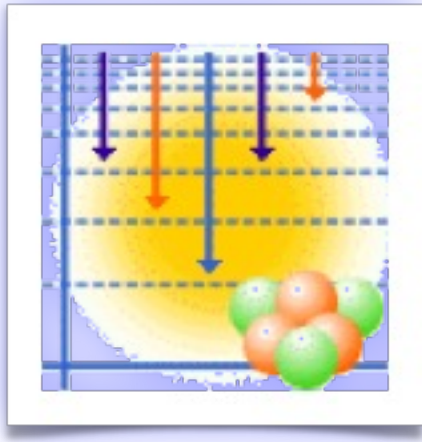
Argonne NATIONAL LABORATORY

The latest AME & NuBase nuclear data tables: how well do we know the basic nuclear physics properties?

F.G. Kondev
Physics Division, Argonne National Laboratory

kondev@anl.gov



Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory, Experiment and Evaluation, Trieste IT 2022

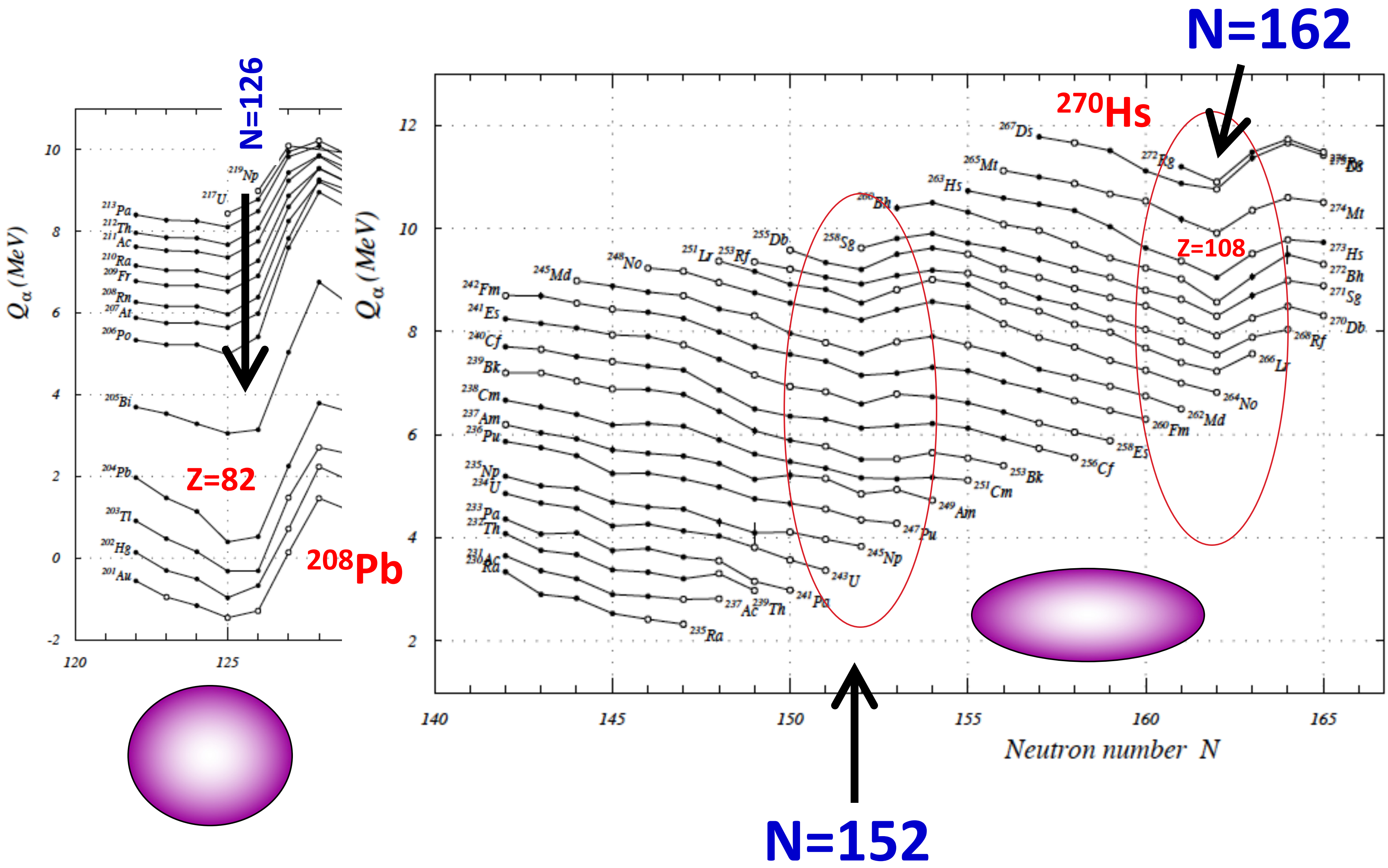
U.S. DEPARTMENT OF ENERGY

Atomic Mass Evaluation & NuBase

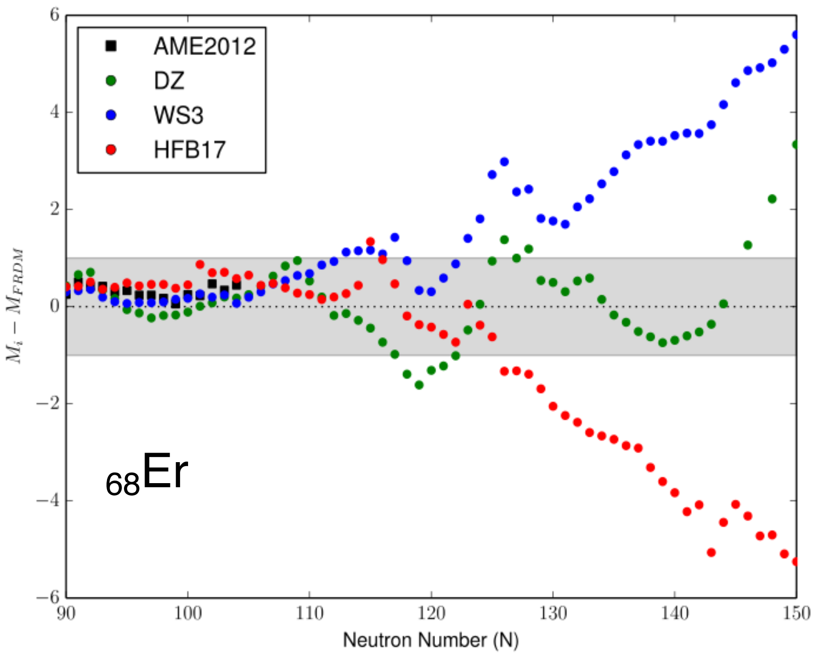
- Correlations
  - ✓ pairing
  - ✓ p-n
- Binding energy
  - ✓ mass models
  - ✓ shell structure
- Reaction & decay phase space
  - ✓ Q values
  - ✓ reaction probabilities
- The limits of existence
  - ✓ drip lines
- Nuclear astrophysics
  - ✓ nucleosynthesis pathways & scenarios
- Fundamental symmetries
- Metrology

post COVID-19

Shell structure - example

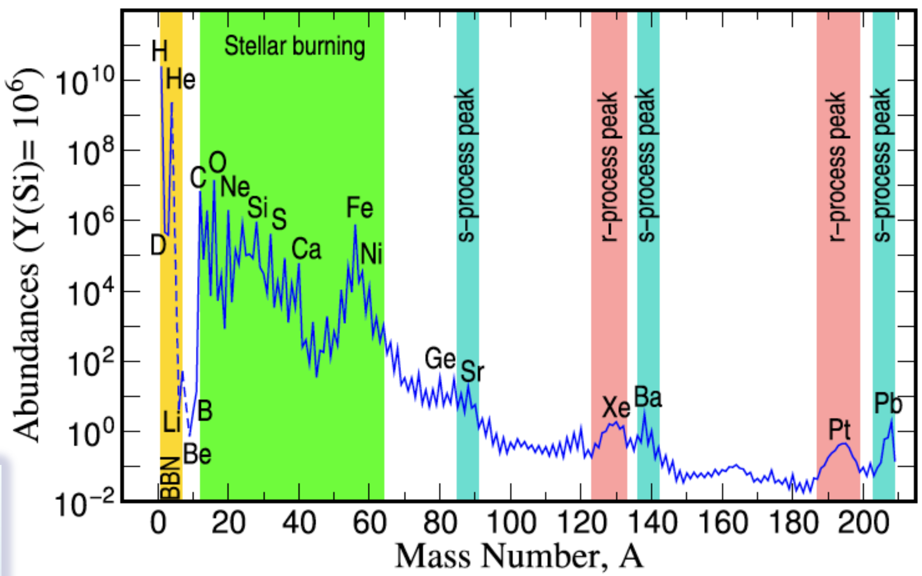


Theory & Astrophysics - examples



M.R. Mumpower *et al.*, J. Phys. G: Nucl. Part. Phys. **42**, 034027 (2015)

- beneficial to nucleosynthesis modeling – basic nuclear data: *m*, $T_{1/2}$, BR, P_n, *etc.* – AME & NuBase provide **complete**, **up-to-date**, **credible** & **properly referenced** data



J. Covan *et al.*, Rev. Mod. Phys. **93** (2021) 015002

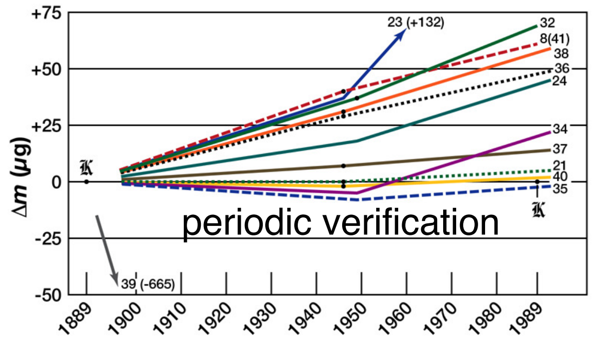
- beneficial to theory development
  - models agree (to some extent) in region where data exist
  - diverge wildly outside the recommended AME data

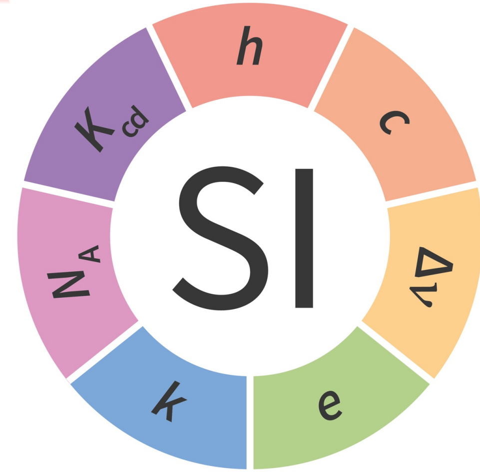
Metrology - New International System of Units

1889

1(IPK) + 6 at BIPM national prototypes, *e.g.* 5 at US

Bureau International des Poids et Mesures





2019

OPEN ACCESS
IOP Publishing | Bureau International des Poids et Mesures   Metrologia

Metrologia **55** (2018) 125–146   https://doi.org/10.1088/1681-7575/aa99bc

Data and analysis for the CODATA 2017 special fundamental constants adjustment*

Peter J Mohr, David B Newell, Barry N Taylor and Eite Tiesinga

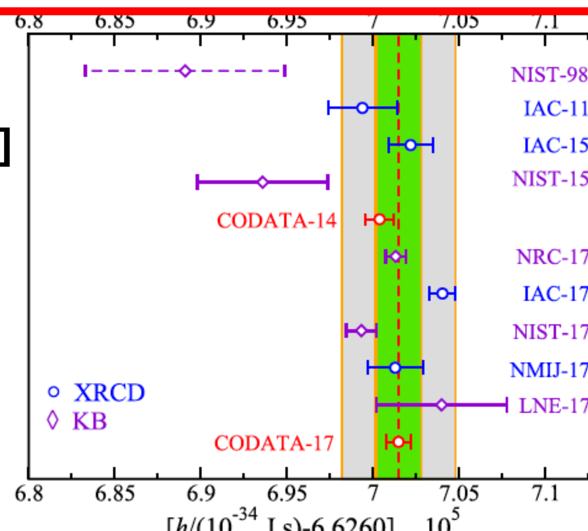
h = **6.6260701510-34 J.s [kg.m^2.s^{-1}]**

s = const/$\Delta\nu(^{133}$Cs)

m = const$_1$ x c/$\Delta\nu(^{133}$Cs)

kg = const$_2$ x $\boldsymbol{h}.\Delta\nu(^{133}$Cs)/c^2

rel. unc. 10^{-8} or 10 μg



Masses from AME16

Atom	Relative atomic mass A_r(X)	Relative standard uncertainty u_r
n	1.008 664 915 82(49)	4.9×10^{-10}
^{1}H	1.007 825 032 241(94)	9.3×10^{-11}
^{2}H	2.014 101 778 11(12)	6.0×10^{-11}
^{3}H	3.016 049 281 98(23)	7.7×10^{-11}
^{3}He	3.016 029 322 65(22)	7.3×10^{-11}
^{4}He	4.002 603 254 130(63)	1.6×10^{-11}
^{12}C	12	(exact)
^{28}Si	27.976 926 534 99(52)	1.9×10^{-11}
^{36}Ar	35.967 545 105(29)	8.1×10^{-10}
^{38}Ar	37.962 732 10(21)	5.5×10^{-9}
^{40}Ar	39.962 383 1238(24)	6.0×10^{-11}
^{87}Rb	86.909 180 5312(65)	7.4×10^{-11}

- KB - Kibble balance
- XRCD - x-ray crystal density needs $m(^{28}$Si) – from AME

Historical Perspective

APRIL 15, 1935 PHYSICAL REVIEW VOLUME 47

LETTERS TO THE EDITOR

Masses of Light Atoms from Transmutation Data*

H. BETHE

Cornell University,
March 27, 1935.

REVIEWS OF
MODERN PHYSICS

VOLUME 9 JULY, 1937 NUMBER 3

Nuclear Physics

C. Nuclear Dynamics, Experimental*

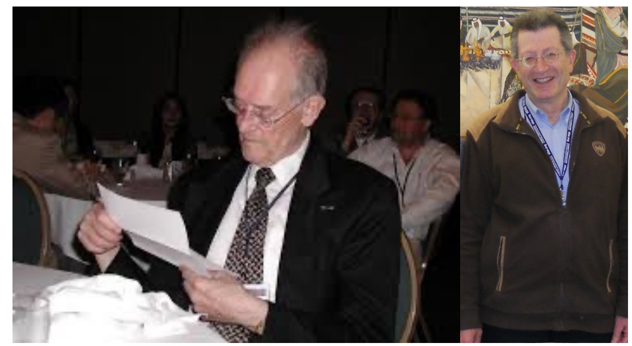
M. STANLEY LIVINGSTON AND H. A. BETHE†
Cornell University, Ithaca, New York

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
International Journal of Mass Spectrometry 251 (2006) 85–94
International Journal of Mass Spectrometry
www.elsevier.com/locate/ijms

The history of nuclidic masses and of their evaluation

Georges Audi*

"Doing this job makes us see almost all aspects of the nuclear physics problems and many also beyond. Often, we have the privilege to be the first ones to see new phenomena."



A. Wapstra & G. Audi

1943	S. Flügge and J.H.E. Mattauch	1955	A.H. Wapstra and J.R. Huizenga	1971	A.H. Wapstra and M.B. Gove
1944	G. Seaborg	1956	J. Mattauch *et al.*	1977	A.H. Wapstra and K. Bos
1946	G. Seaborg	1957	J.H.E. Mattauch and F. Everling	1985	A.H. Wapstra and G. Audi
1946	J. Suruque	1960	F. Everling *et al.*	1993	G. Audi and A.H. Wapstra
1948	A.H. Wapstra	1962	L.A. König *et al.*	2003	G. Audi *et al.*
1953	A.H. Wapstra	1965	J.H.E. Mattauch *et al.*		

CPC(HEP & NP), 2012, **36**(12): 1603–2014 **Chinese Physics C** Vol. 36, No. 12, Dec., 2012

The AME2012 atomic mass evaluation *

(II). Tables, graphs and references

M. Wang[1,2,3], G. Audi[2,§], A.H. Wapstra[4,†], F.G. Kondev[5], M. MacCormick[6], X. Xu[1,7], and B. Pfeiffer[8,‡]

Kuwait 2013

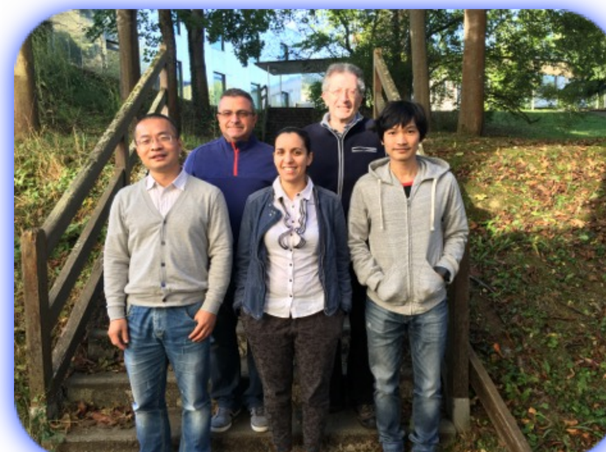
coordinated by G. Audi (AME & NuBase)

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

The AME2016 atomic mass evaluation *

(II). Tables, graphs and references

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]



Orsay 2016

coordinated by M. Wang (AME) and G. Audi (NuBase)

AME2020 & NUBASE2020 - just published

IMP
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
Max-Planck-Institut für Kernphysik Heidelberg
Argonne National Laboratory
RIKEN Nishina

coordinated by M. Wang (AME) and F.G. Kondev (NuBase)

The NUBASE2020 evaluation of nuclear physics properties**

F.G. Kondev [1,*], M. Wang (王猛)[2,3,*], W.J. Huang (黄文嘉)[2,4,5,6], S. Naimi[7], G. Audi (欧乔治)[6]

IOP science

since March 5, 2021

28000 downloads!

The AME2020 atomic mass evaluation **

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

W.J. Huang (黄文嘉)[1,2,3,4] Meng Wang (王猛)[1,5,*] F.G. Kondev[6] G. Audi (欧乔治)[3] S. Naimi[7]

The AME2020 atomic mass evaluation **

(II). Tables, graphs and references

Meng Wang (王猛)[1,2,*] W.J. Huang(黄文嘉)[1,3,4,5] F.G. Kondev[6] G. Audi (欧乔治)[5] S. Naimi[7]

Where to find the data

pdf & ascii: https://www.anl.gov/phy/atomic-mass-data-resources (ANL)

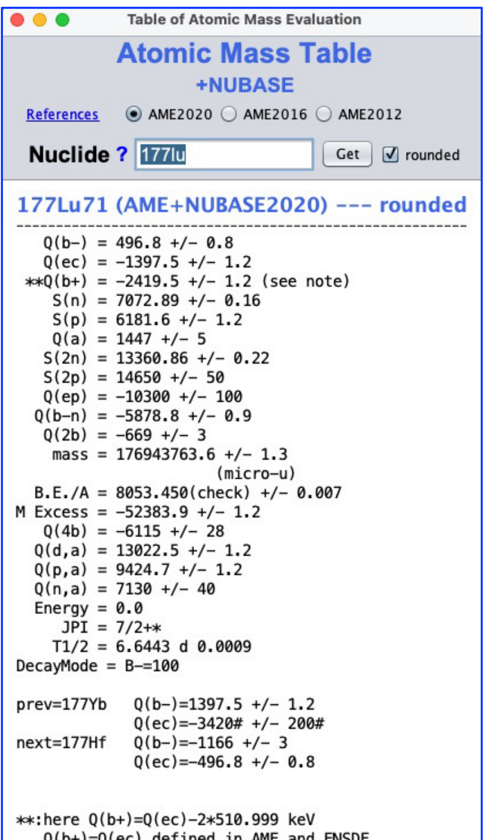
https://www-nds.iaea.org/amdc/ (IAEA)

http://amdc.impcas.ac.cn (IMP)

NSCL FRIB

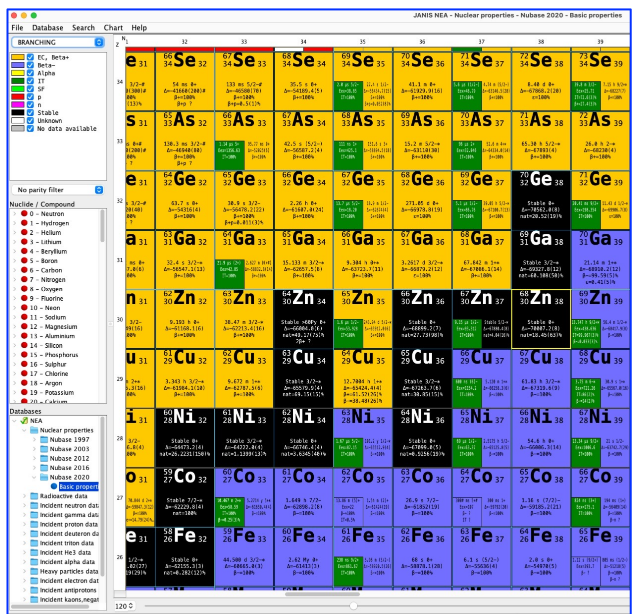
JAVA-AME
J. Chen

stand-alone & www



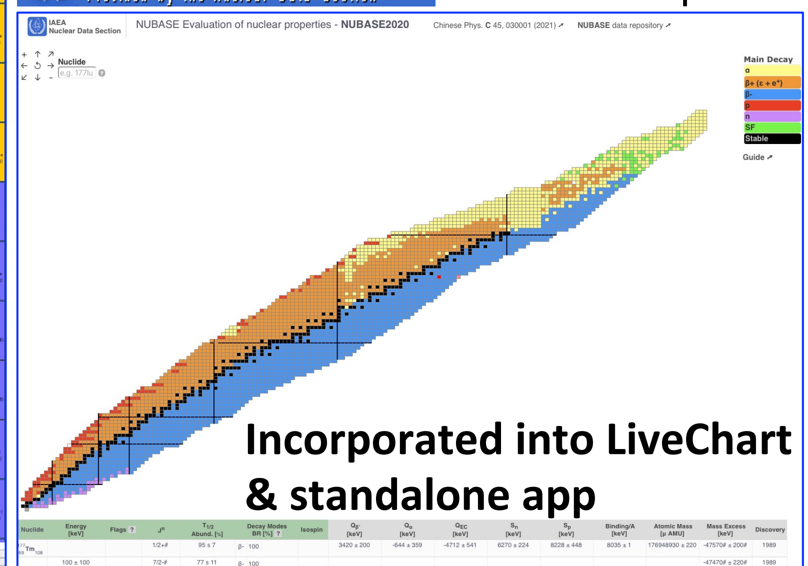
NEA Nuclear Energy Agency

JANIS
NUBASE1997-2020
Nicolas Soppera



International Atomic Energy Agency
Nuclear Data Services
Provided by the Nuclear Data Section

NUBASE2020
Marco Varpelli

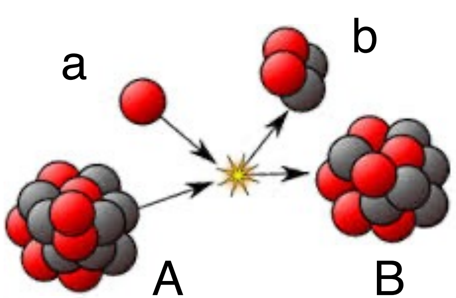


Incorporated into LiveChart & standalone app

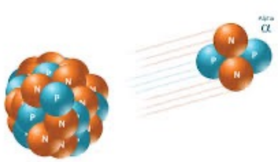
Experimental (Input) Data - compilation

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)



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



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

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

Adjustments to the Input Data

…just a few examples …

- **13812** experimental data, but not all made it to the final adjustments, for example:
  - ▶ 6023 (U – less weight)
  - ▶ 997 (o – old data from the same group)

- statistical analysis of data of the same kind
- reject some experimental results & replace with systematics – **78** cases
- take into account isomers
- adjust uncertainties in the mass spectrometry data

least-squares fit approach

- 2201 primary data determine the masses of 1304 nuclides
  - ▶ 1135 reactions & decays
  - ▶ 1066 mass spectrometry

The AME2020 atomic mass evaluation **

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

W.J. Huang (黄文嘉)[1,2,3,4] Meng Wang (王猛)[1,5,*] F.G. Kondev[6] G. Audi (欧乔治)[3] S. Naimi[7]

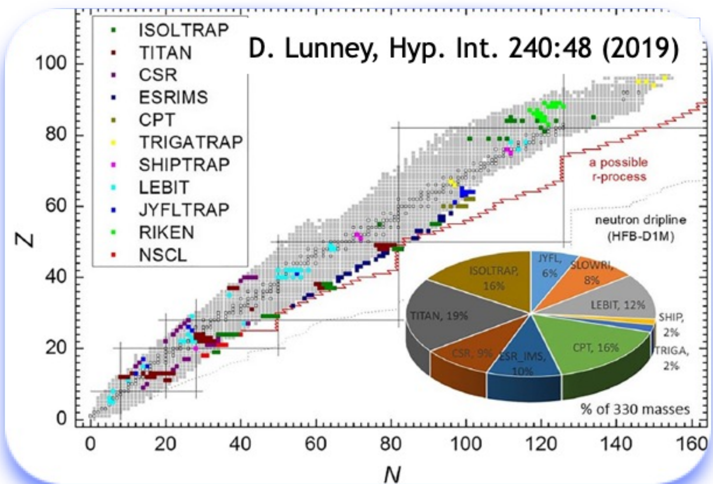
Chinese Physics C Vol. 45, No. 3 (2021) 030002

Table I. Comparison of input data and adjusted values (continued, Explanation of Table on page 030002-30)

Item		Input value		Adjusted value		v_i	Dg	Signf.	Main infl.	Lab	F	Reference	
^{45}Cl−u		−19690	140	−19610	150	0.4	o			GA4	1.5	00Sa21	
		−20300	700			0.7	U			TO3	1.5	90Tu01	
		−19850	460			0.4	o			GA5	1.5	00Sa21	
		−19710	107			0.7	2			GA7	1.5	07Ju03	
		−19098	236			−1.4	2			GA8	1.5	12Ga45	
^{45}V−u		−34225.7	9.7	−34231.5	0.9	−0.6	U			LZ1	1.0	11Tu09	
		−34230	11			−0.1	U			LZ1	1.0	18Zh29	
^{45}Cr−u		−20390	540	−20950	40	−0.7	U			GT1	1.5	04St05	*
		−20950	38				2			LZ1	1.0	12Zh34	*
^{45}Ar−^{39}K$_{1.154}$		9922.45	0.55				2			MA8	1.0	03Bl17	
^{45}K−^{39}K$_{1.154}$		2574.21	0.56				2			MA8	1.0	07Ya08	
^{45}V−^{45}Ti		7647.74	0.23	7647.74	0.23	−0.0	1	100	100 ^{45}V	JY1	1.0	14Ka22	
^{45}Sc(p,α)^{42}Ca		2343	8	2339.0	0.7	−0.5	U			MIT		64Sp12	
^{45}Sc(d,α)^{43}Ca		8028	12	8047.4	0.7	1.6	U			MIT		64Sp12	
		8059	12			−1.0	U			Kop		67Ha.A	
^{43}Ca(^{3}He,p)^{45}Sc		10310	20	10305.7	0.7	−0.2	U			Hei		70Sc22	
^{45}Fe(2p)^{43}Cr		1140	40	1800#	200#	16.5	o					02Gi09	
		1100	100			7.0	U					02Pf02	
		1154	16			40.4	D					05Do20	*
^{44}Ca(n,γ)^{45}Ca		7414.8	1.0	7414.82	0.17	0.0	U					69Ar.A	Z
		7414.83	0.3			−0.0	–			MMn		80Is02	Z
		7414.79	0.21			0.1	–			Bdn		06Fi.A	
^{44}Ca(d,p)^{45}Ca		5184	4	5190.25	0.17	1.6	U			MIT		68Be36	
^{44}Ca(n,γ)^{45}Ca	ave.	7414.80	0.17	7414.82	0.17	0.1	1	99	97 ^{45}Ca			average	
^{44}Ca(p,γ)^{45}Sc		6887.8	1.2	6892.6	0.7	4.0	B					74Sc02	Z
^{45}Sc(^{3}He,α)^{44}Sc		9249	15	9250.0	1.9	0.1	U			MIT		71Ra09	
^{45}Sc(d,t)^{44}Sc^{i}		−7846	10	−7848.1	2.6	−0.2	U					71Oh01	*
^{45}V^{i}(p)^{44}Ti		3190	50	3170	9	−0.4	U					74Ja10	*
		3170	9				3			Bor		07Do17	*
^{45}K(β^-)^{45}Ca		4180	200	4196.6	0.6	0.1	U					64Mo18	
^{45}Ca(β^-)^{45}Sc		258	2	260.1	0.7	1.0	1	14	11 ^{45}Sc			65Fr12	
^{45}Ti(β^+)^{45}Sc		2066	5	2062.1	0.5	−0.8	U					66Po04	
^{45}Sc(p,n)^{45}Ti		−2844.2	4.	−2844.4	0.5	−0.1	U			Ric		55Br16	Y
		−2843.6	4.0			−0.2	U			Can		70Kn03	
		−2844.4	0.5			−0.0	1	100	100 ^{45}Ti	PTB		85Sc16	Z
^{45}Sc(^{3}He,t)^{45}Ti^{i}		−6801	4	−6800	3	0.3	1	61	60 ^{45}Ti^{i}			71Be29	*
*^{45}S−u	Trends from Mass Surface TMS suggest ^{45}S 650 keV less bound											GAu	**
*^{45}Cr−u	$M-A$=–18940(500) keV for mixture gs+m at 107(1) keV											Nub211	**
*^{45}Cr−u	Same result in reference											13Ya03	**
*^{45}Fe(2p)^{43}Cr	Trends from Mass Surface TMS suggest ^{45}Fe 650 keV less bound											GAu	**

Penning Trap input data - example

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 (molecule) to determine the mass of the nuclide of interest

original publication …

PHYSICAL REVIEW C **101**, 041304(R) (2020)

Rapid Communications

Precision mass measurements of ^{67}Fe and ^{69,70}Co: Nuclear structure toward $N = 40$ and impact on r-process reaction rates

Nuclide	$T_{1/2}$ (ms)	I^π	r	Δ_{JYFL} (keV)	Δ_{lit} (keV)	Difference (keV)
^{67}Fe	394(9)	(1/2$^-$)	0.797874190(8)	−45709.1(3.8)	−45610(270)	−99(270)
^{69}Co	180(20)	7/2$^-$#	0.821649141(428)[a]	−50383(44)	−50280(140)	−103(147)
^{69}Co^m	750(250)	1/2$^-$#	0.821651504(291)[a]	−50207(36)	−49780(240)#	−430(240)#
^{70}Co[b]	508(7) [50]	(1$^+$, 2$^+$) [50]	0.833615937(21)	−46525(11)	−46430(360)#	−95(360)#

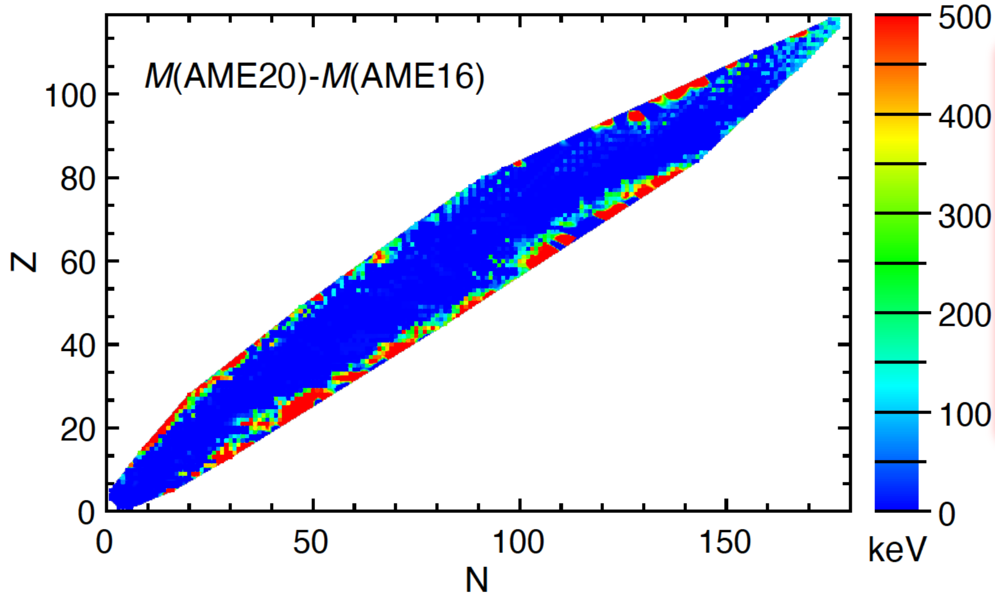
erratum …

PHYSICAL REVIEW C **103**, 029902(E) (2021)

Erratum: Precision mass measurements of ^{67}Fe and ^{69,70}Co: Nuclear structure toward $N = 40$ and impact on r-process reaction rates [Phys. Rev. C 101, 041304(R) (2020)]

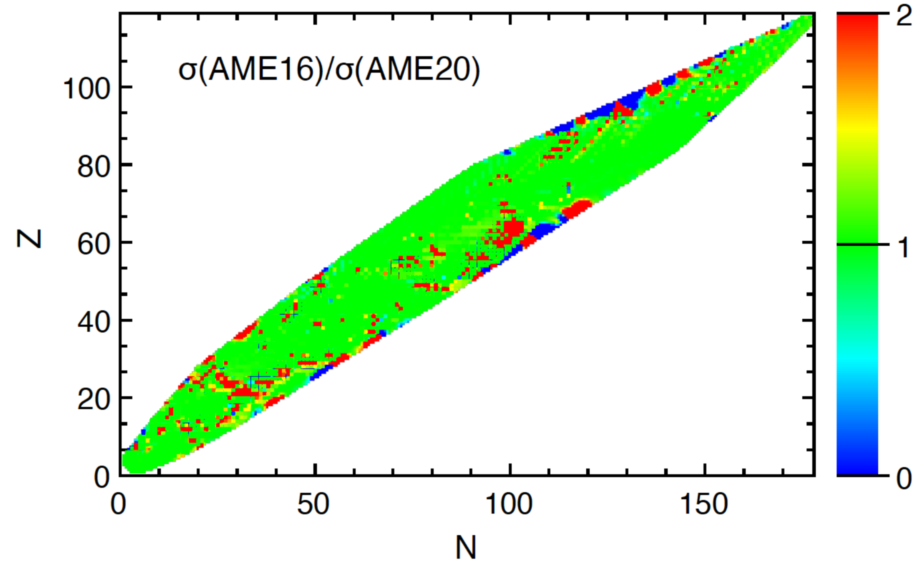
Nuclide	$T_{1/2}$ (ms)	I^π	r	Δ_{JYFL} (keV)	Δ_{lit} (keV)	Difference (keV)
^{67}Fe	394(9)	(1/2$^-$)	0.797874191(49)	−45709.1(3.8)	−45610(270)	−99(270)
^{69}Co	180(20)	7/2$^-$#	0.82164916(110)[a]	−50385(86)	−50280(140)	−105(170)
^{69}Co^m	750(250)	1/2$^-$#	0.82165149(64)[a]	−50203(50)	−49780(240)#	−423(250)#
^{70}Co[b]	508(7) [16]	(1$^+$, 2$^+$) [16]	0.83361594(15)	−46525(11)	−46430(360)#	−95(360)#

AME2020 vs AME2016



- **777** new experimental data
  - **477** mass spectrometry
  - **300** decay energies
- masses for **74** nuclei measured for the first time
- significant impact at the n and p-rich sides
- impact in the region of heavy nuclei

- improved mass uncertainties for **857** nuclides
- worsen mass uncertainty for **313** nuclei – mostly derived from TMS (extrapolation), but some are for measured masses – *e.g.* ^{167}Lu (30 vs 37 keV)



PHYSICAL REVIEW LETTERS 120, 182502 (2018)

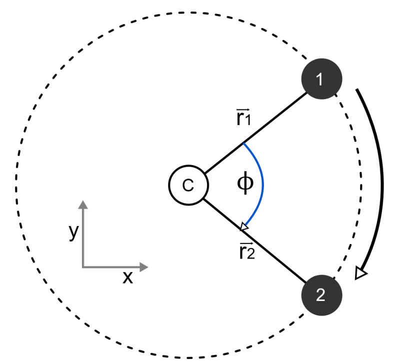
Masses and β-Decay Spectroscopy of Neutron-Rich Odd-Odd ^{160,162}Eu Nuclei: Evidence for a Subshell Gap with Large Deformation at $N = 98$

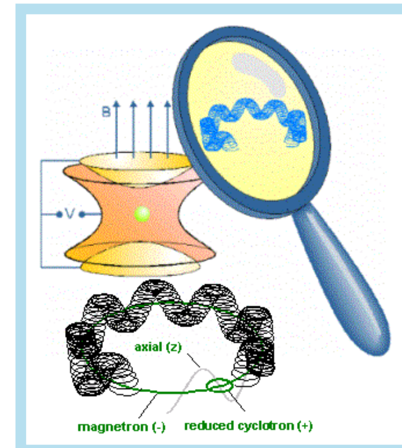
D. J. Hartley,[1] F. G. Kondev,[2] R. Orford,[2,3] J. A. Clark,[2,4] G. Savard,[2,5] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] F. Buchinger,[3] M. T. Burkey,[2,5] M. P. Carpenter,[2] P. Copp,[2,6] D. A. Gorelov,[2,4] K. Hicks,[1] C. R. Hoffman,[2] C. Hu,[7] R. V. F. Janssens,[2,‡] J. W. Klimes,[2] T. Lauritsen,[2]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

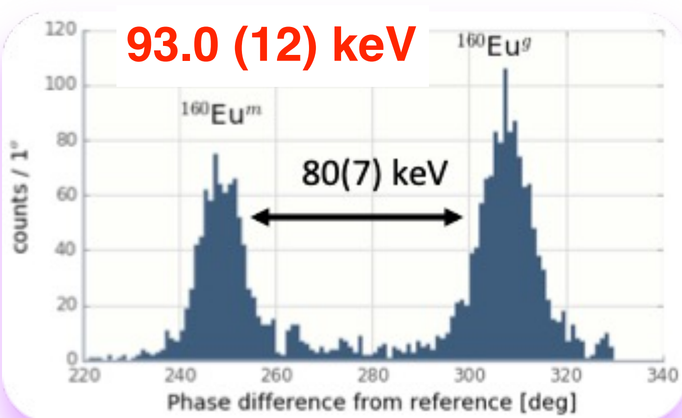
$^{160}_{65}$Tb 95 72.3 d 3− Δ=−67835.5 (1.8) β−=100%	$^{161}_{65}$Tb 96 6.89 d 3/2+ Δ=−67460.8 (1.8) β−=100%	$^{162}_{65}$Tb 97 7.60 m (1−) Δ=−65670 (40) β−=100%	$^{163}_{65}$Tb 98 19.5 m 3/2+ Δ=−64595 (4) β−=100%	$^{164}_{65}$Tb 99 3.0 m (5+) Δ=−62080 (100) β−=100%	$^{165}_{65}$Tb 100 2.11 m 3/2+# Δ=−60570# (200#) β−=100%	$^{166}_{65}$Tb 101 25.1 s (2−) Δ=−57880 (70) β−=100%
$^{159}_{64}$Gd 95 18.479 h 3/2− Δ=−68560.8 (1.6) β−=100%	$^{160}_{64}$Gd 96 Stable >31Ey 0+ Δ=−67940.9 (1. Abndnc=21.86% (19) 2β− ?	$^{161}_{64}$Gd 97 3.646 m 5/2− Δ=−65505.0 (2.0) β−=100%	$^{162}_{64}$Gd 98 8.4 m Δ=−64280 (4 β−=100%	$^{163}_{64}$Gd 99 68 s 7/2+# Δ=−61314 (8) β−=100%	$^{164}_{64}$Gd 100 45 s 0+ Δ=−59770# (200#) β−=100%	$^{165}_{64}$Gd 101 10.3 s 1/2−# Δ=−56490# (300#) β−=100%
$^{158}_{63}$Eu 95 45.9 m (1−) Δ=−67255 (10) β−=100%	$^{159}_{63}$Eu 96 18.1 m 5/2+ Δ=−66043 (4) β−=100%	$^{160}_{63}$Eu 97 38 s (1)(−#) Δ=−63480 (10) β−=100%	$^{161}_{63}$Eu 98 26 s 5/2+# Δ=−61792 (10) β−=100%	$^{162}_{63}$Eu 99 10.6 s Δ=−58690 (60) β−=100%	$^{163}_{63}$Eu 100 7.7 s 5/2+# Δ=−56640 (70) β−=100%	$^{164}_{63}$Eu 101 4.2 s Δ=−53330# (210#) β−=100%

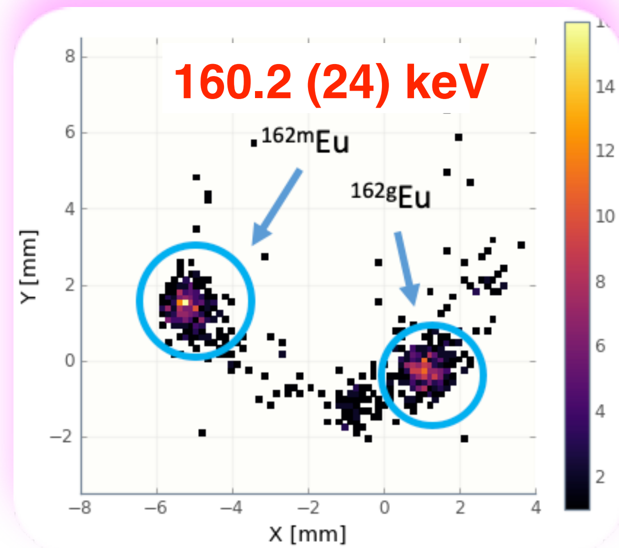




phase-imaging ion-cyclotron-resonance (PI-ICR) technique

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





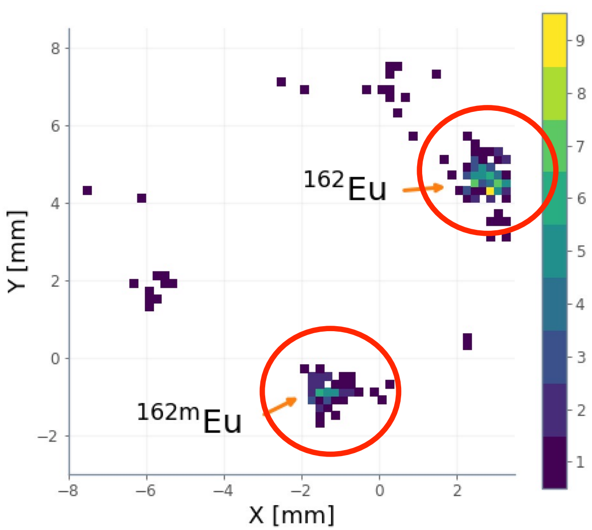
PHYSICAL REVIEW LETTERS 120, 262701 (2018)

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

ME(JYFL) =-58658 (4)

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)

Issues – Q(β^+) for ^{99}Rh

Q(ε) for ^{99}Rh in keV

2043(7) AME12
2044(7) AME16
2041(19) AME20

2059.6(0.1) ENSDF

Q(β^+) for ^{99}Pd in keV

3410(20) 69Ph01

M.E.Phelps & D.G.Sarantites, Nucl.Phys. A135, 116 (1969)

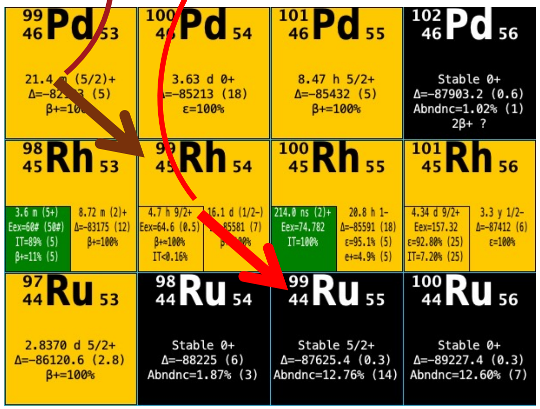
ME(^{99}Pd)=-82183(5) keV

Jy 09El08

Q(β^+) for ^{99}Rh in keV

2038(10) 52Sc11
2053(10) 59To25
2170(30) 74An23

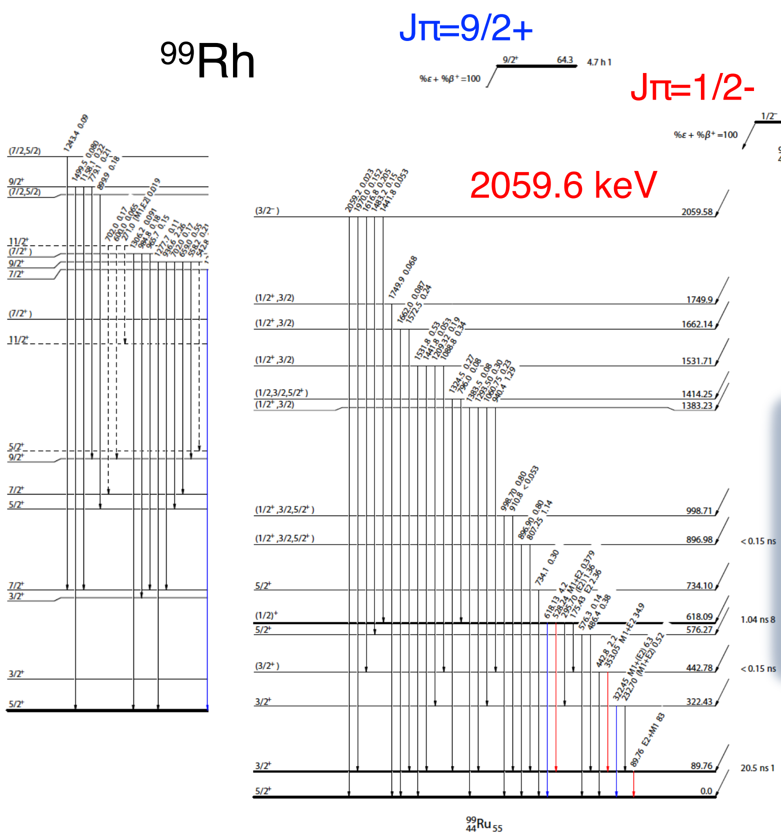
N.M. Antonev et al., Bull. Acad. Sci. USSR, 38, 61 (1974)



ME(^{100}Ru)=-89227.4(0.3)

Jy 08Ra09

E_{γ} (n,γ)=9673.324(0.026) keV
ME(^{99}Ru)=-87625.4(0.3) keV



What would be useful to have

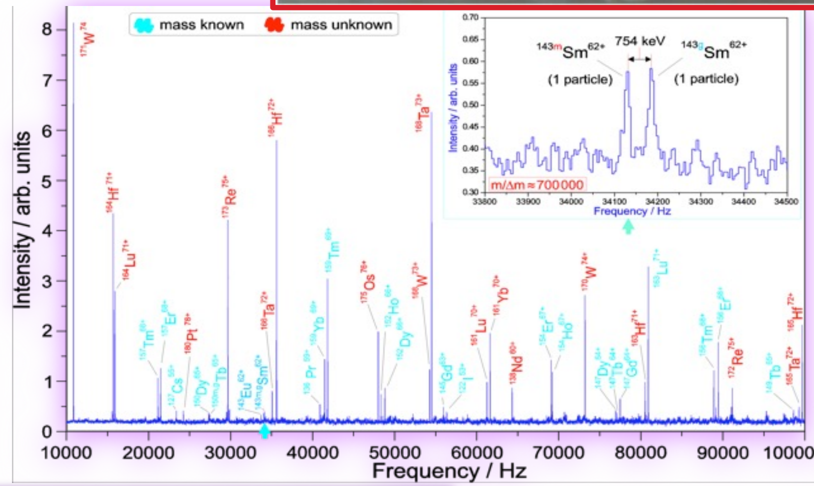
- Penning trap measurement of ^{99}Rh
- decay spectroscopy data to solve the ordering of the low & high-spin decaying states

Connection to Nuclear Structure

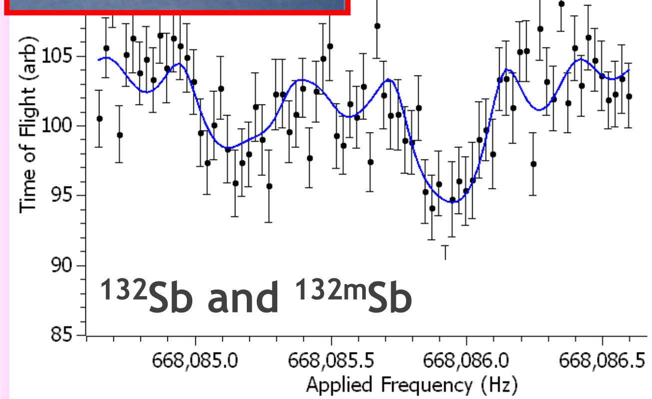
Beware of Isomers

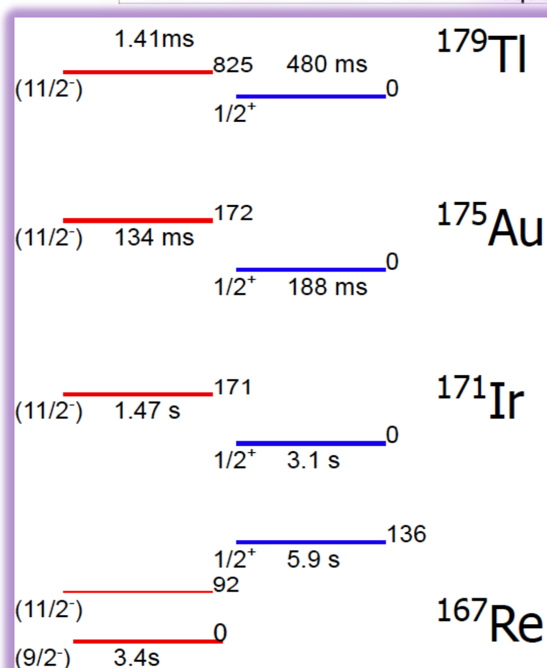
Do we have the right relation?

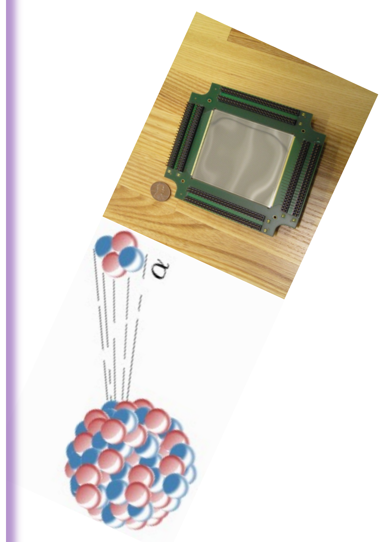
- Excitation energy
- Lifetime
- Decay mode



J. Van Schelt et al., PRL111 (2013) 061102







Chinese Physics C Vol. 45, No. 3 (2021) 030001

The NUBASE2020 evaluation of nuclear physics properties**

F.G. Kondev [1,*], M. Wang (王猛)[2,3,*], W.J. Huang (黄文嘉)[2,4,5,6], S. Naimi[7], G. Audi (欧乔治)[6]

^{162}Eu	−58722.9	1.3					∼ 10	s		1^+#	07	17Wu04	T	1987	β^-=100	
^{162}Eu^m	−58565.0	1.3	158.0	1.7	MD		15.0	s	0.5	(6^+)	07	18Ha19	TJ	2016	β^-=100	
^{162}Gd	−64281	4					8.4	m	0.2	0^+	07			1967	β^-=100	
^{162}Tb	−65879.5	2.0					7.60	m	0.15	(1^-)	16			1965	β^-=100	
^{162}Tb^m	−65594.0	2.5	286	3			10#	m		4^-#		20Or03	EJ	2020	β^- ?; IT ?	
^{162}Dy	−68181.2	0.7					STABLE			0^+	07			1934	IS=25.475 36	
^{162}Dy^m	−65993.1	0.8	2188.1	0.3			8.3	μs	0.3	8^+		11Sw02	ETD	2011	IT=100	
^{162}Ho	−66041	3					15.0	m	1.0	1^+*	07			1957	β^+=100	
^{162}Ho^m	−65935	3	105.87	0.06			67.0	m	0.7	6^-*	07			1961	IT=62;β^+=38	
^{162}Er	−66334.2	0.8					STABLE		>140Ty	0^+	07	56Po16	T	1938	IS=0.139 5;α ?;2β^+ ?	*
^{162}Er^m	−64308.2	0.8	2026.01	0.13			88	ns	16	$7(^-)$	07	12Sw01	TJ	1974	IT=100	
^{162}Tm	−61477	26					21.70	m	0.19	1^-*	07			1963	β^+=100	
^{162}Tm^m	−61350	50	130	40			24.3	s	1.7	5^+	07	74De47	EDJ	1974	IT=81 4;β^+=19 4	*
^{162}Yb	−59821	15					18.87	m	0.19	0^+	07			1963	β^+=100	
^{162}Lu	−52830	80				*	1.37	m	0.02	1^-*	07			1978	β^+=100	
^{162}Lu^m	−52710#	220#	120#	200#		*	1.5	m		4^-#	07			1980	β^+≈100;IT ?	
^{162}Lu^n	−52530#	220#	300#	200#	EU		1.9	m		9^-#	07			1980	β^+ ?;IT ?	*
^{162}Hf	−49168	9					39.4	s	0.9	0^+	07			1982	β^+=99.992 1;α=0.008 1	
^{162}Ta	−39780	60				*	3.57	s	0.12	3^-#	16			1985	β^+=99.926 10;α=0.074 10	
^{162}Ta^m	−39660#	80#	120#	50#		*	5#	s		7^+#					β^+ ?;IT ?;α ?	
^{162}W	−33999	18					1.19	s	0.12	0^+	16			1973	β^+ ?;α=45.2 16	
^{162}Re	−22450#	200#					107	ms	13	$(2)^-$	07			1979	α=94 6;β^+ ?	
^{162}Re^m	−22280#	200#	175	9	AD		77	ms	9	$(9)^+$	07			1979	α=91 5;β^+ ?	
^{162}Os	−14500#	300#					2.1	ms	0.1	0^+	07			1989	α=100	

*^{162}Sm^m T : other 17Pa25=1.7(0.2) **
*^{162}Eu T : 17Wu04=11.8(1.4) 87Gr12=10.6(1.0) but values include both gs and isomer **
*^{162}Eu J : from 18Ha19; conf p5/2[413]n7/2[633],K=1+ **
*^{162}Er T : the lower limit is for α decay **
*^{162}Tm^m E : from 66.90+x keV; x<125 keV from 74De47 **
*^{162}Lu^n I : existence is tentative and needs confirmation **

What is NuBase?

- masses (Ex) for isomers ($T_{1/2}$>100 ns) and their method of deduction – integral part of AME
- $T_{1/2}$, Jπ, decay modes and BR for both ground states (**3558**) and isomers (**1983**)
- properties of **205** Isobar Analog States (IAS)

Why NuBase?

- **complete** - include all measured quantities and their uncertainties
- **up-to-date** - include results from all recent publications
- **credible and reliable** - identify and resolve contradictory results that exist in the scientific literature, as well as in other nuclear physics databases, *e.g.* **ENSDF**
- **properly referenced** - provide comprehensive bibliographical information for all included properties.

Chinese Physics C Vol. 45, No. 3 (2021) 030001

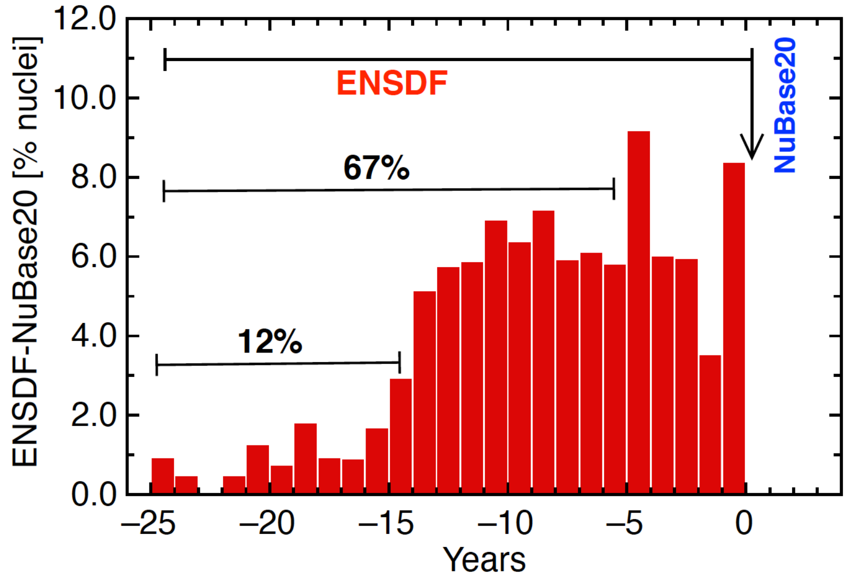
The NUBASE2020 evaluation of nuclear physics properties**

F.G. Kondev [1,*], M. Wang (王猛)[2,3,*], W.J. Huang (黄文嘉)[2,4,5,6], S. Naimi[7], G. Audi (欧乔治)[6]

3558 ground states: 256 not in ENSDF
1983 isomers: 241 not in ENSDF

How is NuBase updated?

- directly from the literature by compiling and evaluating data published in primary and secondary references
- by consulting, and when merited by adopting, recommendations made in topical evaluations
- by consulting, and when merited by adopting, recommendations made in ENSDF

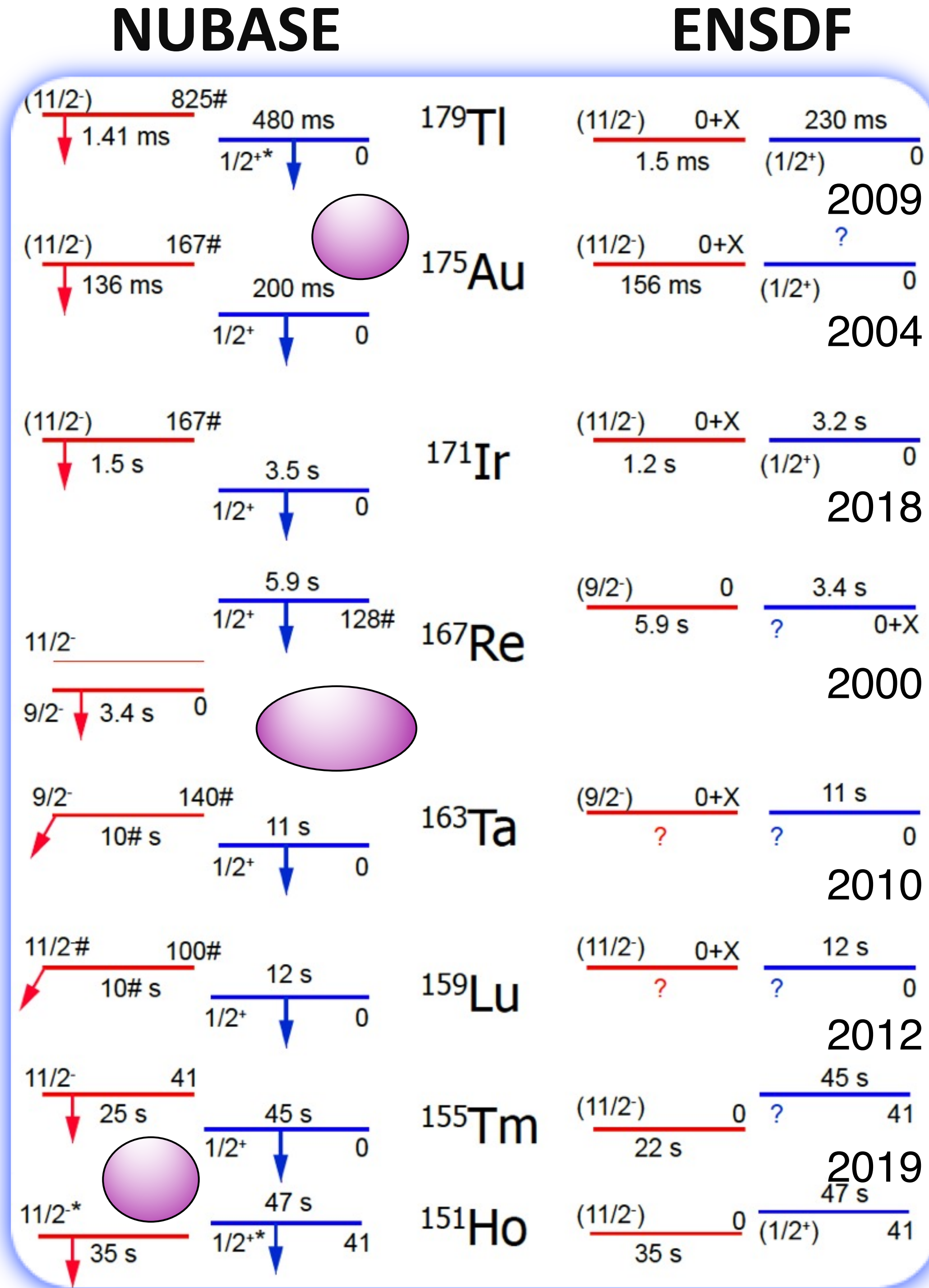


ENSDF is a **treasure** to the NP community

- becoming increasingly outdated
- non-uniform in coverage & subjectivity

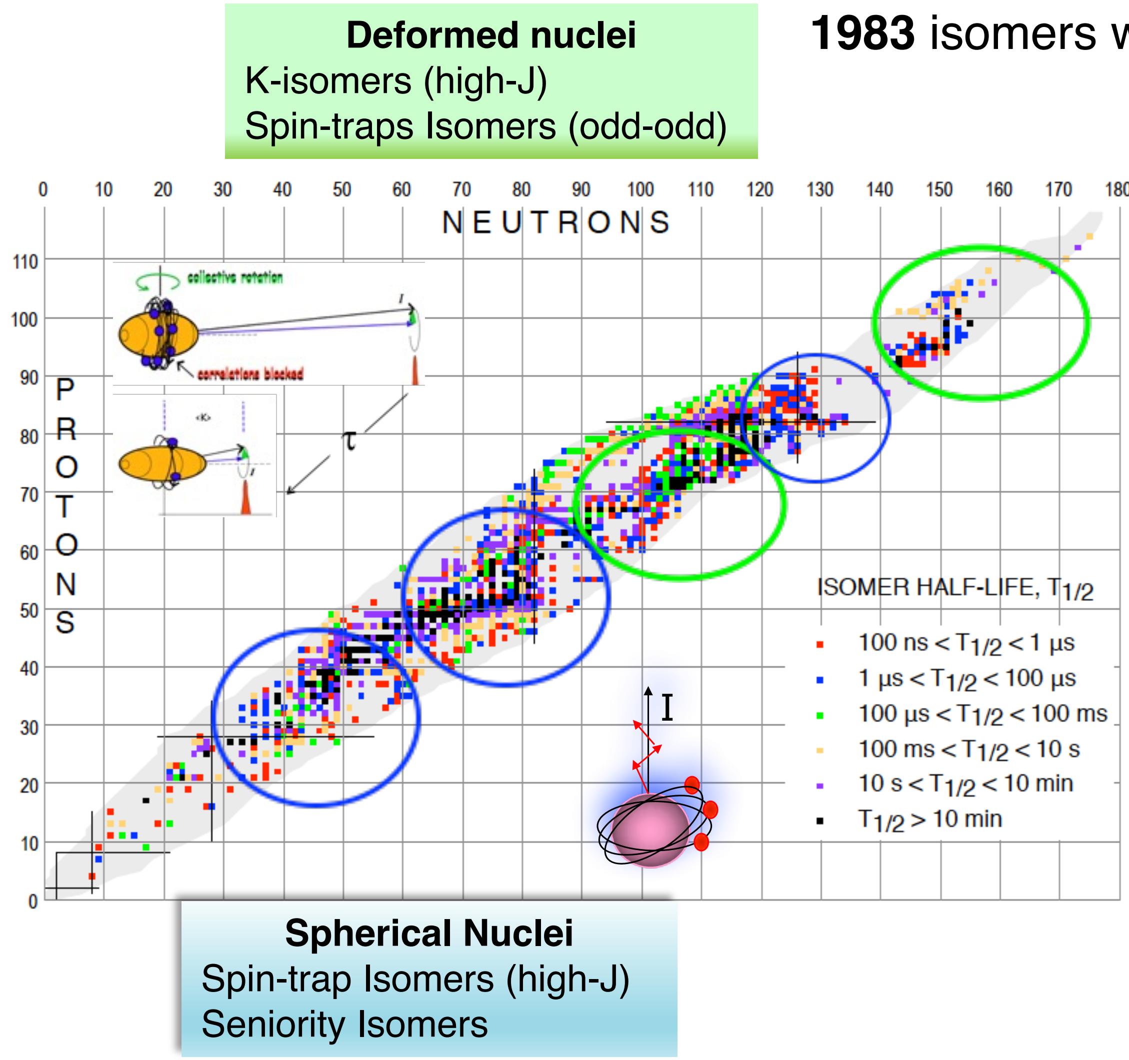
A=179 decay chain

- recommended values for the 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
  - ▶ lifetimes, *e.g.* ^{175}Au & ^{179}Tl
  - ▶ ordering – *e.g.* ^{155}Tm
- consistent Jπ assignment
  - ▶ shape changes



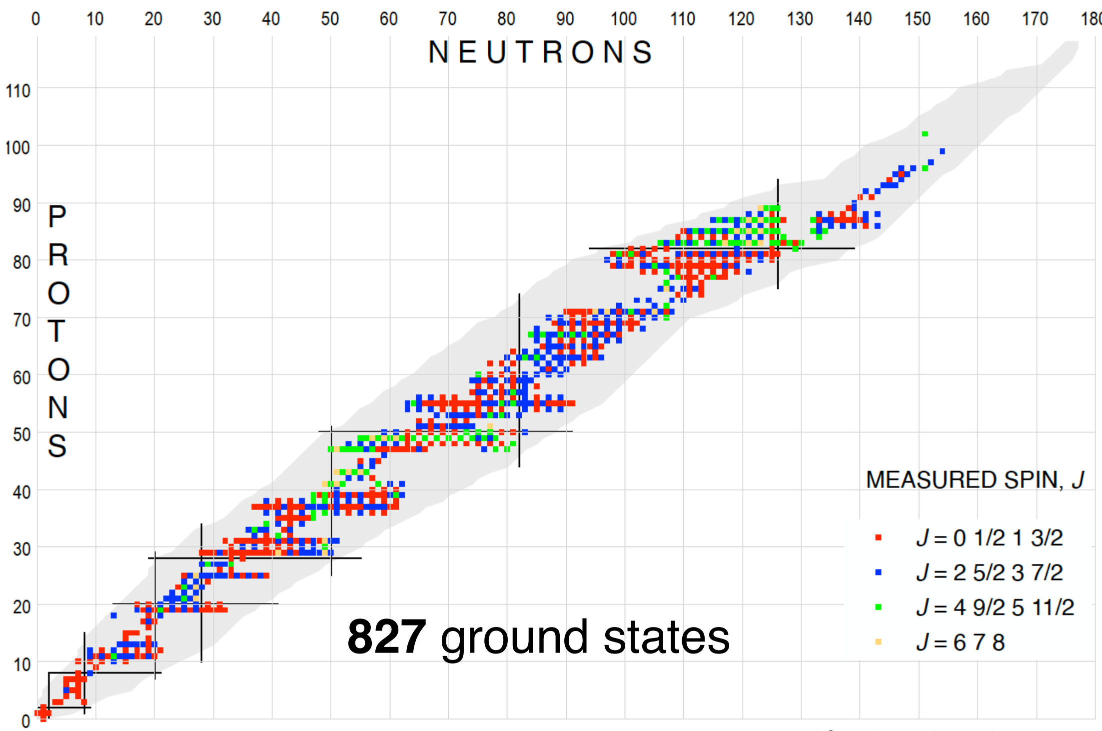
Isomers

1983 isomers with $T_{1/2}$ > 100 ns



- Excitation energy (E_x) & $T_{1/2}$
  - ▶ E_x=160#(40#) keV in NuBase, but +X(+Y, …) in ENSDF
  - ▶ $T_{1/2}$ - "#" from systematics – Trend in Neighboring Nuclei (TNN) - e.g.$T_{1/2}(^{233}Th^m)$=2# s – from the known BE3 for $^{235}U^m$ - the same configuration change
- not clear which state is the ground state or the isomer
  - ▶ '*' in col [59:59] – $\Delta E_x > E_x/2$
  - ▶ '&' in col [60:60]
- previous assignments in doubt
  - ▶ EU in col [61:62] – **11** cases, *e.g.* $^{138}Pm^m$ (10 s) – gs in ENSDF
  - ▶ RN in col [61:62] – **9** cases, *e.g.* $^{181}Pb^m$
- uncertainties are symmetrized – $X(+\Delta X_1-\Delta X_2)$ to $Y(\Delta Y)$

Directly measured spins

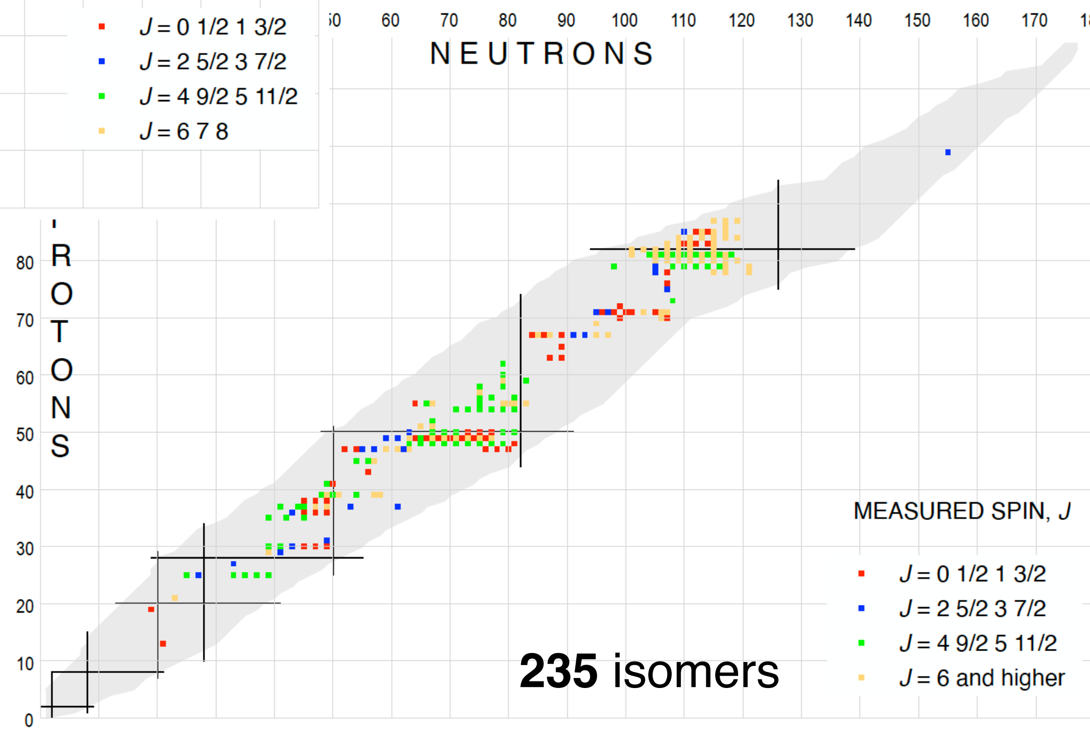


ENSDF: Jπ=(1/2-)
- weak experimental arguments
- systematics or theory

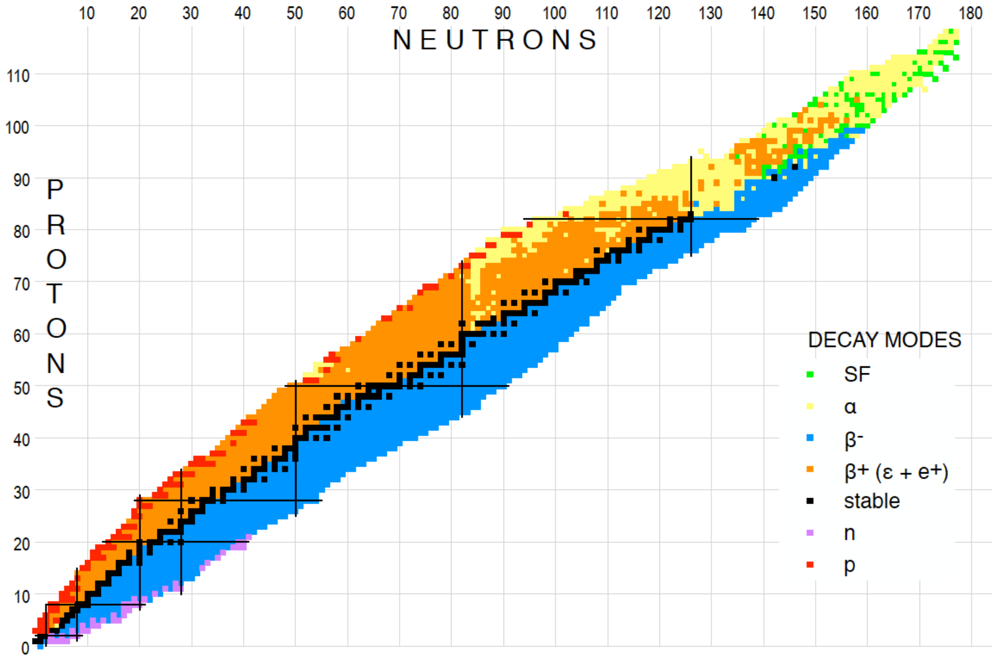
NuBase: Jπ=(1/2-)
- weak experimental arguments

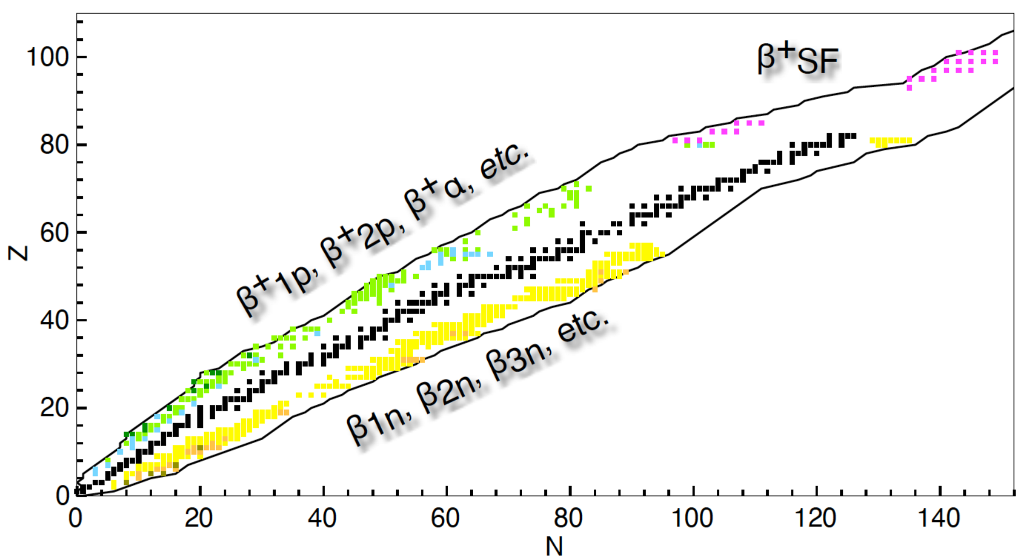
NuBase: Jπ=1/2-#
- systematics or theory

NuBase: Jπ=1/2-*
- directly measured spins – a wealth of new information using “in-source” (*e.g.* RILS at ISOLDE and TRILIS at TRIUMF) and “collinear” (*e.g.* CRIS at ISOLDE) laser spectroscopy
- parity from other spectroscopic data



Decay branching ratios





ENSDF: EC=β⁺ + ε

%α=60; %EC=40%

- often not clear which one was measured
- systematics or theory

NuBase: β⁺=e⁺ + ε

- %α=60; %β⁺=40
- %α=60; %β⁺= ?
- %α=60; %β⁺ ?

complete, up-to-date & reliable information about the beta-delayed emission probabilities

Conclusions & Outlook

- the new AME & NuBase evaluations have been just released – complete, up-to-date & reliable information about the basic NP properties

https://www-nds.iaea.org/amdc/ (IAEA) http://amdc.impcas.ac.cn (IMP)

https://www.anl.gov/phy/atomic-mass-data-resources (ANL)

- if you spot a typo or error or if something is not clear please let us know:
  kondev@anl.gov (F.G. Kondev) and/or wangm@impcas.ac.cn (M. Wang)

future additions & improvements

- extension to other NP properties – magnetic & quadrupole moments, charge radii & isotope shifts, cross sections needed for astrophysics simulations & other properties needed to various applications
- improving treatment of data correlations & extrapolations