

The Heaviest Elements: Latest Results from Berkeley

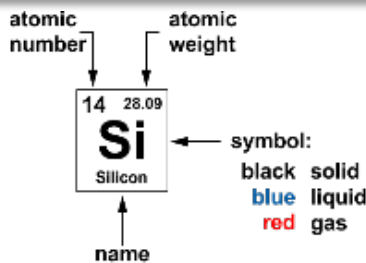
Rod Clark

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

1 1.01 H Hydrogen																	2 4.003 He Helium		
3 6.94 Li Lithium	4 9.01 Be Beryllium																	10 20.18 Ne Neon	
11 22.99 Na Sodium	12 24.31 Mg Magnesium																	18 39.95 Ar Argon	
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton		
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon		
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon		
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac Actinium	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (268) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium				112 (277) Cn Copernicium	113 (278) Nh Nihonium	114 (288) Fl Flerovium			115 (288) Mc Moscovium	116 (292) Lv Livermorium	117 (293) Ts Tennessine	118 (294) Og Oganesson
(119)	(120)	(121)	(122)	(123)	(124)	(125)	(126)	(127)	(128)	(129)	(130)	(131)	(132)	(133)	(134)	(135)	(136)	(137)	(138)



- alkali metals
- alkaline earth metals
- transitional metals
- other metals
- non metals
- noble gases

Lanthanides →

58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.40 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
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Actinides →

90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 237.05 Np Neptunium	94 (244) Pu Plutonium	95 (243) Am Americium	96 (247) Cm Curium	97 (247) Bk Berkelium	98 (251) Cf Californium	99 (252) Es Einsteinium	100 (257) Fm Fermium	101 (260) Md Mendelevium	102 (259) No Nobelium	103 (262) Lr Lawrencium
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Superactinides → (122-153)

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?

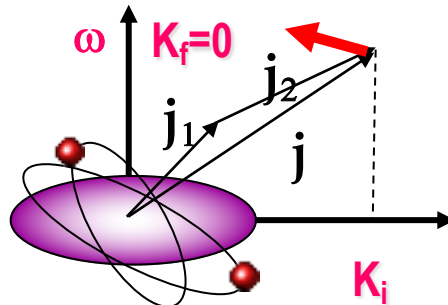
What shapes (high order?), topologies (bubbles?), structures (isomerism?)
can the nucleus display?

How does a nucleus decay and what are the timescales?

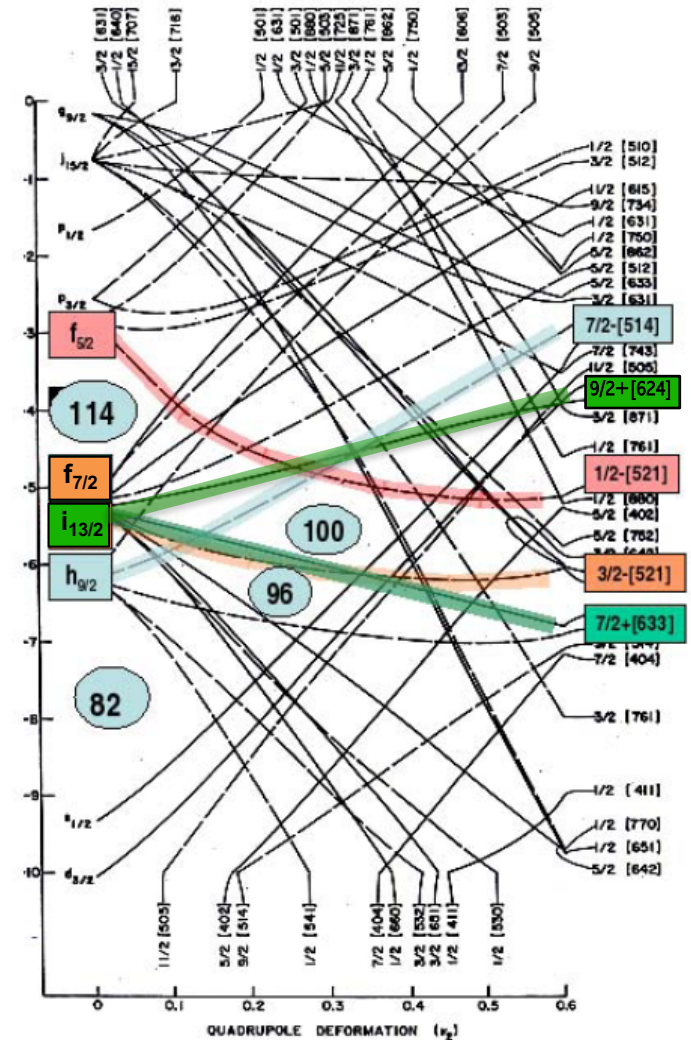
Structure of Deformed Trans-fermium Nuclei

Shapes and Shells

- Single-particle levels \rightarrow 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

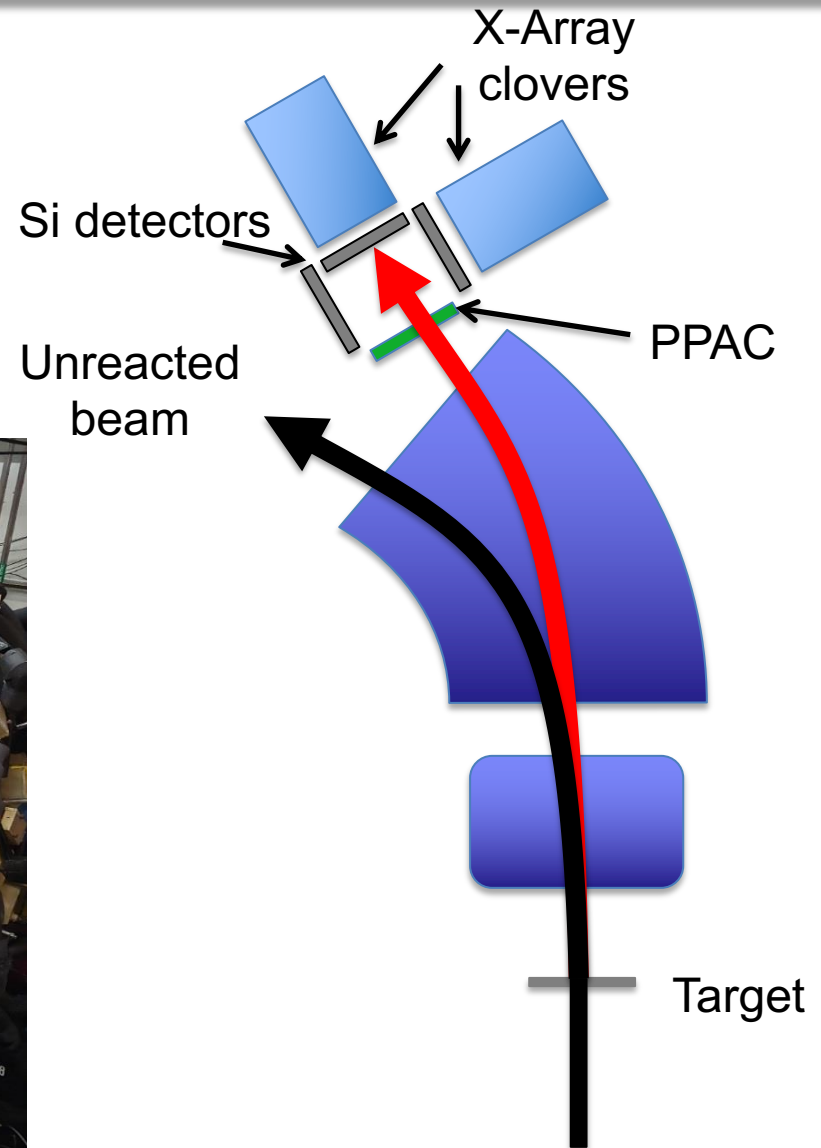
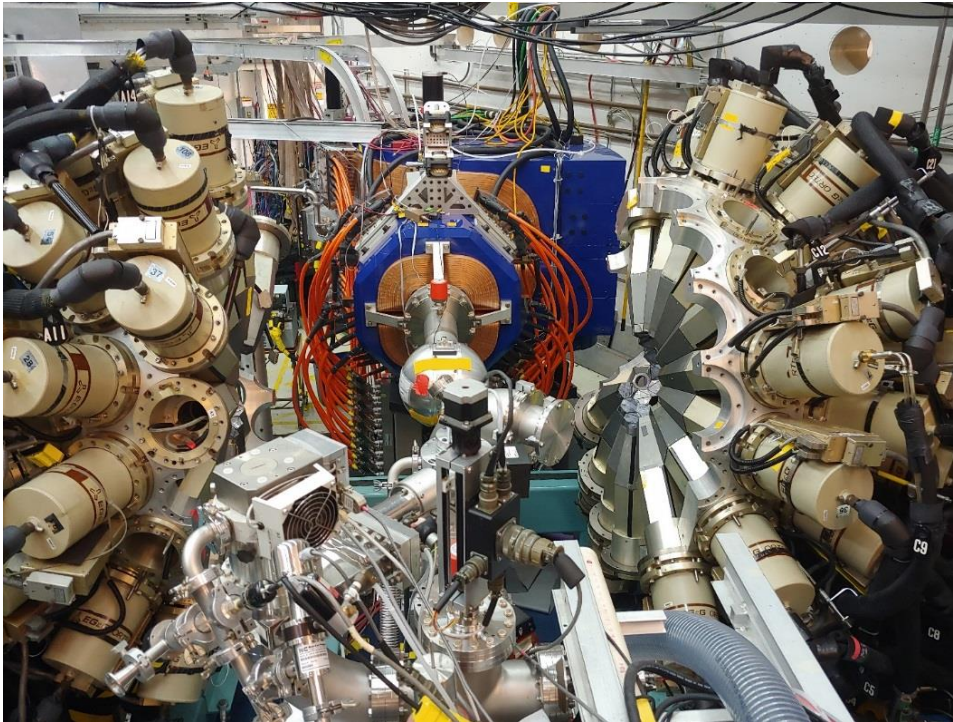


R. R. Chasman et al.,
Rev. Mod. Phys. 49 833 (1977)

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)

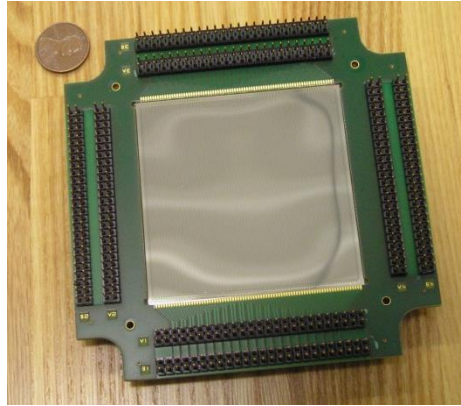


Isomer Spectroscopy

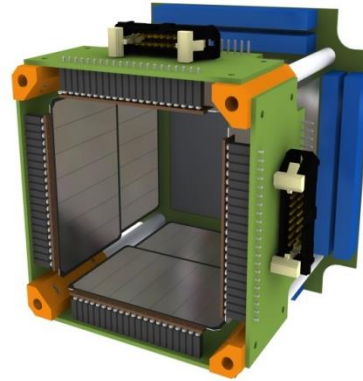


Digital DAQ

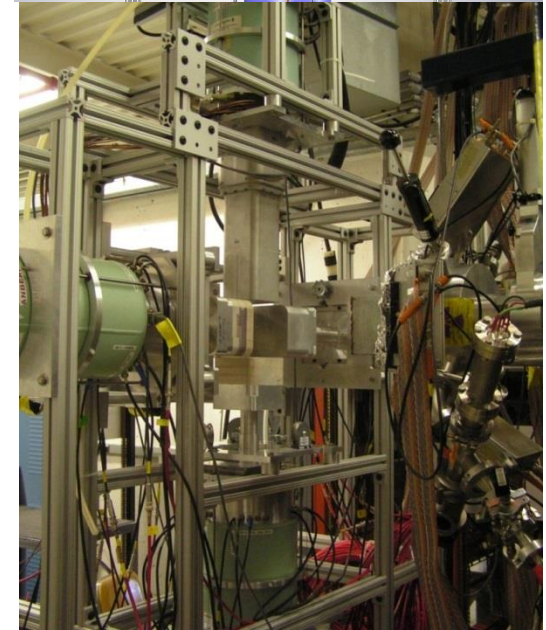
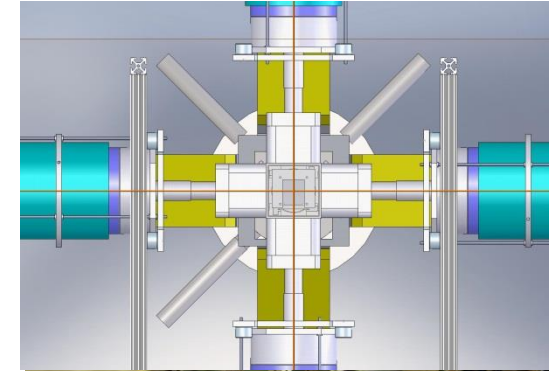
Stolen shamelessly from
Darek Seweryniak



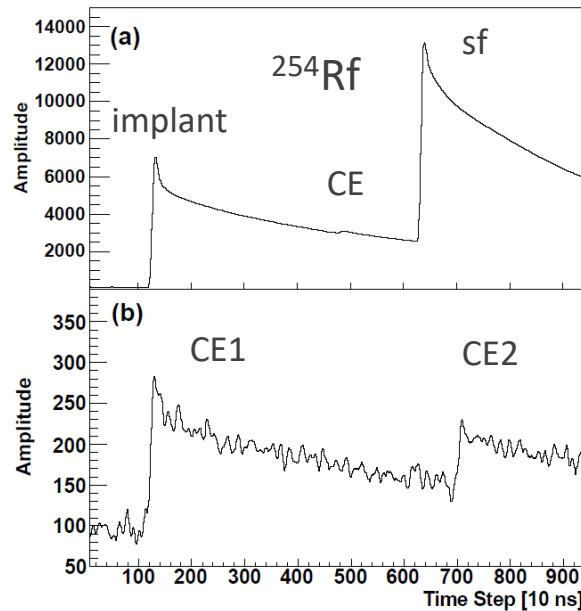
160X160, 64mmX64mm
DSSD



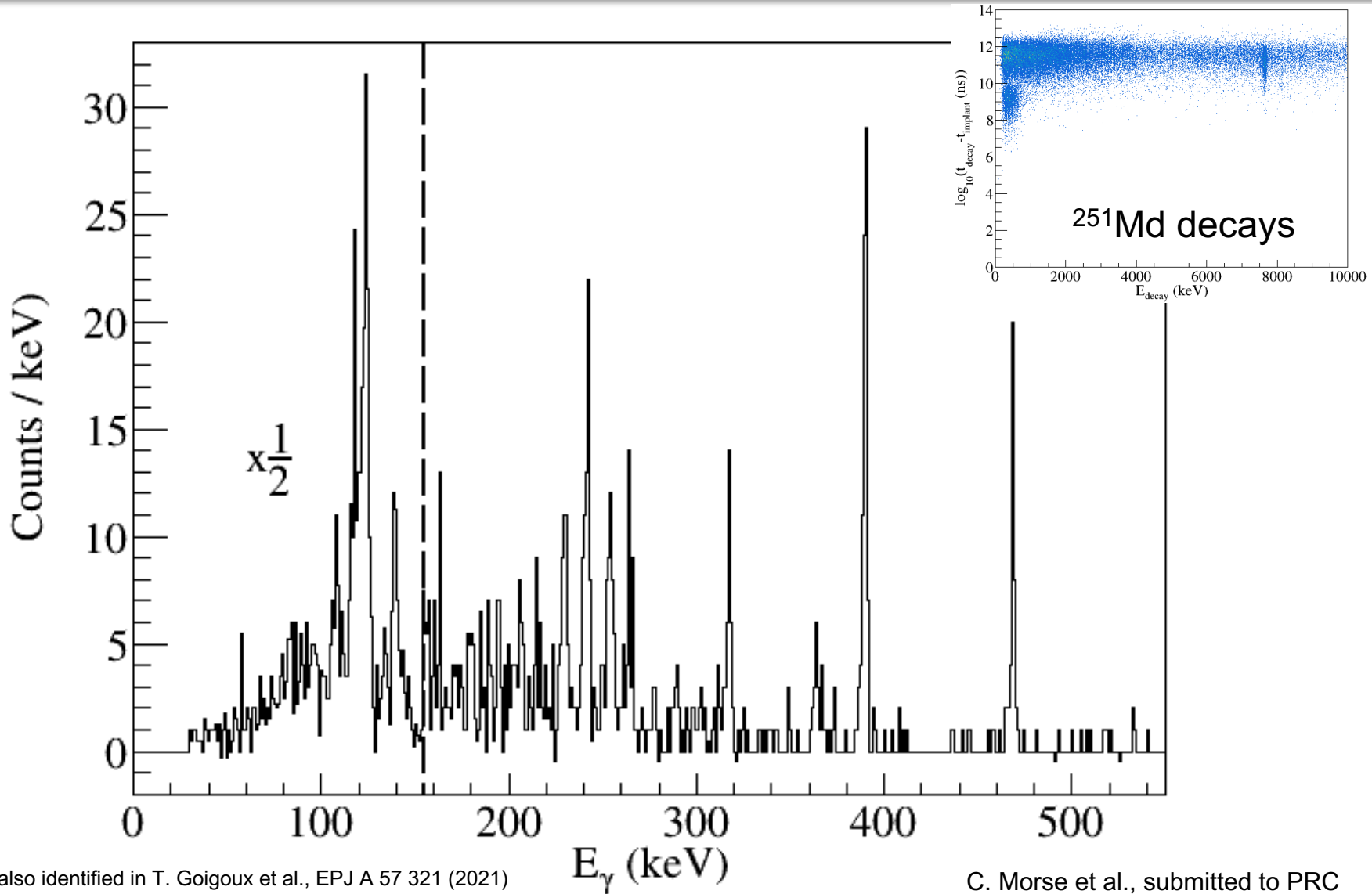
Si tunnel
8 SSSD's



X-Array, 5 clovers
in box geometry



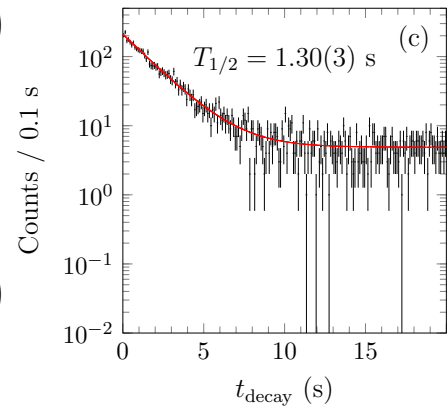
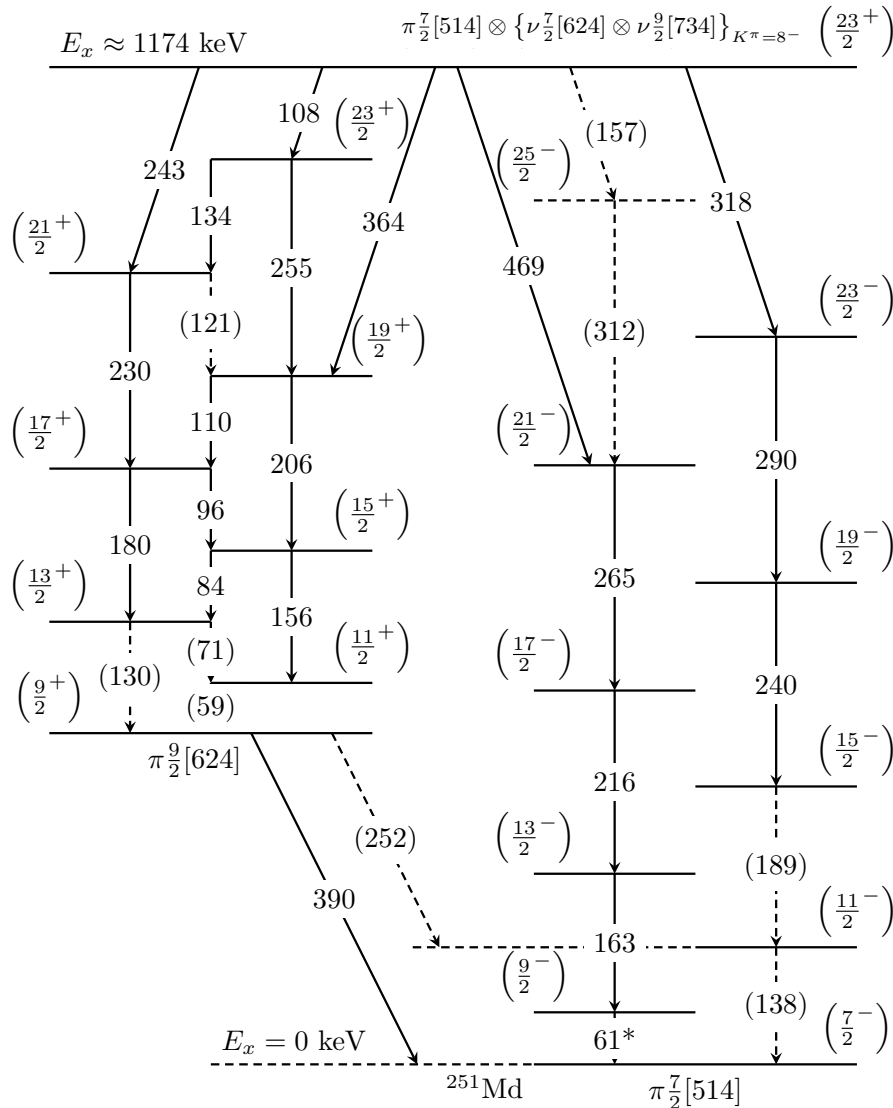
The Case of ^{251}Md



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

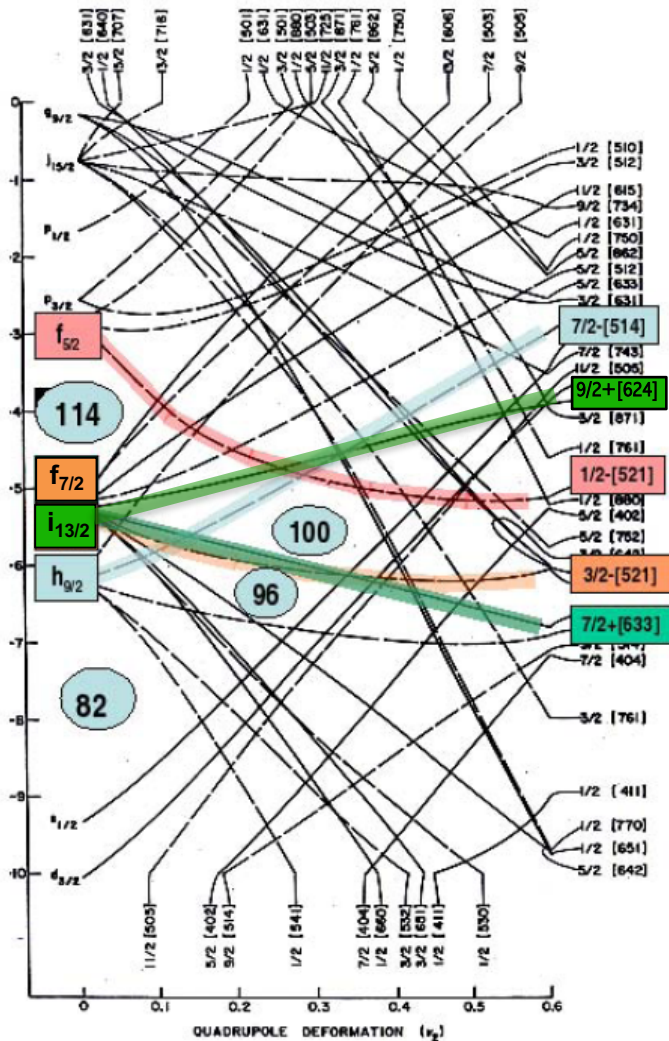


[624]9/2⁺
Band

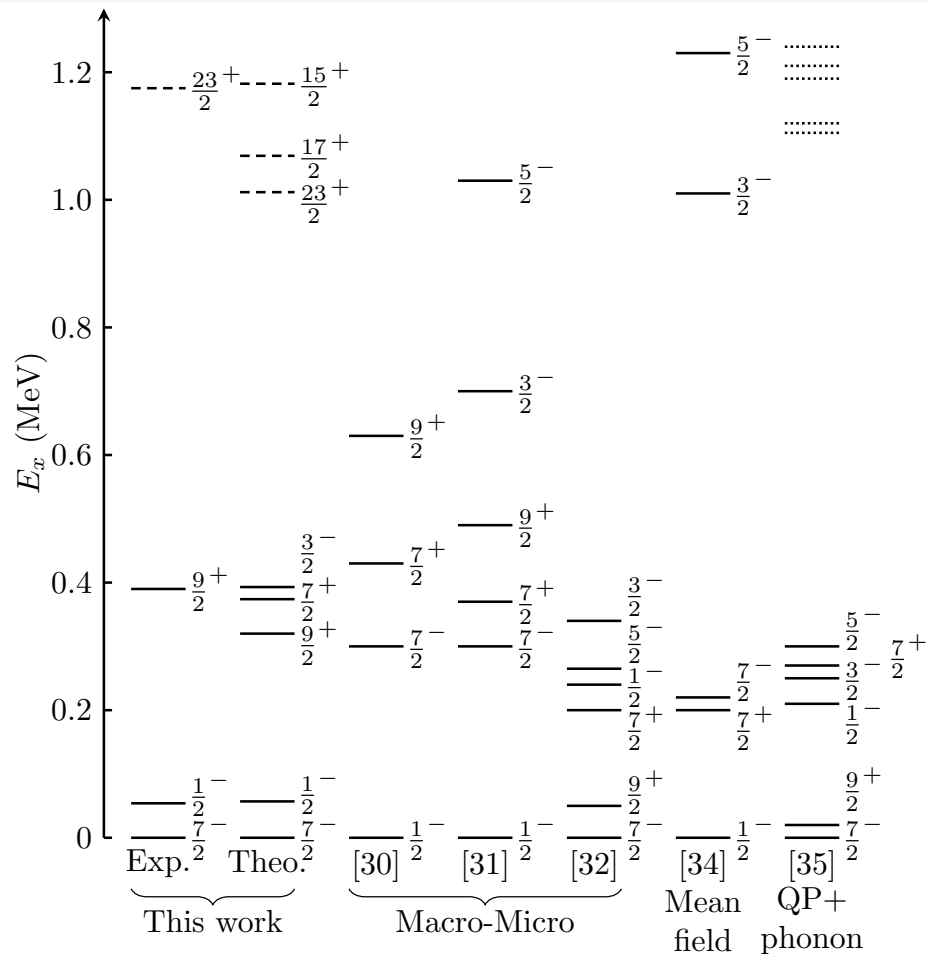
[514]7/2⁻
Band

C.Morse et al., submitted to PRC

Indirectly Testing Models of SHE



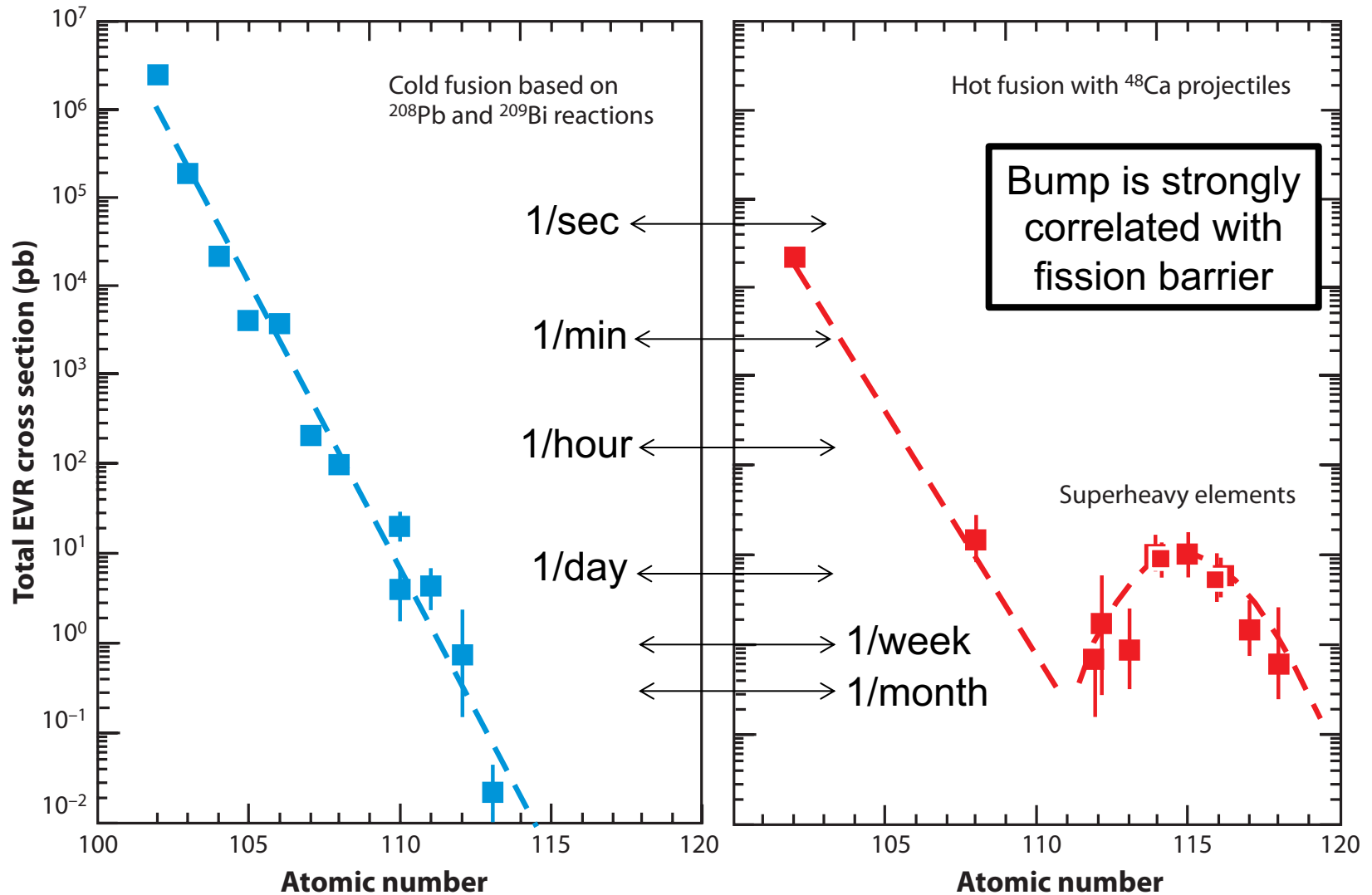
R. R. Chasman et al., Rev. Mod. Phys. 49 833 (1977)



[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

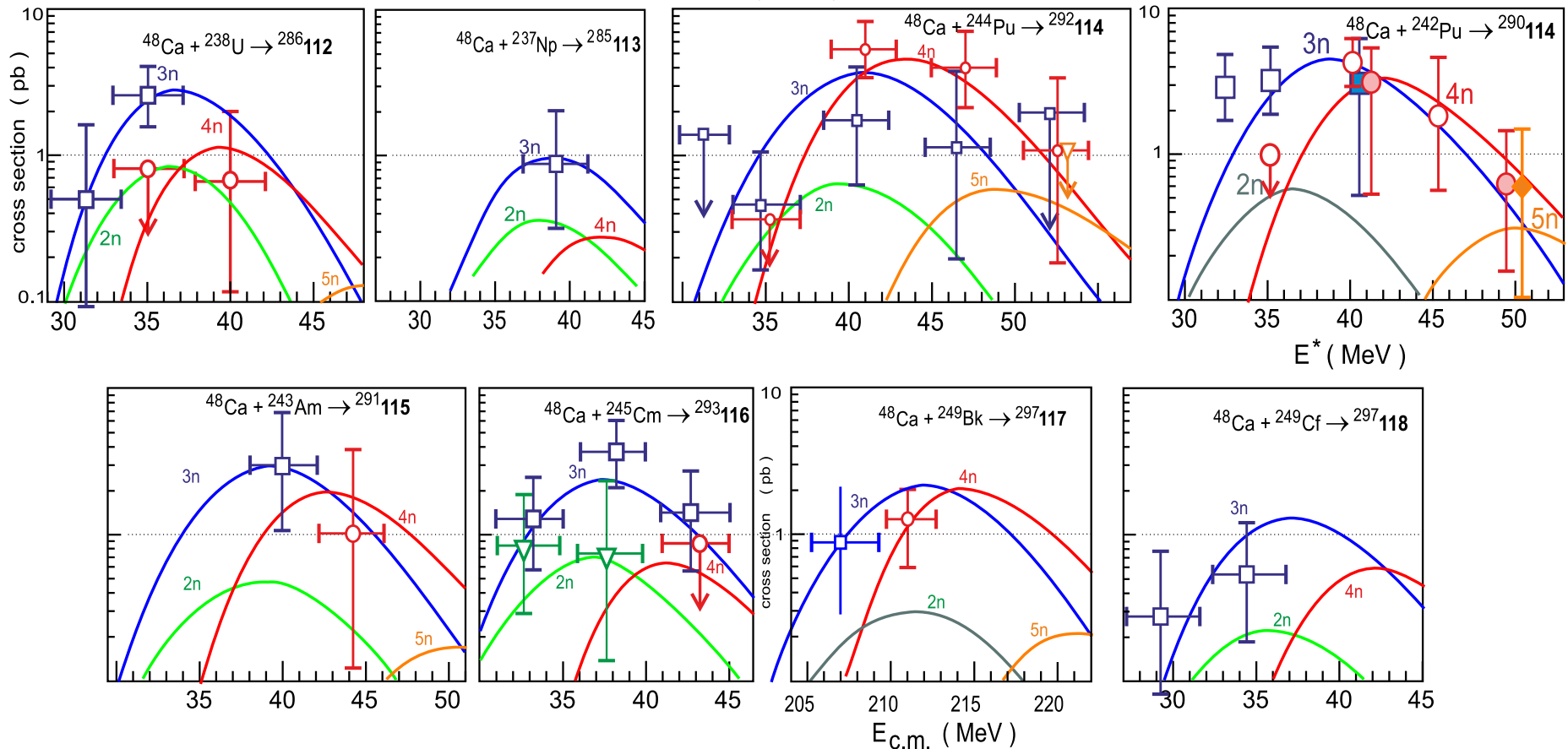


J.H.Hamilton, S. Hofmann, Y.T.Oganessian, Ann. Rev. Nucl. Part. Sci. 63 282 (2013).

Theory Reproducing Experiment

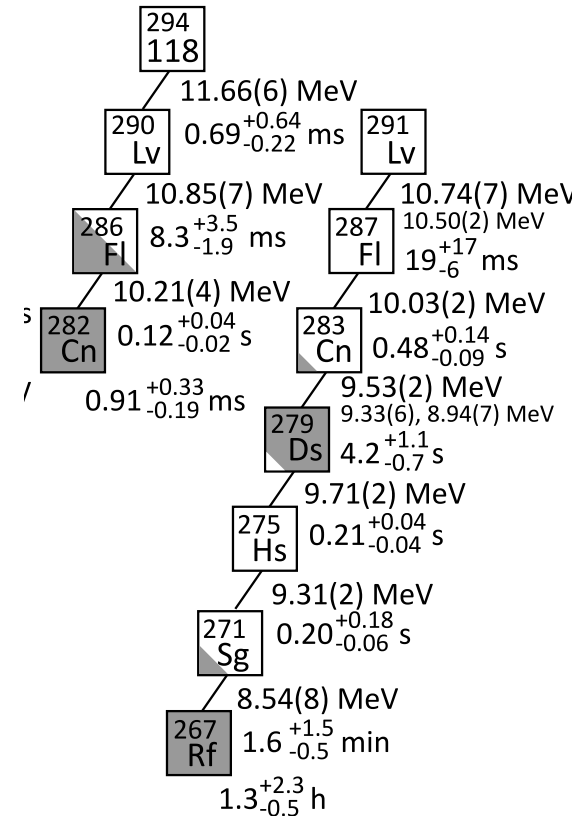
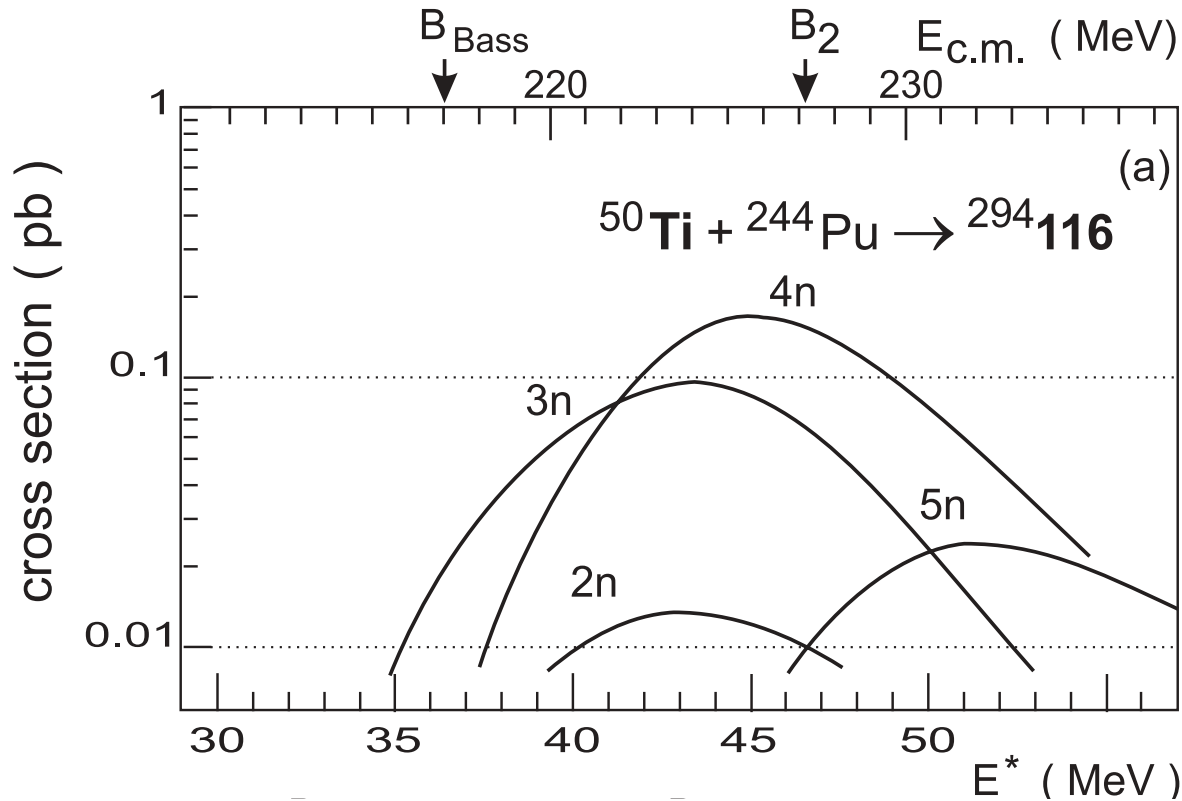
$$\sigma_{\text{SHN}} = \sigma_{\text{cap}} \times P_{\text{CN}} \times P_{\text{sur}}$$

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



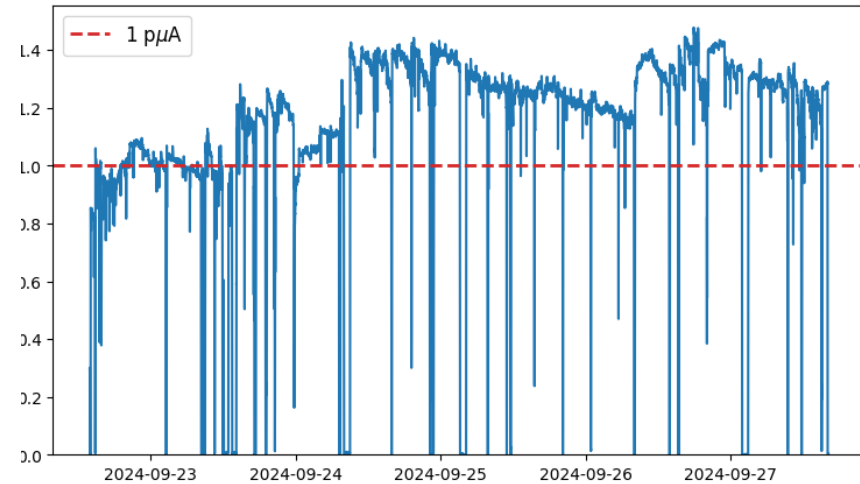
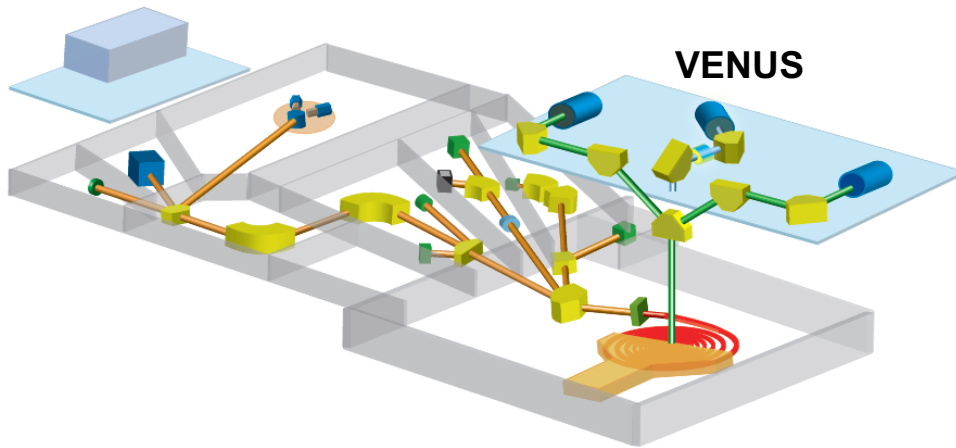
V.I. Zagrebaev and W. Greiner, Nucl. Phys. A 944 257 (2015).

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



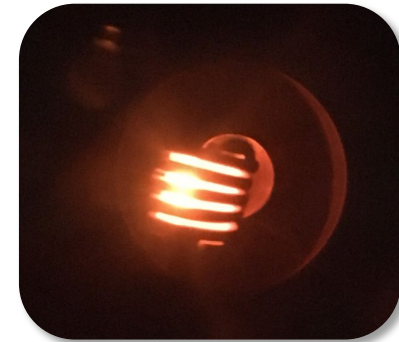
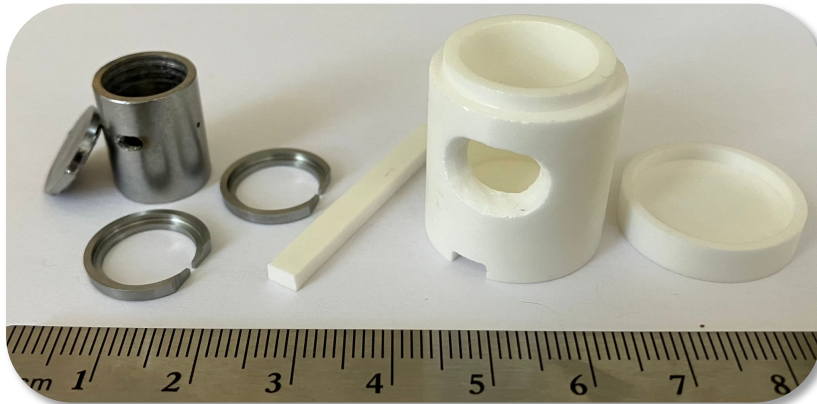
- Testing the calculations with a measurement of $^{50}\text{Ti}+^{244}\text{Pu}$, which makes the known isotopes of $^{290,291}\text{Lv}$.
- We could then try to make E120 with the $^{50}\text{Ti}+^{249}\text{Cf}$ reaction?!


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



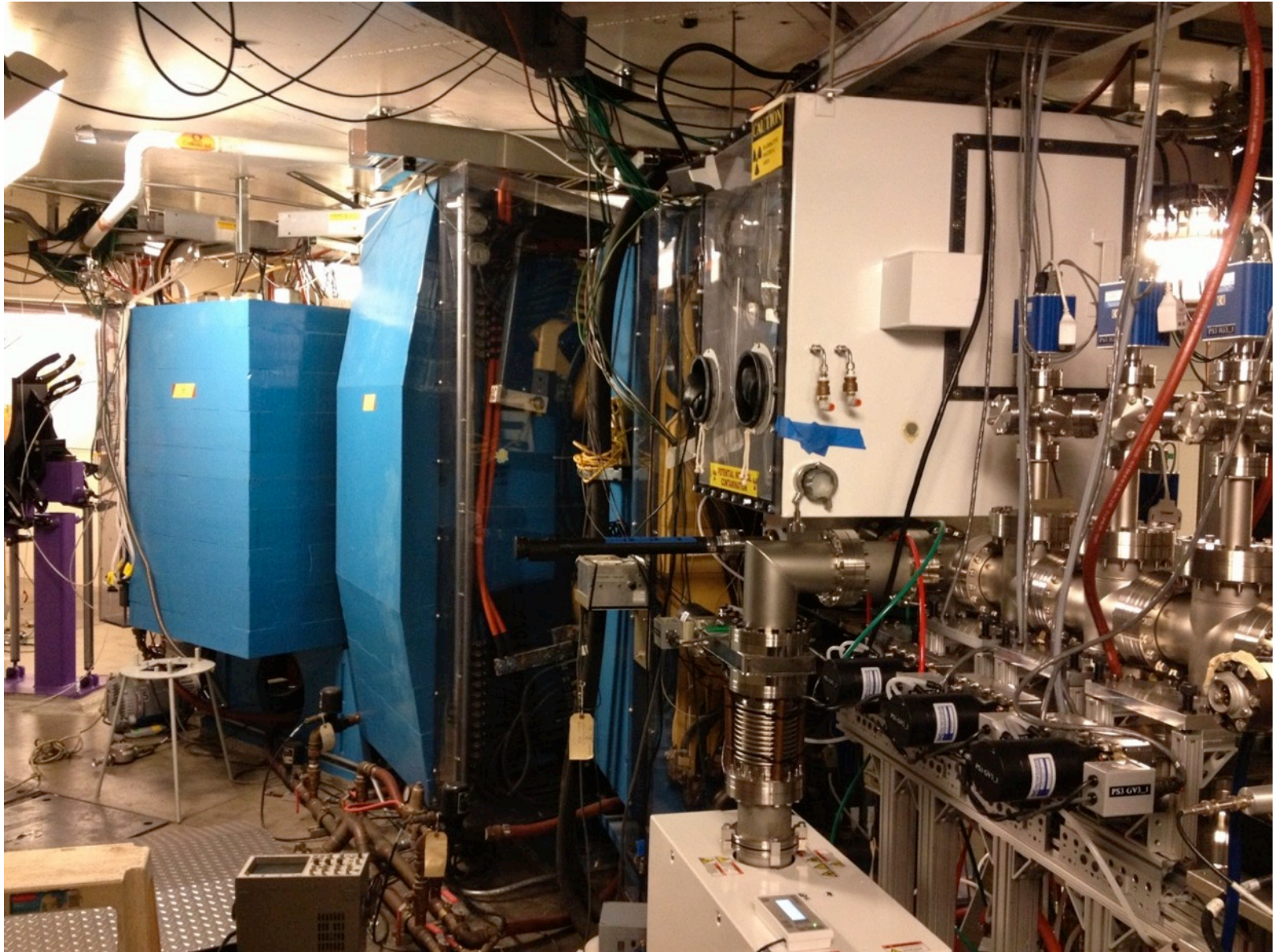
New high-temperature induction oven

D. Todd et al



Current consumption rate $\sim 2.6\text{mg/hr}$. TiO_2 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

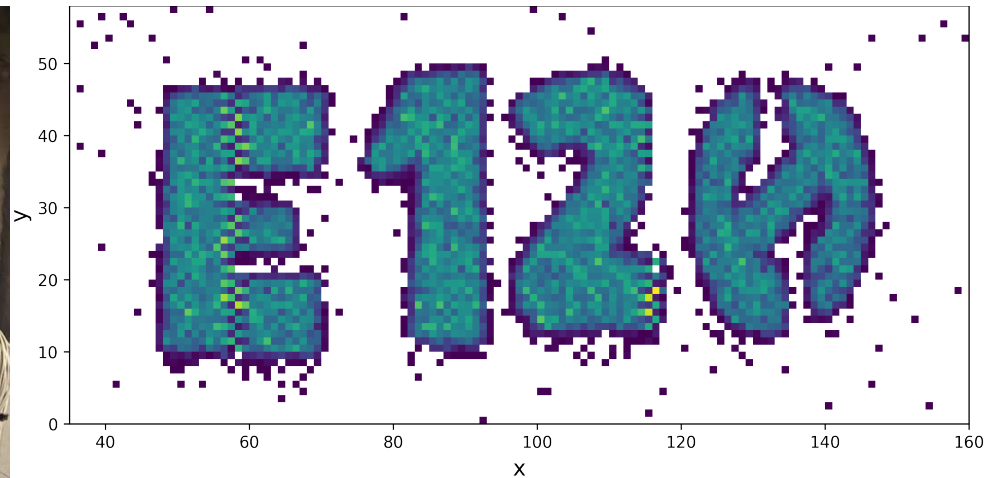
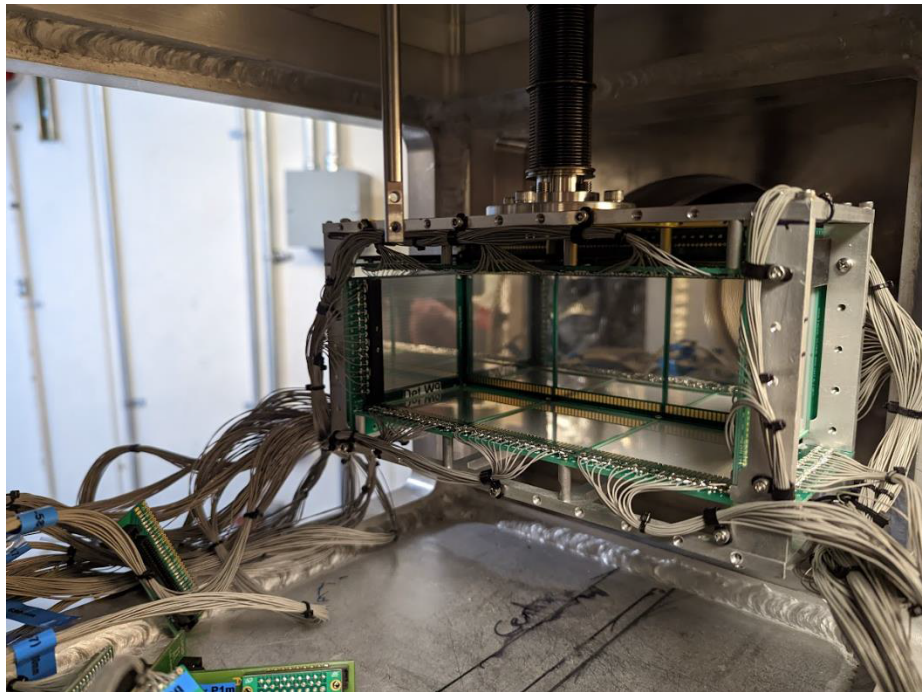
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Submitted to NIMA



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

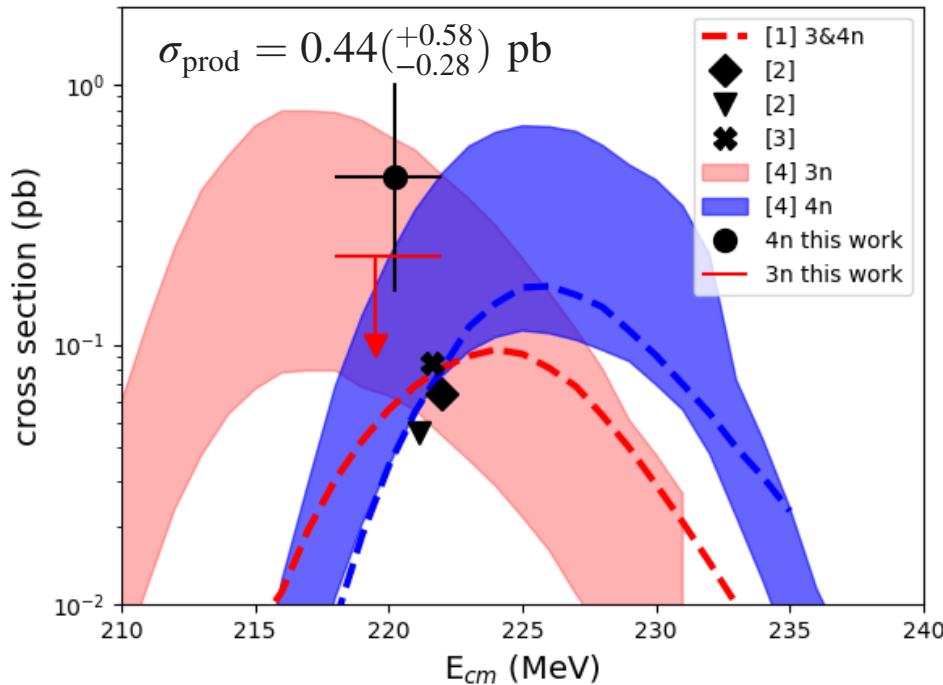
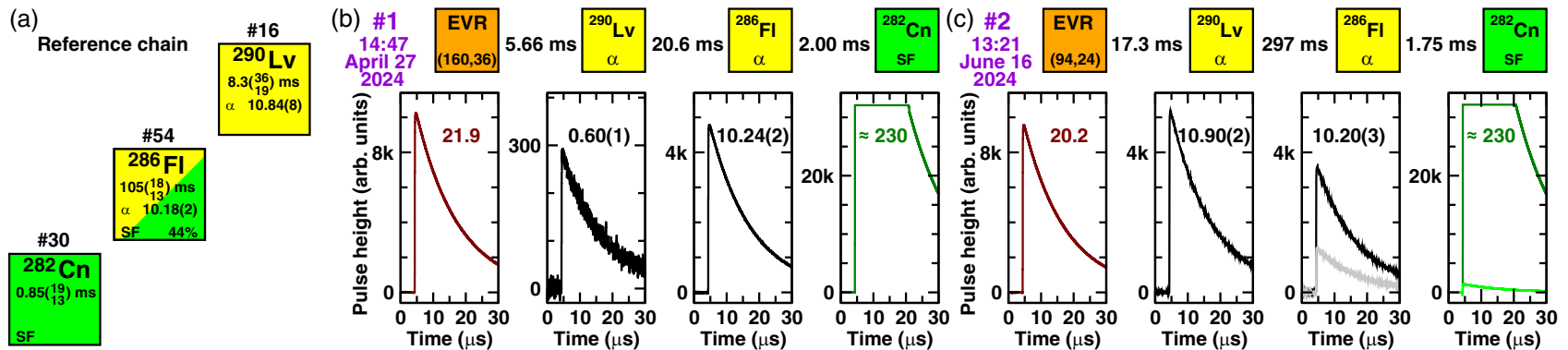


LUNDS
UNIVERSITET

$^{244}\text{Pu}(^{50}\text{Ti}, xn)^{294-x}\text{Lv}$: 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}
- ◆ $\sigma_{\text{prod}} \approx 40 \text{ fb}$
- ◆ One event every ≈ 200 days of beam-on-target

- [1] Zagraev 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	$^{54}\text{Cr} + ^{238}\text{U} \rightarrow ^{292}\text{Lv}^*$	Events seen
Dubna	Russia	$^{50}\text{Ti} + ^{242}\text{Pu} \rightarrow ^{292}\text{Lv}^*$	Events seen

Ongoing/Planned Experiments for New Element Discovery

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

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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

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Thanks !