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Update on Atomic Mass Evaluation & NUBASE

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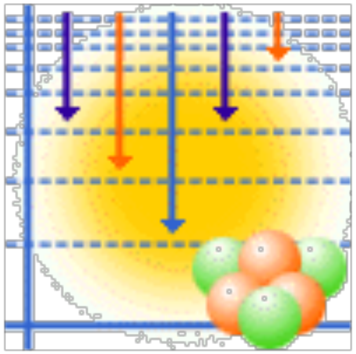
Physics Division, Argonne National Laboratory

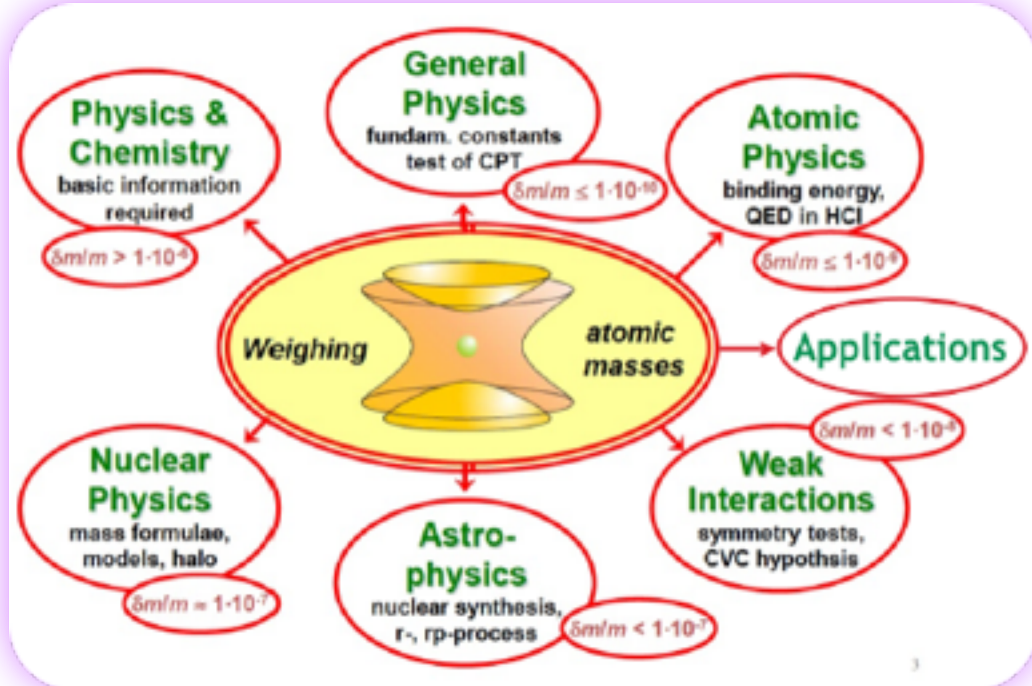


Supported by the Office of Nuclear Physics, Office of Science, DOE

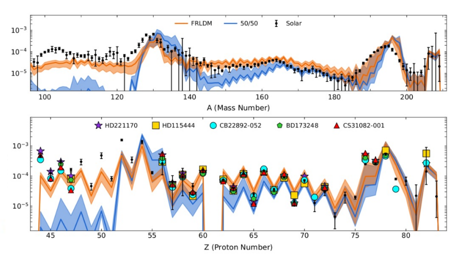
U.S. DEPARTMENT OF ENERGY | Office of Science

Atomic Mass Evaluation & NuBase

- Correlations
  - pairing
  - p-n
- Binding energies
  - mass models
  - shell structure
- The limits of existence
  - drip lines
  - specific configurations and topologies
- Reaction & decay phase space
  - Q values
  - decay & reaction probabilities
    - ➡ critical to both ENSDF & ENDF

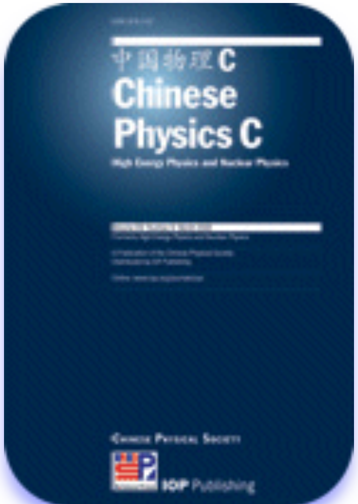


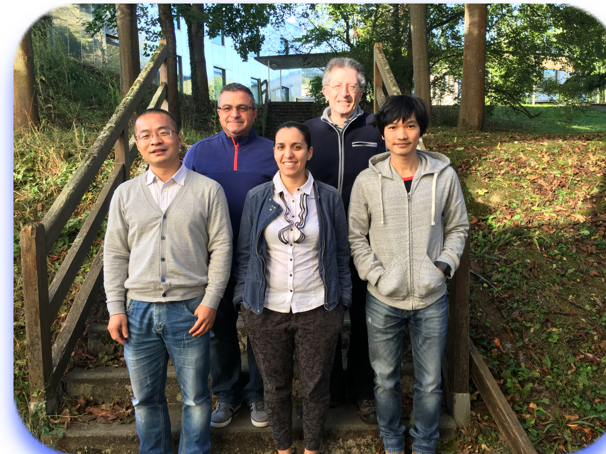
Fission In R-process Elements



- **widely used in astrophysics modeling**
- **important to applications** - nuclear energy, stockpile stewardship, nuclear material certification & others
- **beneficial** to Nuclear Theory development

AME2016 & NUBASE2016





Chinese Physics C Vol. 41, No. 3 (2017) 030003

The AME2016 atomic mass evaluation *

Meng Wang (王猛)[1,2;1)] G. Audi (欧乔治)[3] F.G. Kondev[4] W.J. Huang(黄文嘉)[3] S. Naimi[5] Xing Xu(徐星)[1]

- led by **M. Wang (AME)** and **G. Audi (NuBase)**

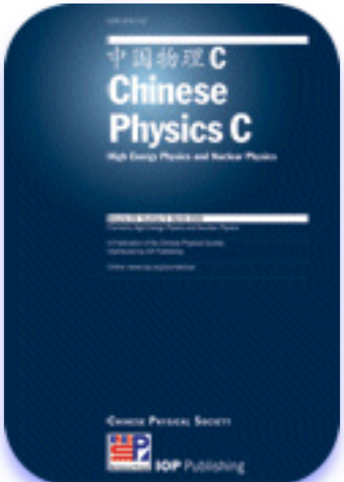
Chinese Physics C Vol. 41, No. 3 (2017) 030001

The NUBASE2016 evaluation of nuclear properties *

G. Audi (欧乔治)[1] F.G. Kondev[2] Meng Wang (王猛)[3,4;1)] W.J. Huang(黄文嘉)[1] S. Naimi[5]

widely used by broader community & highly cited

AME2020 & NUBASE2020



new AME2020 & NUBASE2020 are near completion

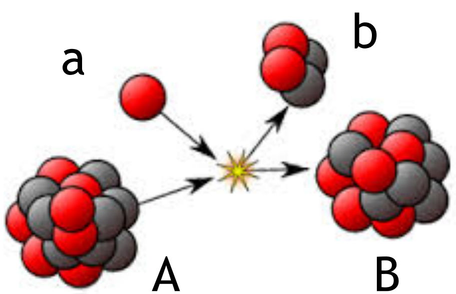
- **led by M. Wang (AME) and F.G. Kondev (NuBase)**

- the new tables will be published in March 2021
  - include all recently published data
  - fixed known issues in the 2016 tables - typos, errors, etc.

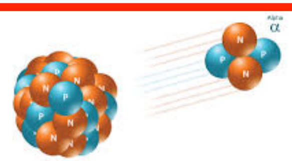
Implications for ENSDF

Experimental Data used in AME

- **Direct methods - mass spectrometry**
  - **TOF & MR-TOF** (very fast BUT low precision & resolution)
  - **Storage Rings** (fast & many nuclei at once)
  - **Penning Traps** (relatively “slow” BUT high precision and high resolution)



$$Q_r = M_A + M_a - M_b - M_B$$

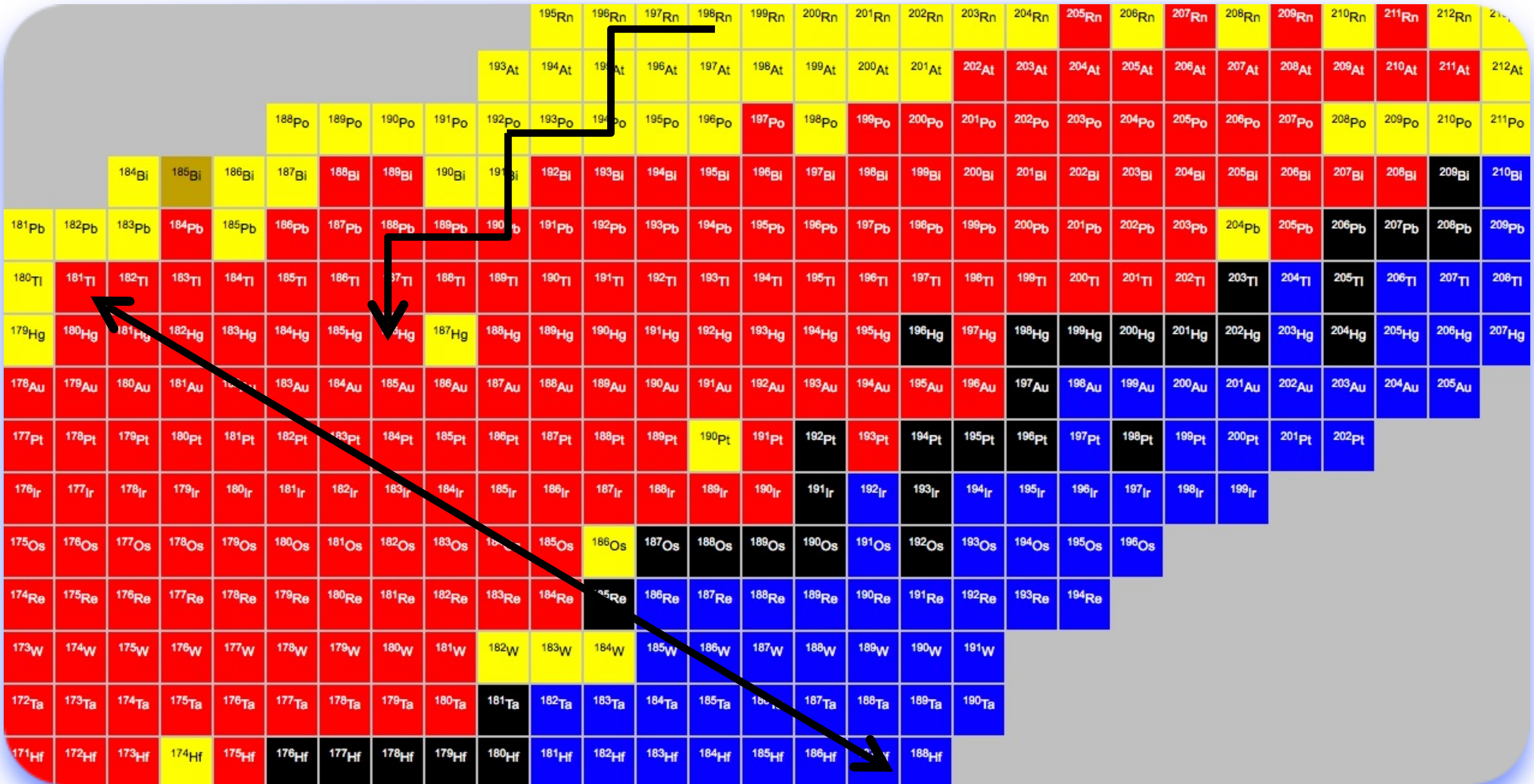


$$Q_d = M_{PD} - M_D - m_{p(\alpha)}$$

- **Indirect methods - reaction and decay energies**
  - **Reaction Energies**
    - (n,γ) and (p,γ) are the backbone
    - self-calibrated - A(a,b)B vs. C(a,b)D
    - close to stability
  - **Decay Energies** in β^-, β^+, α and p decays
    - far from stability - α and p (heavy or proton-rich nuclei) & $Q_{\beta-}$ neutron-rich nuclei

Implications for ENSDF

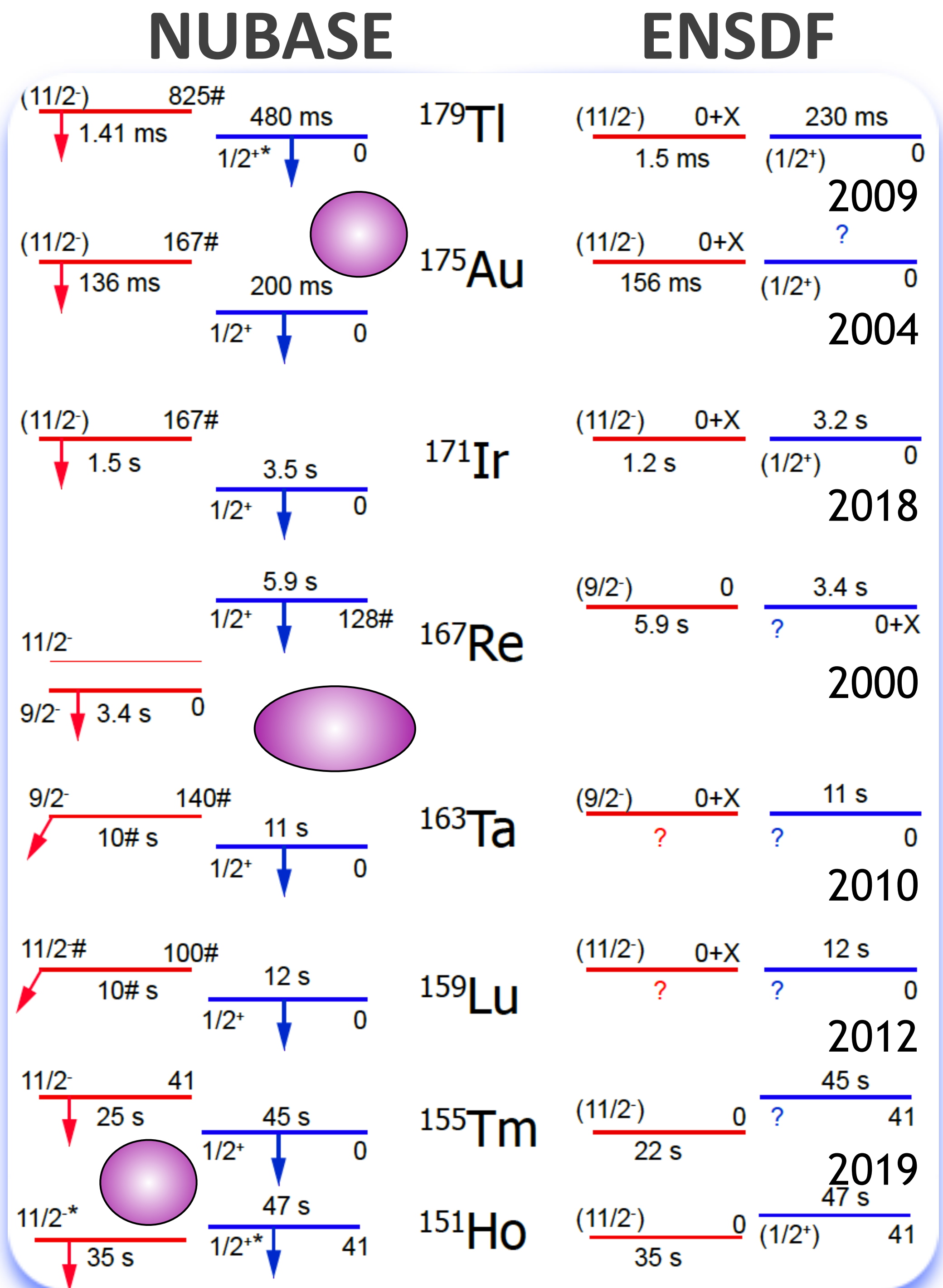
- A-chain (β–decay chain) vs α–decay chain



A=179 decay chain

- up-to-date data on basic NP properties for ground states and isomers ($T_{1/2}$>100 ns)
  - m, E_x, $T_{1/2}$, Jπ, BR
- resolve isomers
  - excitation energies
  - ordering- e.g. ^{155}Tm
- consistent Jπ assignments
  - shape changes

- update Q values in ENSDF (Adopted Levels) - for all A chains - simultaneously
- develop tools to easily follow & modify α-decaying chains



314 *23*	$(5)^{+}$	2.99 s *11*	B D	$\%\beta^{-}=100$ XREF: D(?). It is assumed by the evaluators that the lowest levels populated in the decay of the 13−μs isomer, and in ($t,{}^{3}He$) correspond to this long-lived isomer. E(level): from measured masses of g.s. and isomer (2007Ri01,2007Ha32). 2017Au03 give 313 keV *8*. Evaluators could not find rationale for low uncertainty in 2017Au03.

Penning Trap measurements are NOT absolute!

frequency ratio

unknown mass

$$R=\frac{f_r}{f}=\frac{\mathcal{M}-D-m_e\,q+B}{\mathcal{M}_r-D_r-m_e\,q_r+B_r}\,\frac{q_r}{q}$$

known mass of the reference nuclide (molecule)

- in AME we compile the frequency ratios and use the latest data (both AME & atomic) for the reference nuclide in order to determine the mass of the nuclide of interest
- in case of multiple data - use the least-squares approach

→ Visit the first AME paper where the individual results are compiled

(I). Evaluation of input data; and adjustment procedures

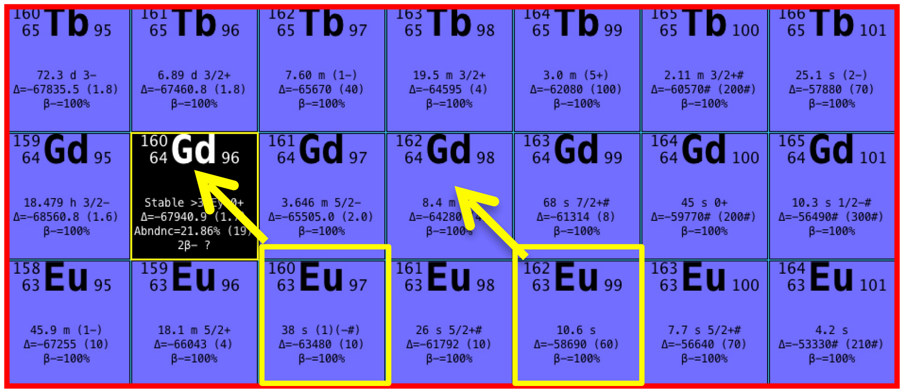
PHYSICAL REVIEW LETTERS 120, 182502 (2018)

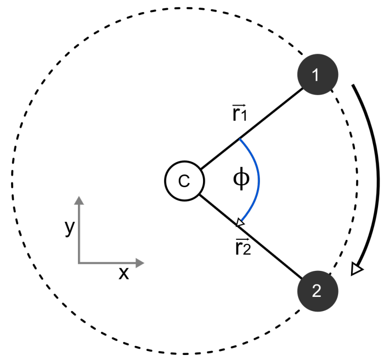
Masses and β-Decay Spectroscopy of Neutron-Rich Odd-Odd ^{160,162}Eu Nuclei: Evidence for a Subshell Gap with Large Deformation at $N=98$

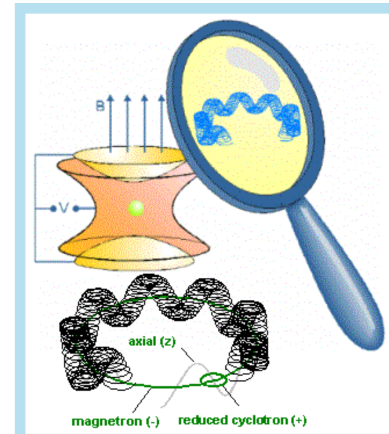
D. J. Hartley,[1] F. G. Kondev,[2] R. Orford,[2,3] J. A. Clark,[2,4] G. Savard,[2,5] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] F. Buchinger,[3] M. T. Burkey,[2,5] M. P. Carpenter,[2] P. Copp,[2,6] D. A. Gorelov,[2,4] K. Hicks,[1] C. R. Hoffman,[2] C. Hu,[7] R. V. F. Janssens,[2,‡] J. W. Klimes,[2] T. Lauritsen,[2] J. Sethi,[2,8] D. Seweryniak,[2] K. S. Sharma,[9] H. Zhang,[7] S. Zhu,[2] and Y. Zhu[7]

CPT: mass measurements

R = m/Δm ~ 20,000,000

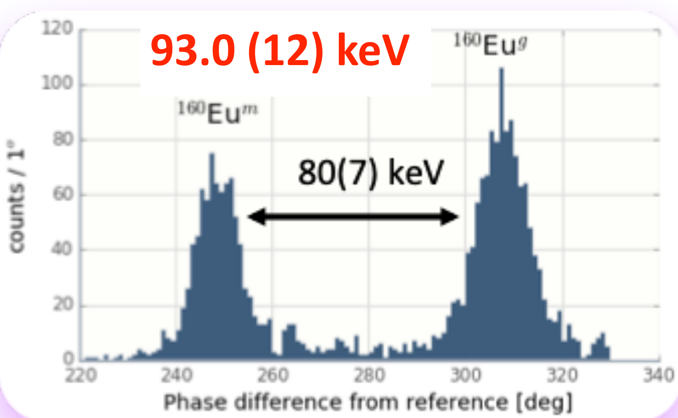


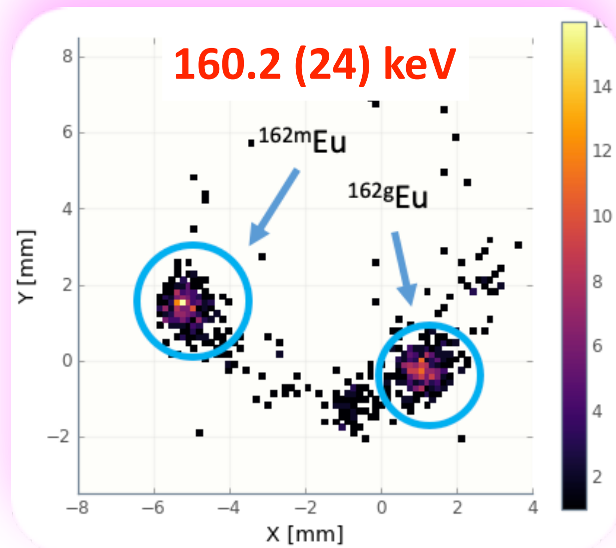




phase-imaging ion-cyclotron-resonance (PI-ICR) technique

- faster measurements - nuclei with shorter lifetimes
- improved sensitivity & accuracy - resolving isomers





PHYSICAL REVIEW LETTERS 120, 262701 (2018)

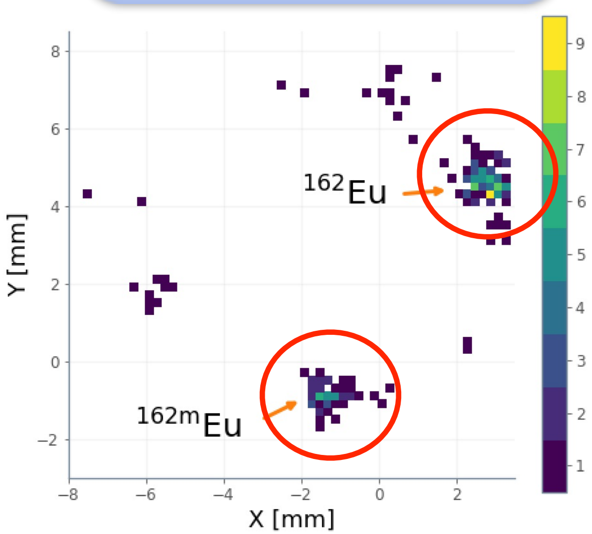
Precision Mass Measurements on Neutron-Rich Rare-Earth Isotopes at JYFLTRAP: Reduced Neutron Pairing and Implications for r-Process Calculations

M. Vilen,[1,*] J. M. Kelly,[2,†] A. Kankainen,[1] M. Brodeur,[2] A. Aprahamian,[2] L. Canete,[1] T. Eronen,[1] A. Jokinen,[1] T. Kuta,[2] I. D. Moore,[1] M. R. Mumpower,[2,3] D. A. Nesterenko,[1] H. Penttilä,[1] I. Pohjalainen,[1] W. S. Porter,[2] S. Rinta-Antila,[1] R. Surman,[2] A. Voss,[1] and J. Äystö[1]

Isotope	Reference	ME_{REF}(keV)	$r = \nu_{c,ref}/\nu_c$	ME_{JYFL}(keV)	ME_{AME16}(keV)	$\Delta ME_{JYFL-AME16}$(keV)
^{156}Nd	^{136}Xe	-86429.159(7)	1.147 366 924(19)	-60210(2)	-60470(200)	260(200)
^{158}Nd	^{136}Xe	-86429.159(7)	1.162 132 772(290)	-53897(37)	-54060(200)#	160(200)#
^{158}Pm	^{158}Gd	-70689.5(12)	1.000 078 752(9)	-59104(2)	-59089(13)	-15(13)
^{160}Pm	^{136}Xe	-86429.159(7)	1.176 857 014(130)	-52851(16)	-53000(200)#	149(201)#
^{162}Sm	^{136}Xe	-86429.159(7)	1.191 560 914(39)	-54381(5)	-54530(200)#	149(200)#
^{162}Eu	^{136}Xe	-86429.159(7)	1.191 527 132(28)	-58658(4)	-58700(40)	42(40)
^{163}Eu	^{163}Dy	-66381.2(8)	1.000 065 633(23)	-56420(4)	-56480(70)	60(70)
^{163}Gd	^{163}Dy	-66381.2(8)	1.000 034 135(22)	-61200(4)[a]	-61314(8)	114(9)
^{164}Gd	^{171}Yb	-59306.810(13)	0.959 046 522(14)	-59694(3)	-59770(100)#	76(100)#
^{165}Gd	^{171}Yb	-59306.810(13)	1.058 489 243(23)[b]	-56522(4)	-56450(120)#	-72(120)#
^{166}Gd	^{136}Xe	-86429.159(7)	1.220 992 828(29)	-54387(4)	-54530(200)#	143(200)#
^{164}Tb	^{171}Yb	-59306.810(13)	0.959 031 473(21)	-62090(4)	-62080(100)	-10(100)

TOF-ICR

ME(JYFL) =-58658 (4)



ME(gs) =-58723.9 (15)
ME(is) =-58563.9 (19)

PRL 118, 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

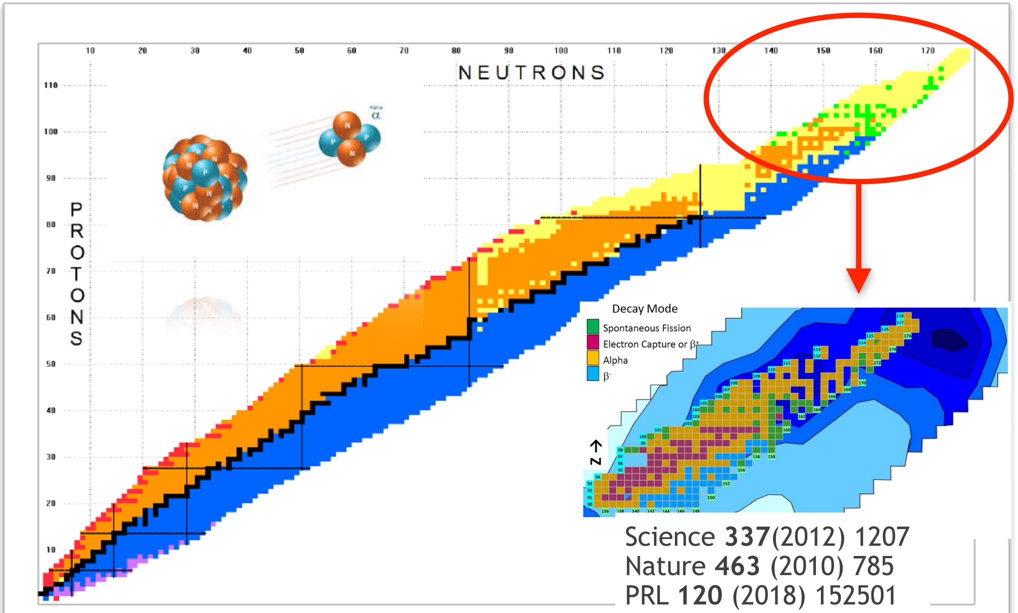
94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation

J. Wu,[1,2,*] S. Nishimura,[2] G. Lorusso,[2,3,4] P. Möller,[5] E. Ideguchi,[6] P.-H. Regan,[3,4] G. S. Simpson,[7,8,9] P.-A. Söderström,[2] P. M. Walker,[4] H. Watanabe,[10,2] Z. Y. Xu,[11,12] H. Baba,[2] F. Browne,[13,2] R. Daido,[14] P. Doornenbal,[2] Y. F. Fang,[14] G. Gey,[7,15,2] T. Isobe,[2] P. S. Lee,[16] J. J. Liu,[11] Z. Li,[1] Z. Korkulu,[17] Z. Patel,[4,2] V. Phong,[18,2] S. Rice,[4,2] H. Sakurai,[2,12] L. Sinclair,[19,2] T. Sumikama,[2] M. Tanaka,[6] A. Yagi,[14] Y. L. Ye,[1] R. Yokoyama,[20] G. X. Zhang,[10] T. Alharbi,[21] N. Aoi,[6] F. L. Bello Garrote,[22] G. Benzoni,[23] A. M. Bruce,[13] R. J. Carroll,[4] K. Y. Chae,[24] Z. Dombradi,[17] A. Estrade,[25] A. Gottardo,[26,27] C. J. Griffin,[25] H. Kanaoka,[14] I. Kojouharov,[28] F. G. Kondev,[29] S. Kubono,[2] N. Kurz,[28] I. Kuti,[17] S. Lalkovski,[4] G. J. Lane,[30] E. J. Lee,[24] T. Lokotko,[11] G. Lotay,[4] C.-B. Moon,[31] H. Nishibata,[14] I. Nishizuka,[32] C. R. Nita,[13,33] A. Odahara,[14] Zs. Podolyák,[4] O. J. Roberts,[34] H. Schaffner,[28] C. Shand,[4] J. Taprogge,[35,36] S. Terashima,[10] Z. Vajta,[17] and S. Yoshida[14]

^{152}Ba	0.139(8)	^{156}Pr	0.444(6)	^{161}Eu	30.1(90)	^{172}Dy	$3.94(^{+28}_{-37})$
^{153}Ba	0.116(52)	^{157}Pr	$0.295(^{+29}_{-11})$	^{162}Eu	11.8(14)	^{172m}Dy	0.674(66)

15.0 (5) s from β-γ (time)
D.J. Hartley et al., PRL120 (2018)

Masses of the very Heavy Nuclei



Science **337**(2012) 1207
Nature **463** (2010) 785
PRL **120** (2018) 152501

Experimental Approaches

- magnetic spectrometers
  - ✓ relative
  - ✓ absolute (BIPM, Paris)
- Si detectors
  - ✓ Si(Au)
  - ✓ PIPS
  - ✓ DSSD (direct implantation)
- bolometers & micro-calorimeters
- SHIPTRAP@GSI & TRIGATRAP@Mainz
- MR-TOF@RIKEN

- experimental masses for 1/4 of the Chart of Nuclei rely on **α-decay data** - measured by means of **magnetic spectrographs** or/and **Si detectors**
- most of these measurements are **relative to standard values** that may change over time - **standards:** values recommended by **A. Rytz (1973,1979 &1991)** that are adopted by the AME collaboration
- recently, direct measurements using **Penning Traps** (high resolution & high precision) & **MR-TOF** (fast, but low precision) are performed - provide new anchor points in the region of very heavy nuclei

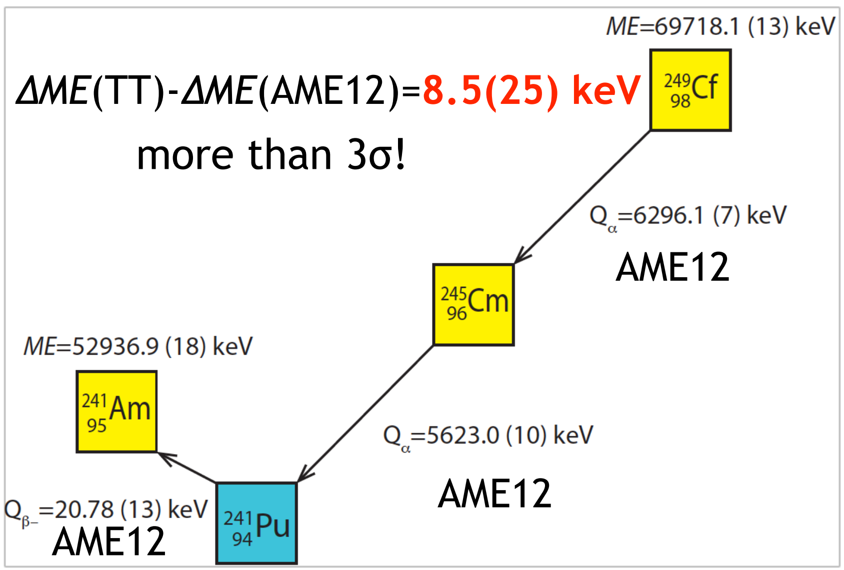
PHYSICAL REVIEW C **89**, 064318 (2014)

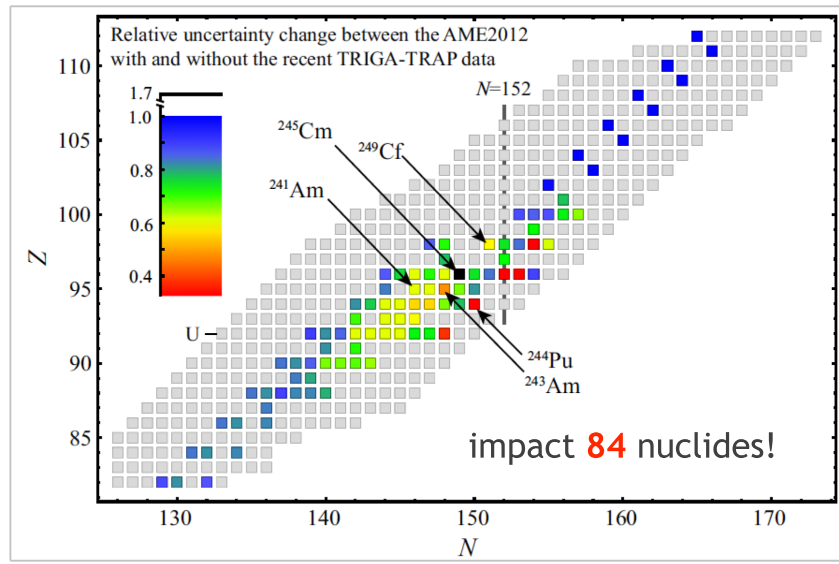
Direct high-precision mass measurements on ^{241,243}Am, ^{244}Pu, and ^{249}Cf

M. Eibach,[1,2,*] T. Beyer,[1] K. Blaum,[1] M. Block,[3] Ch. E. Düllmann,[3,4,5] K. Eberhardt,[2,5] J. Grund,[4] Sz. Nagy,[1] H. Nitsche,[6,7] W. Nörtershäuser,[2,3,8] D. Renisch,[2] K. P. Rykaczewski,[9] F. Schneider,[2,10] C. Smorra,[1,†] J. Vieten,[11] M. Wang,[1,12,13] and K. Wendt[10]

TRIGA-TRAP@Mainz: measured masses of ^{241,243}Am, ^{244}Pu & ^{249}Cf

$$ME_{TT}(^{249}Cf) - ME_{TT}(^{241}Am) = Q_\alpha(^{249}Cf) + Q_\alpha(^{245}Cm) + Q_\beta(^{241}Pu) + 2 \times m_\alpha$$



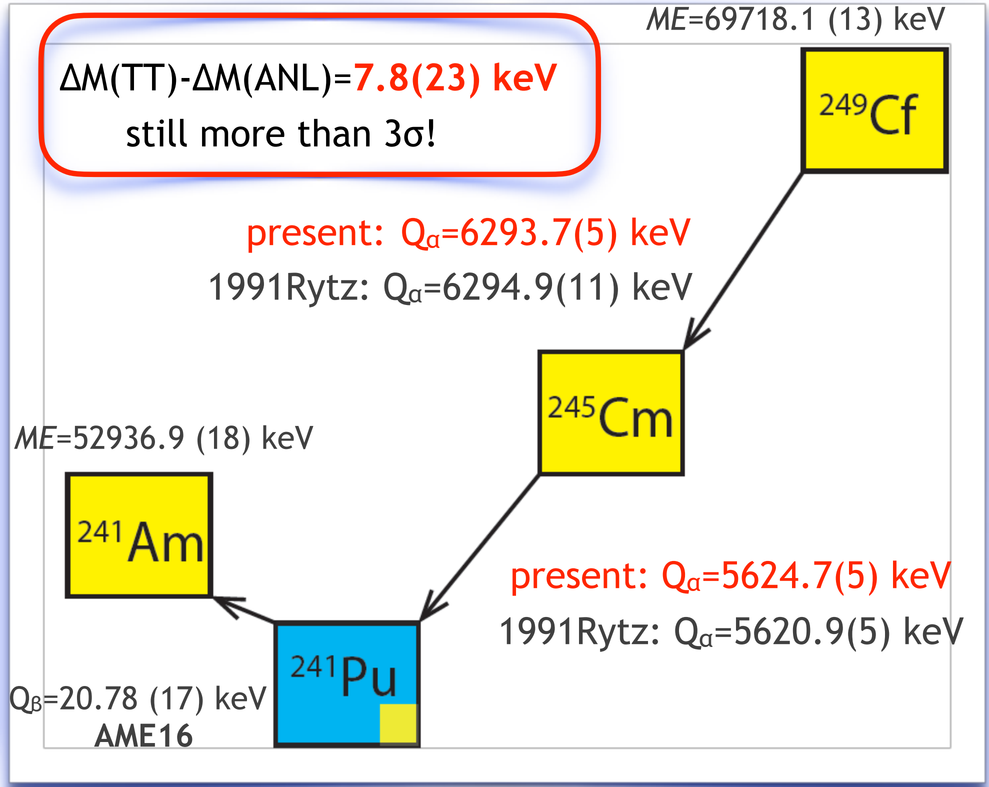


possible source of discrepancy - α-decay energies of ^{245}Cm and ^{249}Cf?

^{249}Cf-^{241}Am mass anomaly - cont.

What might went wrong?

- Q_β value for ^{241}Pu - 4 independent & consistent (within 1 keV) values - Q_β(AME16)=**20.78(17)** keV, BUT Q_β=**18.2(27)** keV from ME(^{241}Am), ME(^{237}U) and Qα(^{241}Pu) - ΔM(TT)-ΔM(ANL)=**5.3(33) keV**, **e.g. less than 2σ**
- TRIGA TRAP data for ^{249}Cf - unlikely? - good consistency (within 1 keV) for ^{241,243}Am and ^{244}Pu, BUT need to be confirmed?
- issues with the Rytz recommended (absolute) Eα values - this could have a huge impact since we must reconsider all α-decay energies in the Nuclear Chart?



Outlook

- **(short term)** new measurement program at ANL (CPT group) to directly test Ritz absolute Eα using a **^{228}Th** source - a chain of α emitters, e.g. **^{228}Th, ^{224}Ra, ^{220}Rn, ^{216}Po** (G. Savard's group at ANL)
- **(long term)** continuation of the Ritz evaluation work is urgently needed - incorporation of the new measurements using Si detectors (PIPS & DSSD), Penning Traps & MR-TOF - area of interest to ANL ND & collaborations are welcome

Nuclear Inst. and Methods in Physics Research, A 940 (2019) 56–60

High-precision α-particle energies in the decay of Es, Fm, and Md Isotopes

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Nuclear Archeology

Table 2
Alpha-particle energies determined in the present work. Published values were corrected for new α energies of the standards.

Nuclide	Half-life	Previously published		Present work	
Alpha group	[14]	Standard used	E_α (keV)	Standard used	E_α (keV)
^{251}Es α_0	33 h	column 2 (Table 1)	6492 ± 2 [15]	7040.0 ± 1.0	6491.8 ± 1.0
^{252}Es α_0	471.7 d	6632 (^{253}Es)	6631 ± 3 [16]	6118.10 ± 0.04	6631.5 ± 0.5
α_{590}		6111 (^{242}Cm)	6050 ± 3 [16]	6118.10 ± 0.04	6050.8 ± 0.5
^{254}Es α_{84}	275.7 d	column 2 (Table 1)	6429 ± 2 [9]	6632.51 ± 0.05 6118.10 ± 0.04	6430.5 ± 0.5
^{254m}Es α_{212}	39.3 h	column 2 (Table 1)	6382 ± 2 [9]	6632.51 ± 0.05	6383.5 ± 1.0
^{251}Fm α_0	5.30 h	column 2 (Table 1)	7305 ± 3 [15]	7040.0 ± 1.0	7306.0 ± 1.0
α_{480}		column 2 (Table 1)	6833 ± 2 [15]	7040.0 ± 1.0	6833.4 ± 1.0
^{252}Fm α_0	25.39 h	column 3 (Table 1)	7039 ± 2 [17]	6632.51 ± 0.05	7040.0 ± 1.0
^{253}Fm α_0	3.0 d	6640 (^{253}Es)	7092 ± 4 [18]	6632.51 ± 0.05	7083.9 ± 1.0
α_{417}		6640 (^{253}Es)	6682 ± 3 [18]	6632.51 ± 0.05	6673.7 ± 1.0
^{254}Fm α_0	3.240 h	column 3 (Table 1)	7192 ± 2 [17]	6632.51 ± 0.05	7192.0 ± 1.0
^{255}Fm α_0	20.07 h	column 3 (Table 1)	7127 ± 2 [10]	6632.51 ± 0.05	7126.8 ± 0.5
α_{106}		column 3 (Table 1)	7022 ± 2 [10]	6632.51 ± 0.05	7022.0 ± 0.5
α_{544}		column 3 (Table 1)	6592 ± 2 [10]	6632.51 ± 0.05	6591.3 ± 0.5
^{256}Fm α_0	157.6 min	7022 (^{255}Fm)	6915 ± 4 [19]	7022.0 ± 0.5	6915.0 ± 2.0
^{257}Fm α_{241}	100.5 d	6632 (^{253}Es)	6520 ± 2 [20]	6632.51 ± 0.05	6519.7 ± 1.0
^{255}Md α_{461}	27 min	7022 (^{255}Fm)	7327 ± 4 [19]	7022.0 ± 0.5	7327.0 ± 2.0
^{256}Md $\alpha_{excited}$	77 min	7022 (^{255}Fm)	7206 ± 4 [19]	7022.0 ± 0.5	7207.0 ± 2.0
^{257}Md α_{371}	5.52 h	6911 (^{256}Fm)	7064 ± 5 [21]	6915.0 ± 2.0	7069.0 ± 3.0
^{258}Md $\alpha_{excited}$	51.5 d	6632 (^{253}Es)	6716 ± 5 [21]	6632.51 ± 0.05	6717.0 ± 2.0