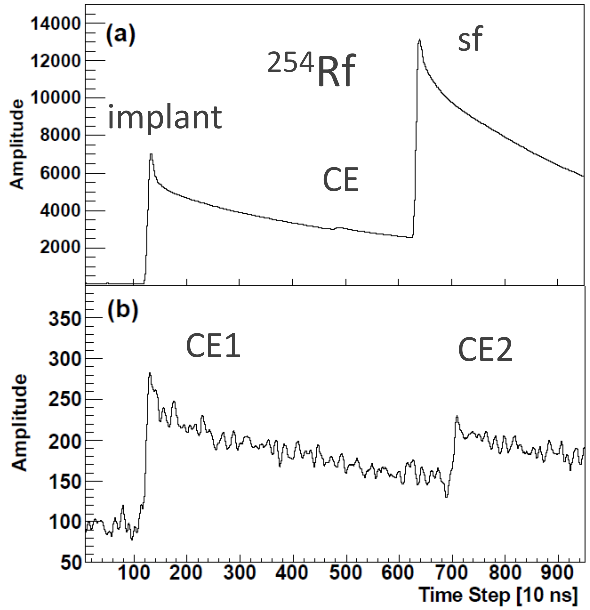
Stolen shamelessly from
Darek Seweryniak

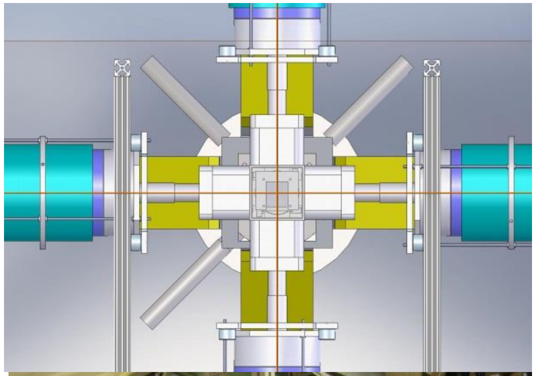


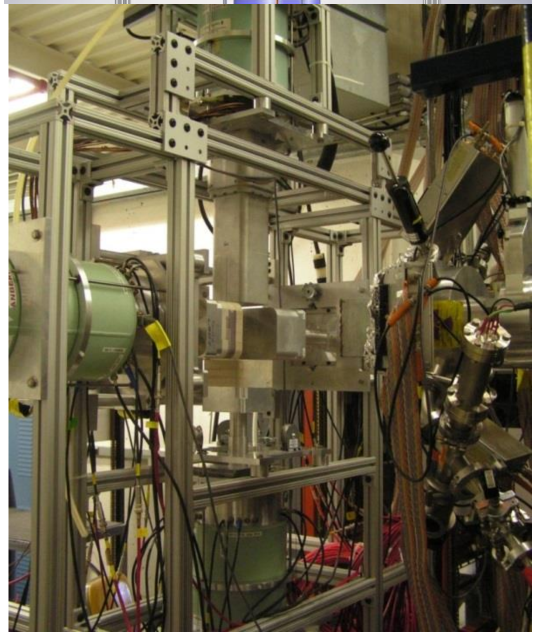
160X160, 64mmX64mm DSSD



Si tunnel
8 SSSD's

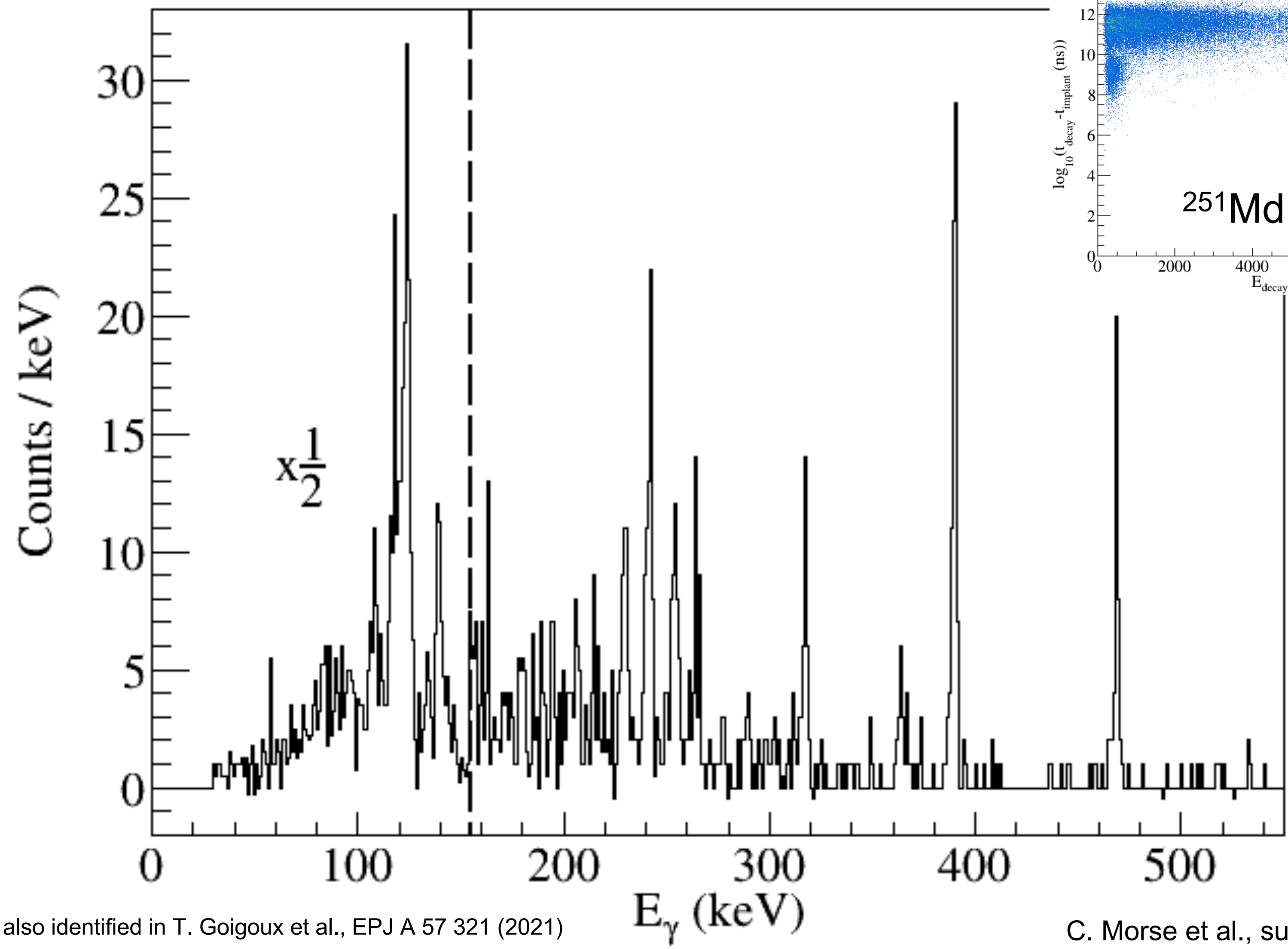


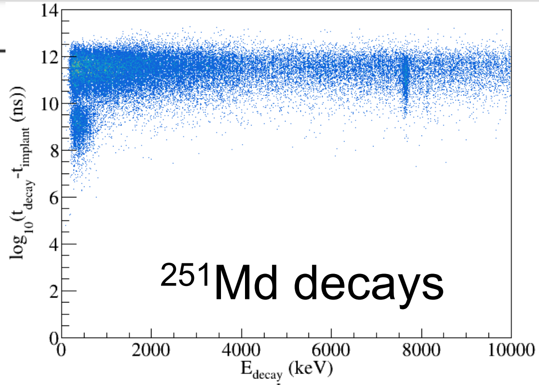




X-Array, 5 clovers in box geometry

The Case of ^{251}Md



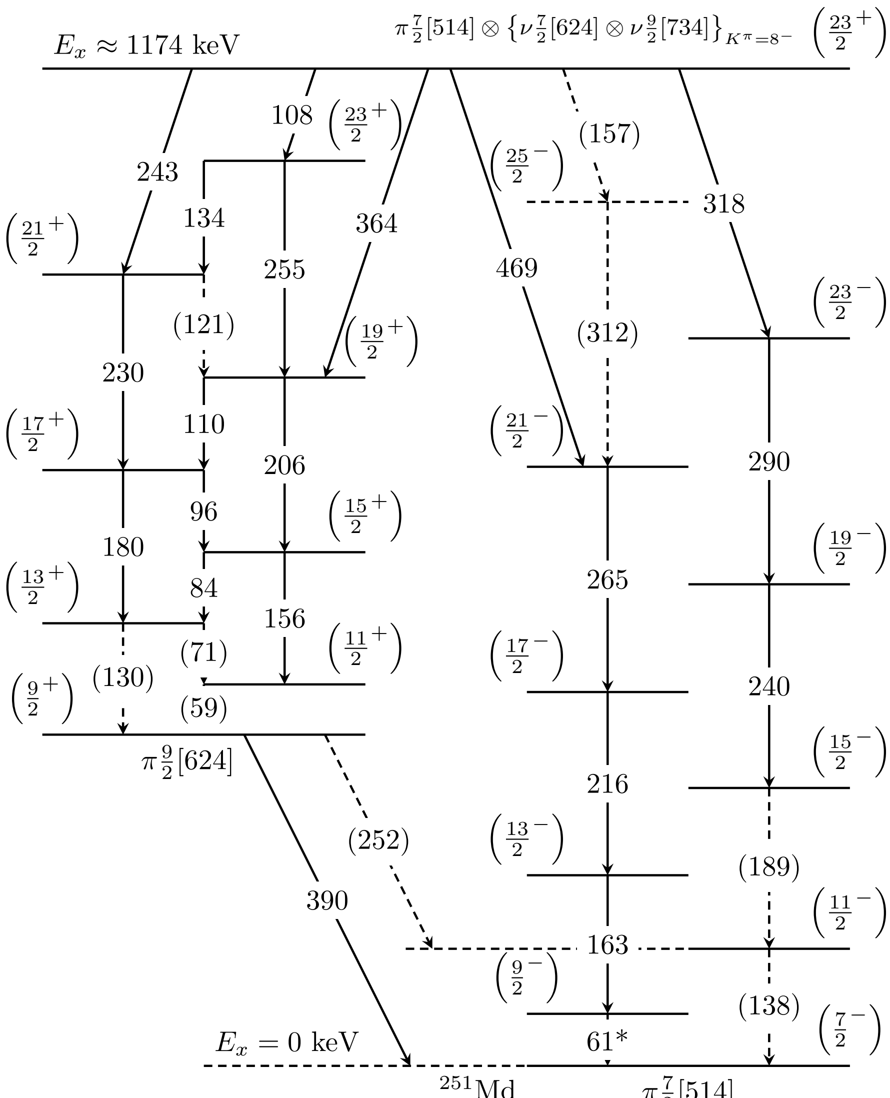


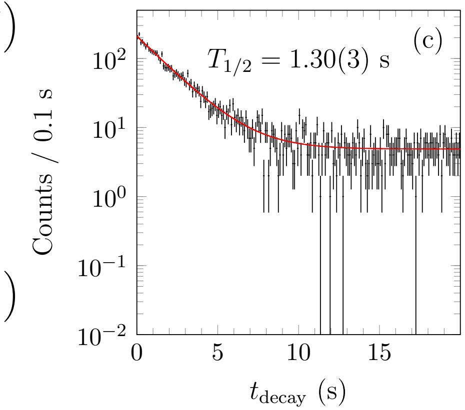
Isomer also identified in T. Goigoux et al., EPJ A 57 321 (2021)

C. Morse et al., submitted to PRC

The Case of ^{251}Md

[624]9/2⁺ Band

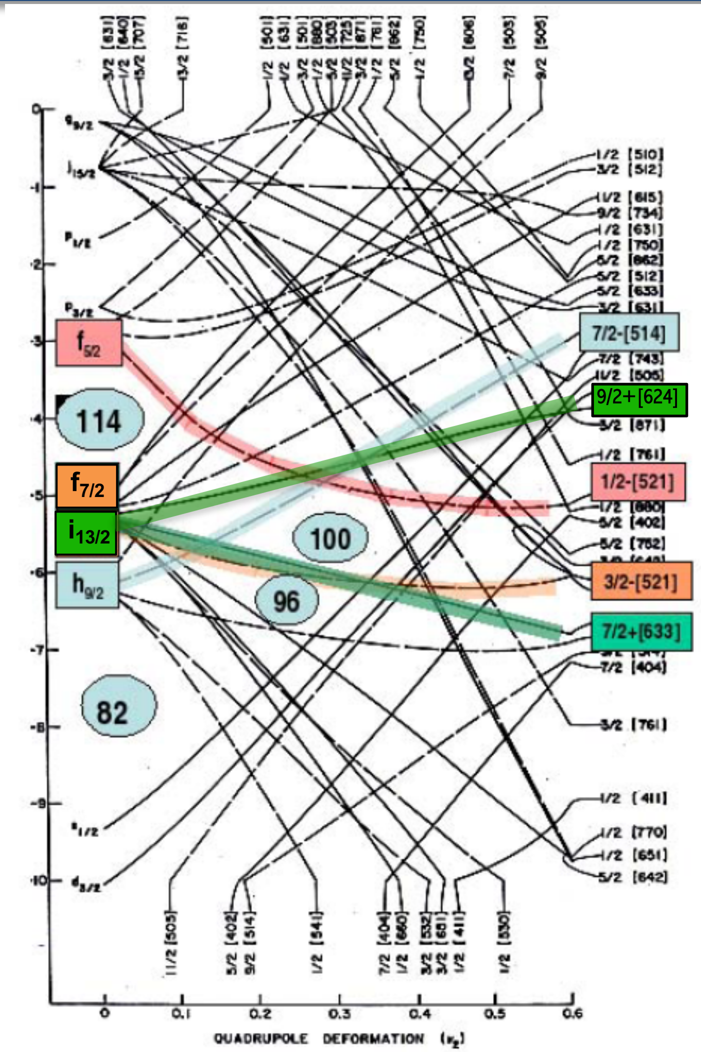




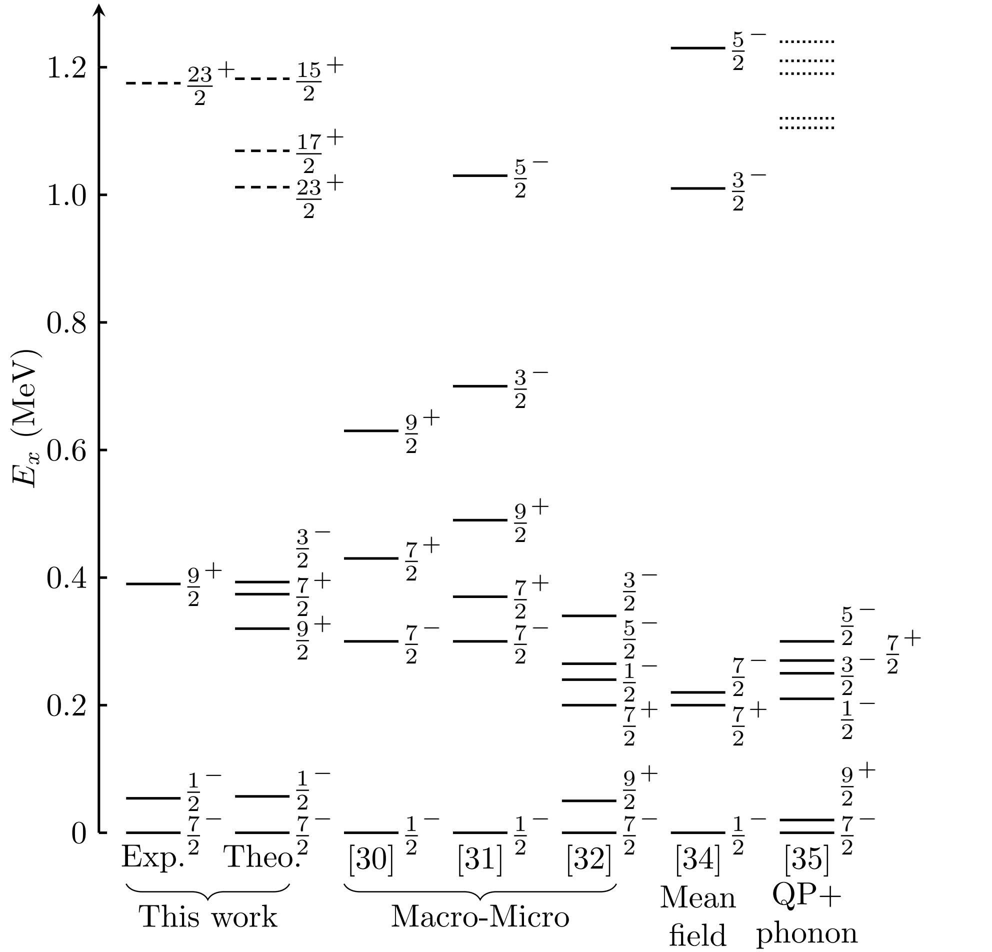
[514]7/2⁻ Band

C.Morse et al., submitted to PRC

Indirectly Testing Models of SHE



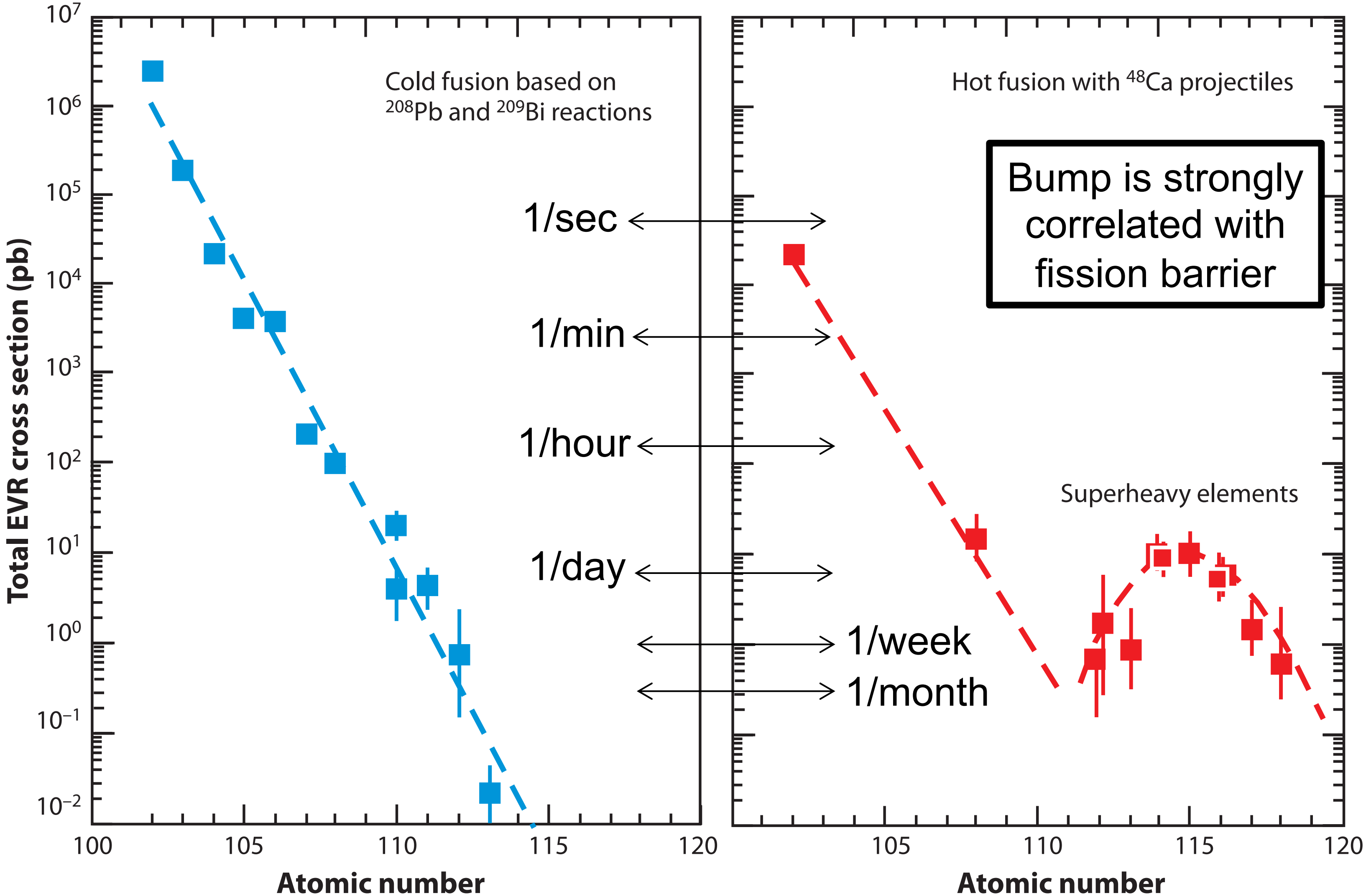
R. R. Chasman et al., Rev. Mod. Phys. 49 833 (1977)



[30] S.Ćwiok, S.Hofmann, W.Nazarewicz , Nucl. Phys. A 573 356 (1994).
[31] A.Parkhomenko and A.Sobiczewski, Acta Phys. Pol. B 35 2447 (2004).
[32] G.G.Adamian et al., Phys. Rev. C 82 054304 (2010).
[34] M.Bender, P.Bonche, T.Duguet, P.-H.Heenen, Nucl. Phys. A 723 354 (2003).
[35] N.Yu.Shirikova, A.V.Sushkov, R.V.Jolos, Phys. Rev. C 88 064319 (2013),

Directly Making the Heaviest Elements

Cross Sections

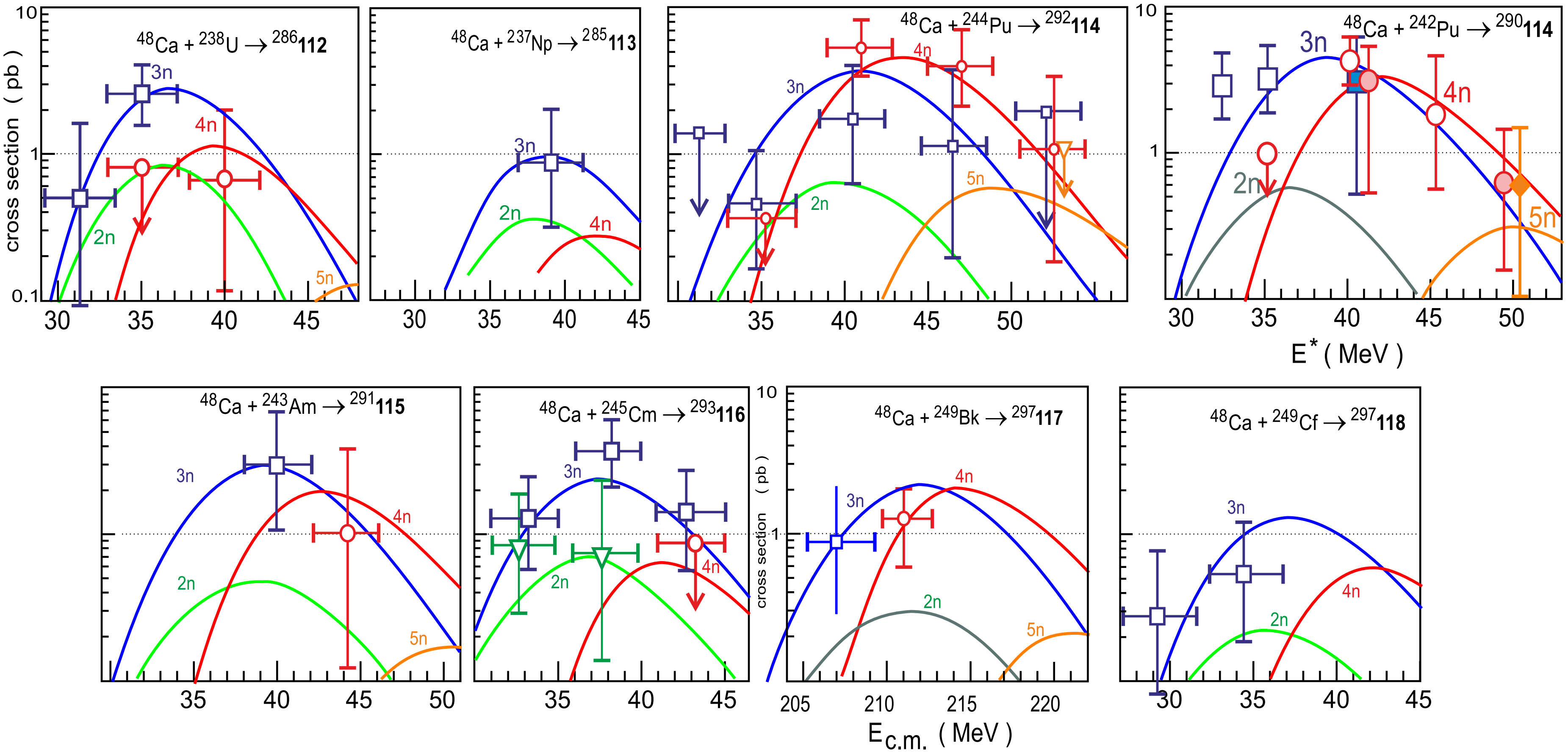


J.H.Hamilton, S. Hofmann, Y.T.Oganessian, Ann. Rev. Nucl. Part. Sci. 63 282 (2013).

Theory Reproducing Experiment

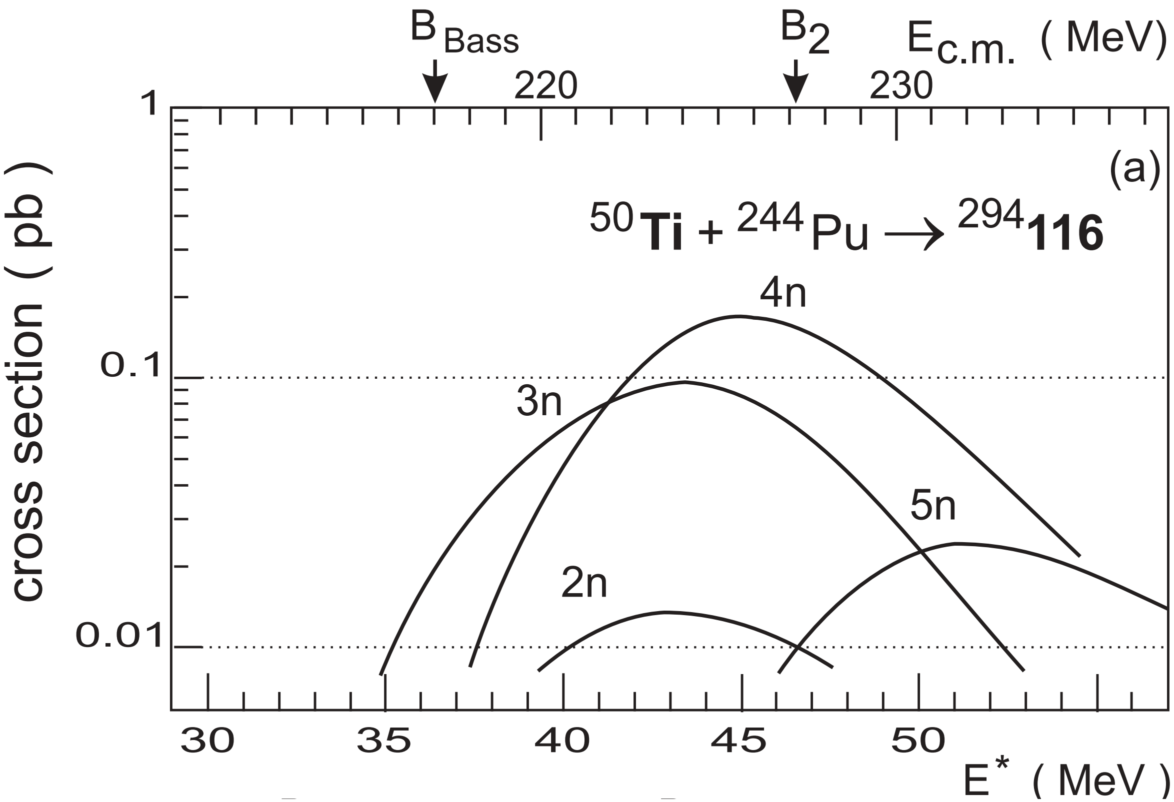
$\sigma_{SHN} = \sigma_{cap} \times P_{CN} \times P_{sur}$

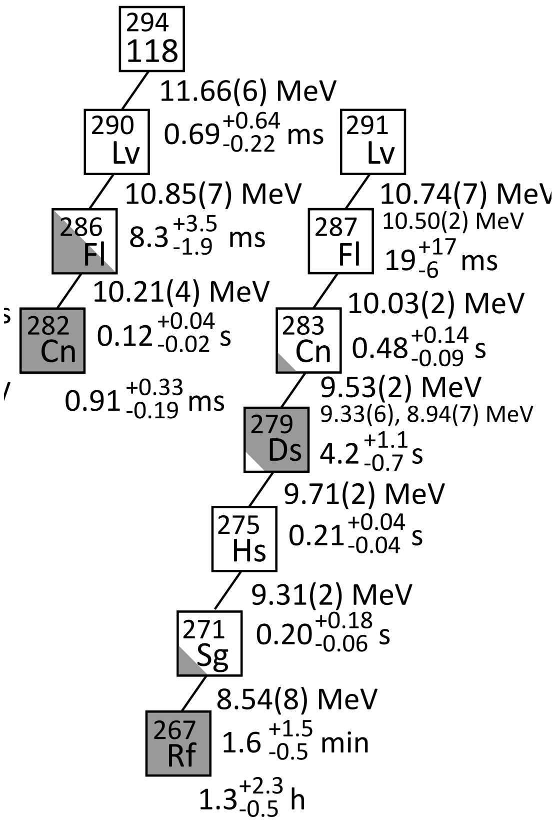
Some theories have been able to reproduce experimental cross-sections near "the bump" of SHE production. What will they say about the next elements?



V.I. Zagrabaev and W. Greiner, Nucl. Phys. A 944 257 (2015).

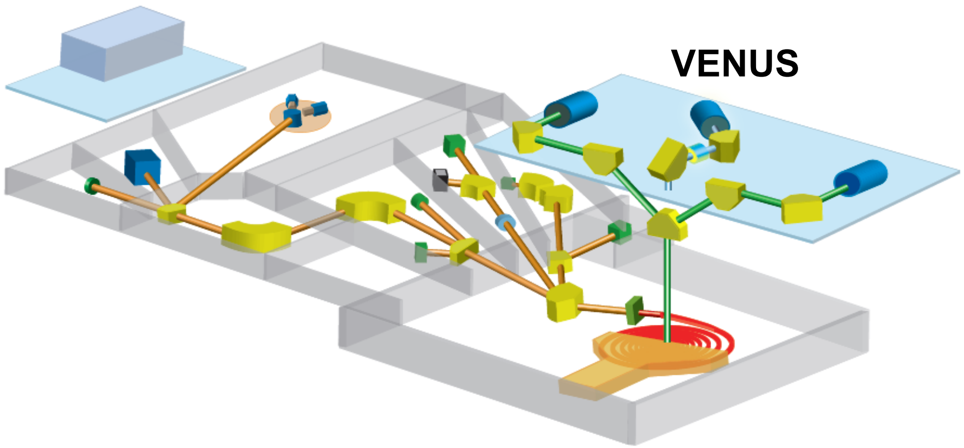
Testing the models for ^{50}Ti-induced reactions

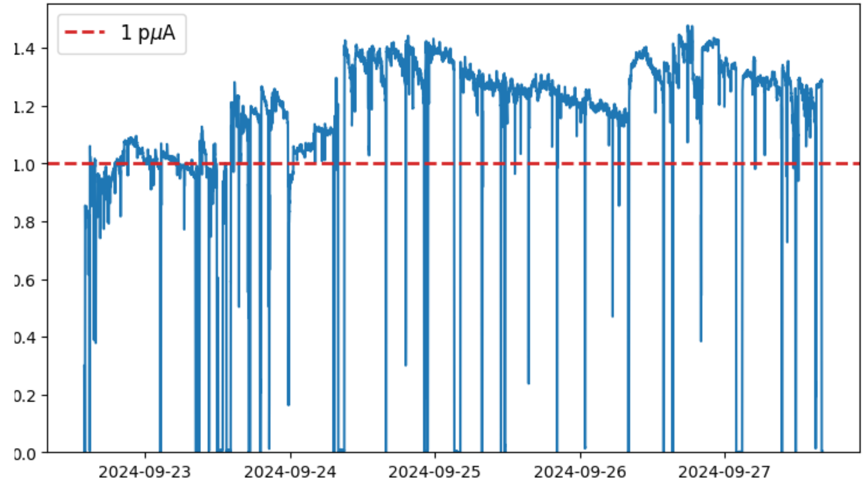




- Testing the calculations with a measurement of ^{50}Ti+^{244}Pu, which makes the known isotopes of ^{290,291}Lv.
- We could then try to make E120 with the ^{50}Ti+^{249}Cf reaction?!

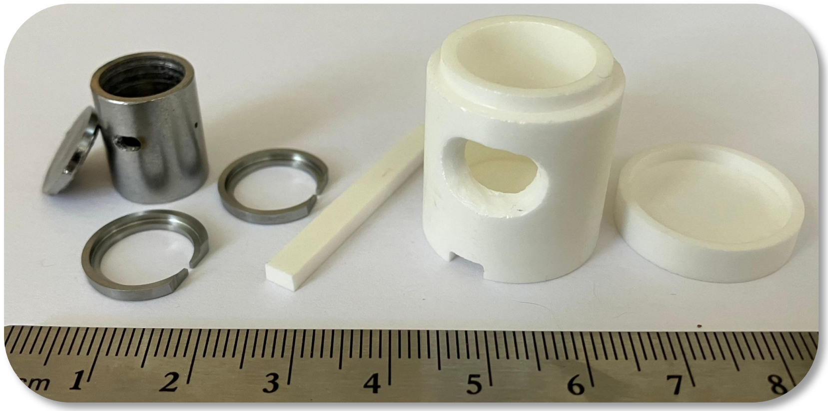
High-Intensity ^{50}Ti Beam at the 88-Inch Cyclotron

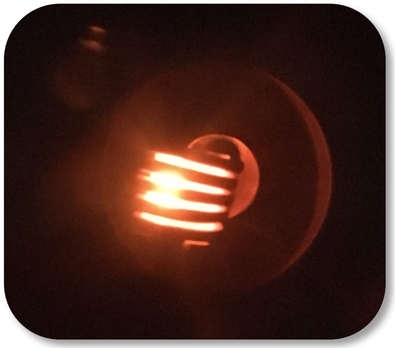




New high-temperature induction oven

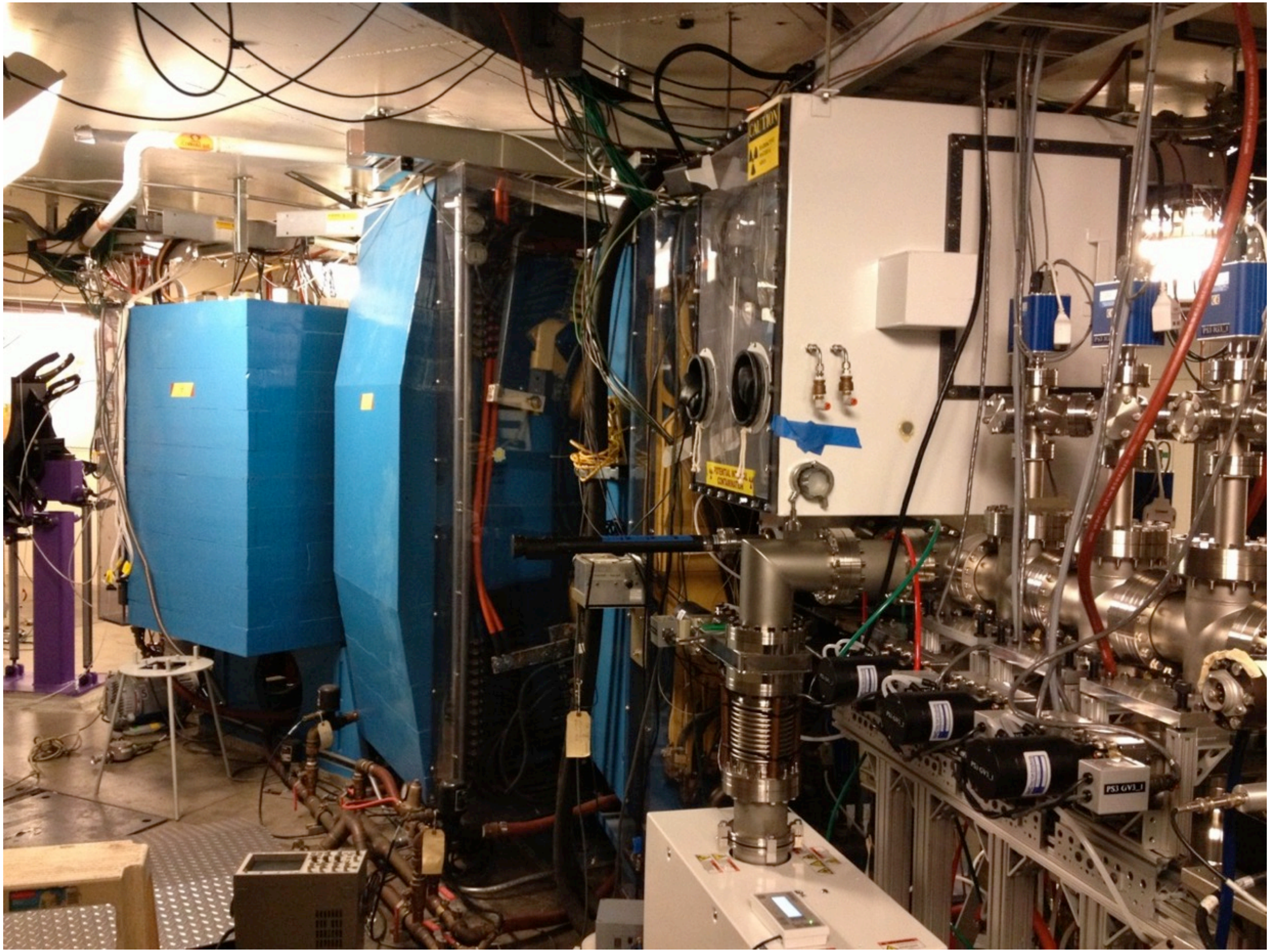
D. Todd et al





Current consumption rate ~2.6mg/hr. TiO2 oxide reduced to metal by Argonne NATIONAL LABORATORY

Berkeley Gas-filled Separator (BGS)



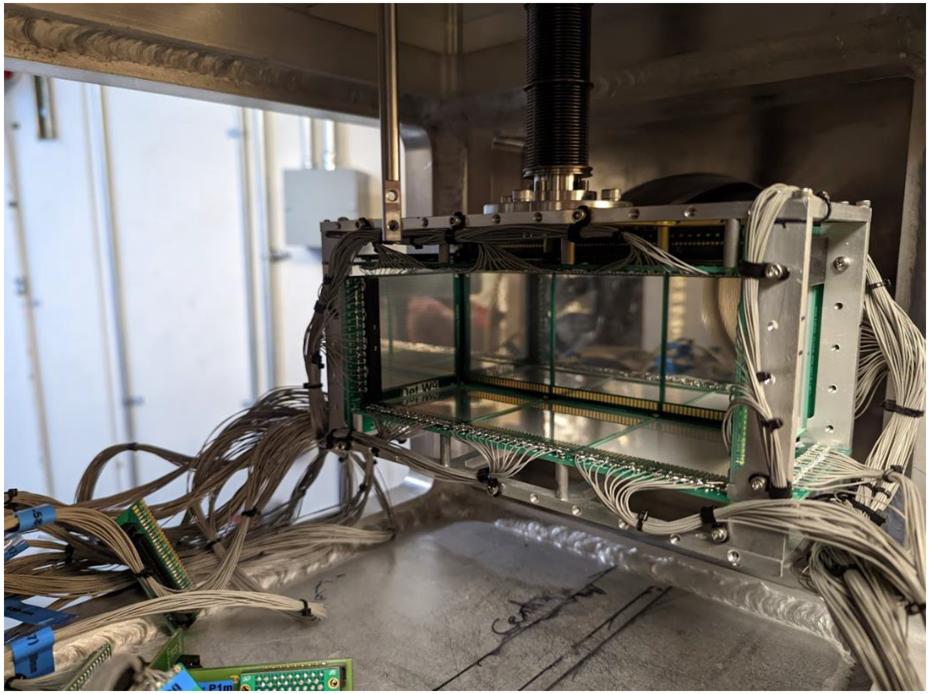
SuperHeavy RECoil (SHREC) Detector

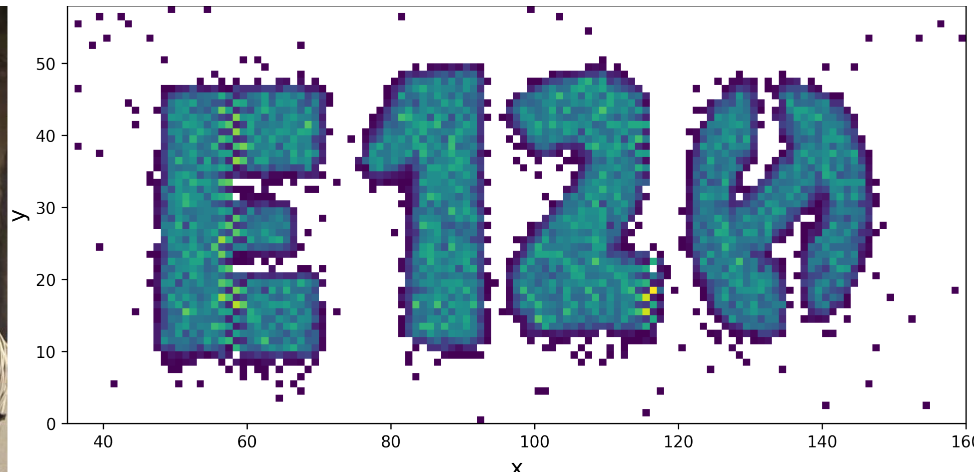
Source Characterization of a Detector for Heavy and Superheavy Nuclei

P. Golubev[a,*], R. Orford[b], F.H. Garcia[b,1], D. Rudolph[a,b], L.G. Sarmiento[a], R.M. Clark[b], J.M. Gates[b], J.A. Gooding[b,c], M. Grebo[b,c], Y. Hrabar[a], T.D. Kramasz[b], M. McCarthy[b,d], M.A. Mohamed[a], J.L. Pore[b], D.M. Cox[a]

[a]*Department of Physics, Lund University, SE-22100 Lund, Sweden*
[b]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States*
[c]*Department of Nuclear Engineering, University of California, Berkeley, CA 94720, United States*
[d]*Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States*

Submitted to NIMA





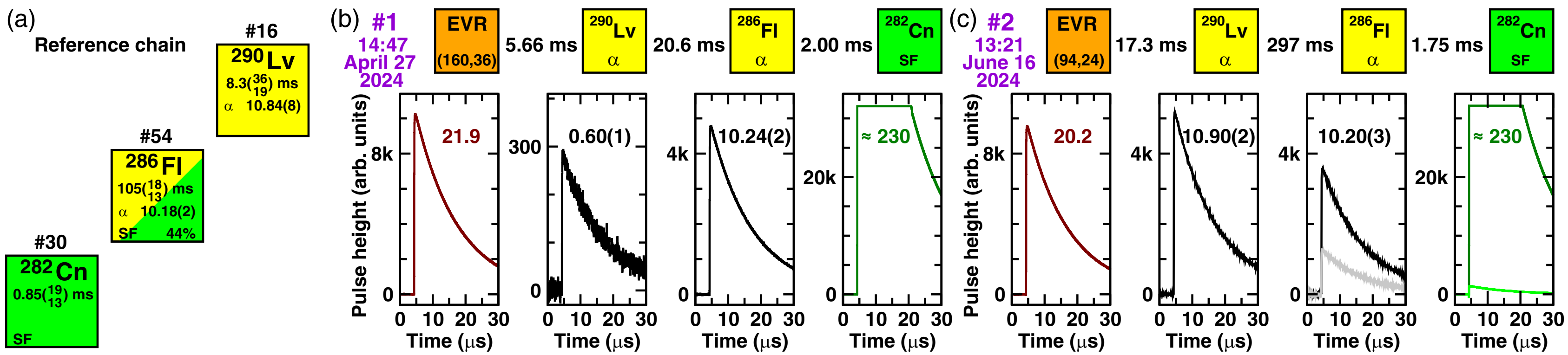
- 6 cm x 18 cm implantation detector surrounded by upstream tunnel and downstream veto detector.
- Commissioned using reactions:
  ^{208}Pb(^{48}Ca,2n)^{254}No
  ^{244}Pu(^{48}Ca,3-4n)$^{289\text{-}288}$Fl
  ^{209}Bi(^{50}Ti,xn)$^{259\text{-}x}$Db

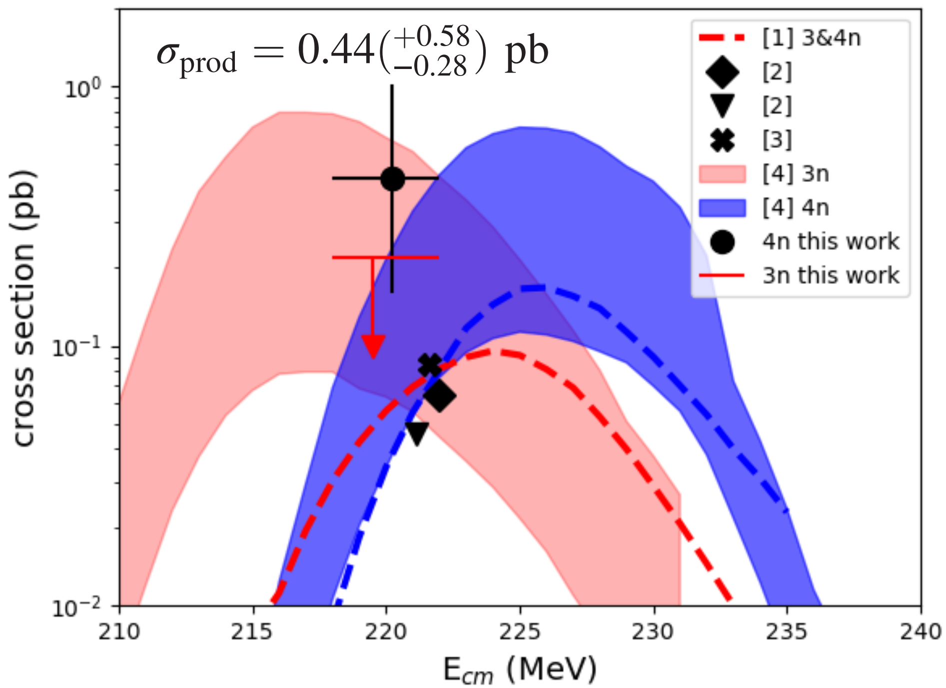
LUNDS UNIVERSITET

$^{244}Pu(^{50}Ti, xn)^{294-x}Lv$: Results

Two events during 22 days of beam on target!

J.M. Gates et al., PRL 133 172502 (2024).





What does this mean for E120?

- Comparison with ^{48}Ca-induced reactions on ^{244}Pu and ^{249}Cf suggests a ÷10 reduction in σ_{prod}
- $\sigma_{prod} \approx$ 40 fb
- One event every ≈200 days of beam-on-target

[1] Zagrabaev et al., PRC **78**, 034601 (2008)
[2] Kuzima et al., PRC **85**, 014319 (2012)
[3] Adamian et al., PRC **101**, 034301 (2020)
[4] T. Cap, private communication

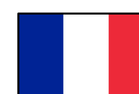
~Status for New Element Experiments

Other Experiments Testing Cross Sections

Dubna	Russia	$^{54}Cr + ^{238}U \rightarrow ^{292}Lv^*$	Events seen
Dubna	Russia	$^{50}Ti + ^{242}Pu \rightarrow ^{292}Lv^*$	Events seen

Ongoing/Planned Experiments for New Element Discovery

RIKEN	Japan	$^{51}V + ^{248}Cm \rightarrow ^{299}119^*$	Nothing seen $\sigma \leq$ few fb
IMP	China	$^{54}Cr + ^{243}Am \rightarrow ^{297}119^*$	Nothing seen >150 days
Dubna	Russia	$^{54}Cr + ^{248}Cm \rightarrow ^{302}120^*$	Yet to start
Berkeley	USA	$^{50}Ti + ^{249}Cf \rightarrow ^{299}120^*$	Yet to start
GSI	Germany	?	?
Ganil	France	?	?



Acknowledgements

Isomer decay spectroscopy of ^{251}Md

C. Morse,[1,2] R.M. Clark,[2] D. Seweryniak,[3] C.J. Appleton,[2] C.M. Campbell,[2] M.P. Carpenter,[3] P. Chowdhury,[4] H.L. Crawford,[2] M. Cromaz,[2] P. Fallon,[2] Z. Favier,[5] T. Huang,[3,6] F.G. Kondev,[3] A. Korichi,[7] T. Lauritsen,[3] D.H. Potterveld,[3] W. Reviol,[3] D. Rudolph,[8] C. Santamaria,[2] G. Savard,[3] G.L. Wilson,[9] and S. Zhu[1,3,*]

[1]*National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3]*Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4]*Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, MA 01854, USA*
[5]*Physics Department, CERN, 1211 Geneva 23, Switzerland*
[6]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[7]*IJCLab, Laboratoire de Physique des 2 Infinis Irène Joliot-Curie, Orsay IN2P3/CNRS France*
[8]*Department of Physics, Lund University, SE-22100 Lund, Sweden*
[9]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803*

PHYSICAL REVIEW LETTERS **133,** 172502 (2024)

Editors' Suggestion | Featured in Physics

Toward the Discovery of New Elements: Production of Livermorium ($Z = 116$) with ^{50}Ti

J. M. Gates,[1,*] R. Orford,[1] D. Rudolph,[2,1] C. Appleton,[1] B. M. Barrios,[3] J. Y. Benitez,[1] M. Bordeau,[4] W. Botha,[3] C. M. Campbell,[1] J. Chadderton,[5] A. T. Chemey,[6] R. M. Clark,[1] H. L. Crawford,[1] J. D. Despotopulos,[7] O. Dorvaux,[4] N. E. Esker,[3] P. Fallon,[1] C. M. Folden III,[8,9] B. J. P. Gall,[4] F. H. Garcia,[1,†] P. Golubev,[2,1] J. A. Gooding,[1,10] M. Grebo,[1,10] K. E. Gregorich,[7] M. Guerrero,[3] R. A. Henderson,[7] R.-D. Herzberg,[5] Y. Hrabar,[2] T. T. King,[11] M. Kireeff Covo,[1] A. S. Kirkland,[8,9] R. Krücken,[1] E. Leistenschneider,[1] E. M. Lykiardopoulou,[1] M. McCarthy,[1,10] J. A. Mildon,[8,9] C. Müller-Gatermann,[12] L. Phair,[1] J. L. Pore,[1] E. Rice,[1,10] K. P. Rykaczewski,[11] B. N. Sammis,[7] L. G. Sarmiento,[2] D. Seweryniak,[12] D. K. Sharp,[13] A. Sinjari,[1,10] P. Steinegger,[14,15] M. A. Stoyer,[7,1] J. M. Szornel,[1] K. Thomas,[7] D. S. Todd,[1] P. Vo,[3] V. Watson,[1] and P. T. Wooddy[7]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, Lund University, 22100 Lund, Sweden*
[3]*San Jose State University, San Jose, California 95192, USA*
[4]*Université de Strasbourg, CNRS, IPHC UMR 7178, 67037 Strasbourg, France*
[5]*University of Liverpool, Liverpool, United Kingdom*
[6]*Oregon State University, Corvallis, Oregon 97331, USA*
[7]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[8]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[9]*Department of Chemistry, Texas A&M University, College Station, Texas 77843, USA*
[10]*University of California, Berkeley, California 94720, USA*
[11]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[12]*Argonne National Laboratory, Lemont, Illinois 60439, USA*
[13]*University of Manchester, Manchester, United Kingdom*
[14]*Department of Chemistry and Applied Biosciences, ETH Zürich, Zurich, Switzerland*
[15]*Nuclear Energy and Safety Division, Paul Scherrer Institute, Villigen PSI, Switzerland*

Thanks !