How Well Do We Know the Basic Properties of Nuclei: Update on the AME and NUBASE Nuclear Data Libraries

F.G. Kondev
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on behalf of AME & NUBASE collaboration

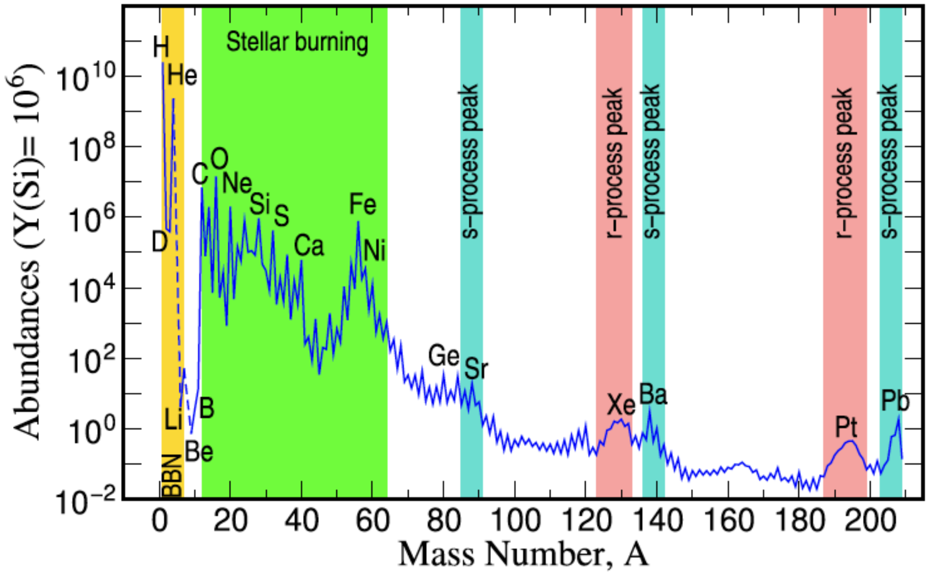
Nuclear Physics Properties & Astrophysics

⇒ major goal of Nuclear Astrophysics is to understand the Stellar Evolution of Stars & the Origin of Elements

- needs comprehensive nuclear data for **ALL** known and **MANY** unknown nuclei in their ground states and excited isomers

⇒ mass is the key nuclear property – nuclear decay & reactions phase spaces, e.g. decay Q values & reaction probabilities

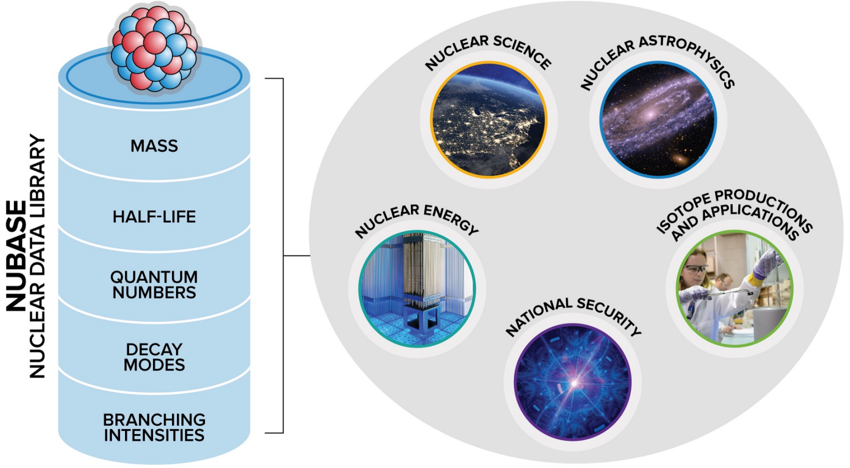
- influence all other nuclear properties $T_{1/2}$, BR, $P_{\beta-n}$, $P_{\beta+p(a)}$, reaction cross sections, etc. -> impact on theoretical models and astrophysics network calculations



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

AME & NUBASE

⇒ provide the evaluated (recommended) values for atomic masses, various decay and reaction Q values & other basic nuclear properties ($T_{1/2}$, Jπ, **decay modes and BR**) for all known (and a few unknown) nuclei in their ground and isomeric ($T_{1/2}$ >100 ns) states



⇒ latest libraries were published in March 2021:

AME2020 & NUBASE2020

- coordinated by M. Wang (IMP) & F.G. Kondev (ANL)
- recommended data for **3558** ground states and **1983** isomers

AME approach

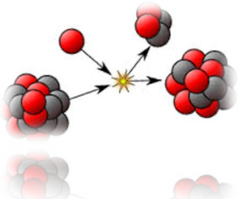
⇒ **COMPILATION of the Worldwide Produced Mass-related Data**

☛ **DIRECT Methods:**

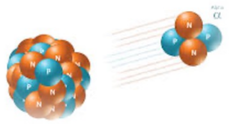
- TOF & MR-TOF, Storage Rings & Penning Traps

☛ **INDIRECT Methods**

- Reaction Energies (n,γ), (p,γ) and (a,b) – close to stability
- Decay Energies – far from stability
  - end-point energies in β^- and β^+ decays – accuracy?
  - β^+–delayed charged-particle energies
  - α and p decay energies – heavy nuclei & proton-rich nuclei



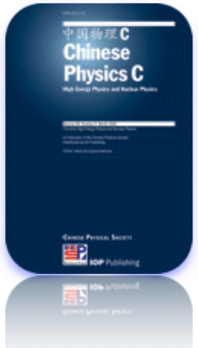
$Q_r = M_A + M_a - M_b - M_B$



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

⇒ **EVALUATION of all experimental data**

- critical examination – many are accepted, some are rejected and/or modified -> identify & resolve conflicting data
- statistical treatment (weighted averages) of data of the same kind



⇒ **LEAST-SQUARES FIT ADJUSTMENT to all selected data**

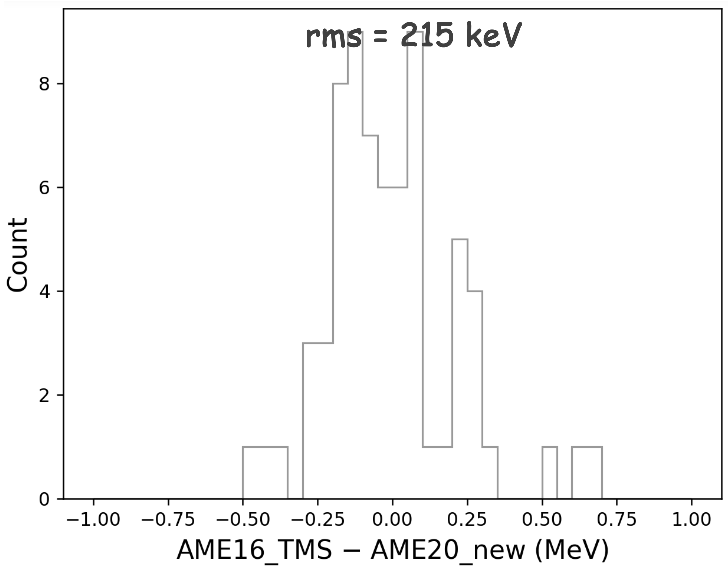
- combine the accepted values using the least-squares fit approach
- **FINAL RESULT** -> mass values & covariances for all known nuclei

AME extrapolations (data with #)

⇒ using an empirical approach by assuming that the Trend of the Mass Surface (TMS) is smooth

- TMS extrapolated mass values for a limited number of unknown nuclei
- replace "irregular" experimental masses by TMS extrapolated values – 77 cases in AME2020

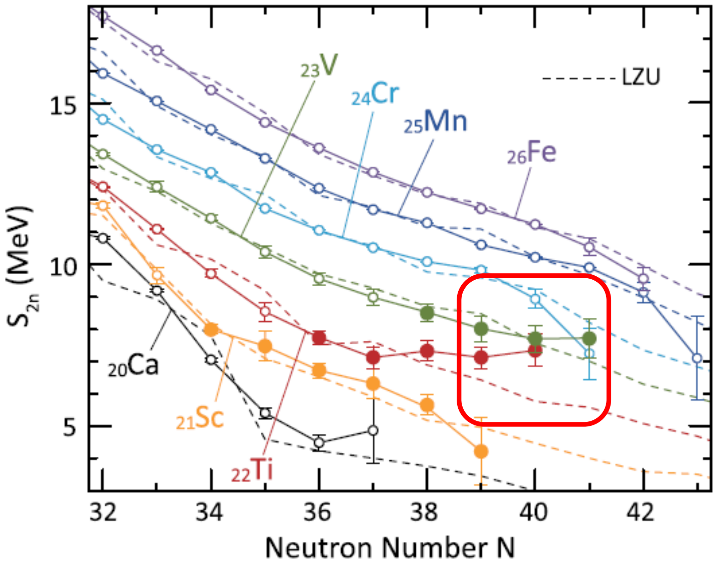
accuracy of the AME extrapolation



TMS in AME2016, BUT exp in AME2020

not always justified … new physics?

S. Michimasa et al., PRL125 (2020) 122501



build up of deformation around N=40

Ground states & Isomers

- beware of isomers – do we have the right relations?

DIRECT

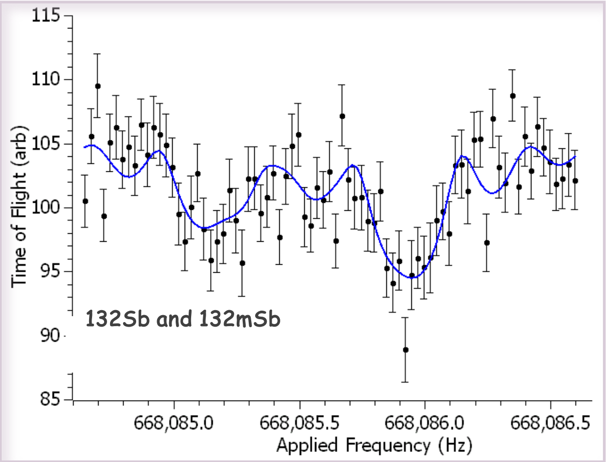
18Ha19	107678.2	1.6	162Eu-84Kr1.929
20Vi04	52124.0	6.0	162Eu-133Cs1.218
18Ha19	107850.1	2.0	162Eum-84Kr1.929
20Vi04	52280.4	2.4	162Eum-133Cs1.218
20Vi04	52292.4	8.1	162Eum-133Cs1.218

INDIRECT

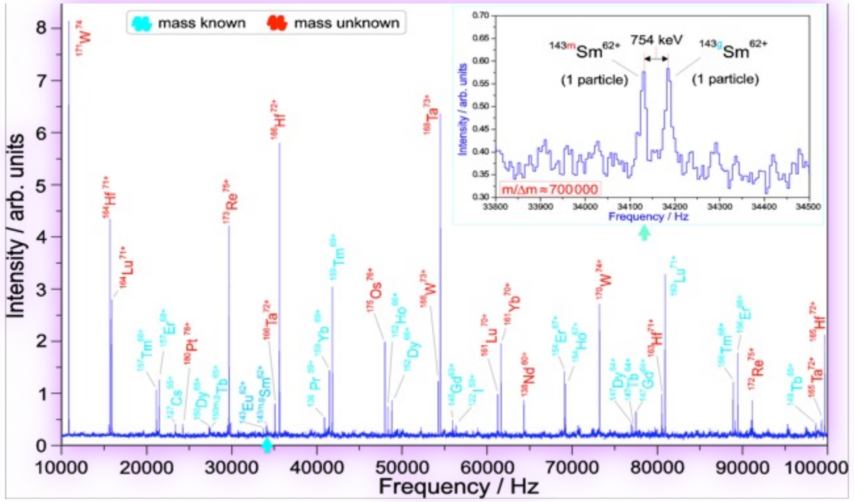
20Ma27	9725.2	30.6	220Pa(a)216Ac
21Ma66	9725.2	30.6	220Pa(a)216Ac
18Hu13	9730.3	20.4	220Pam(a)216Ac
21Ma66	9843.3	40.7	220Pam(a)216Ac
21Ma66,*	9843.3	40.7	220Pan(a)216Ac

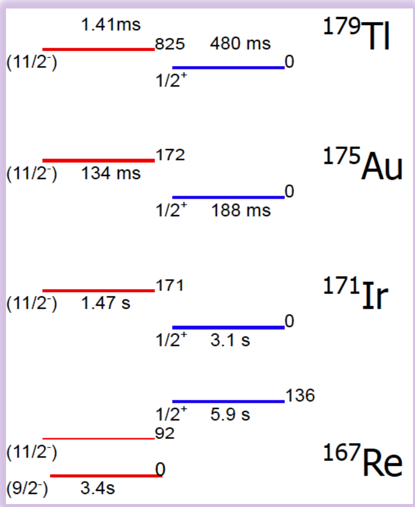
⇒ need to assign a mass measurement result to a specific nuclear state (ground state or isomer)

- cases where the experimental Δm/m is insufficient to resolve ground state from isomers
- cases where excitation energy of the isomer is used to determine the ground state mass (e.g. ^{183m}Tl)



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





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

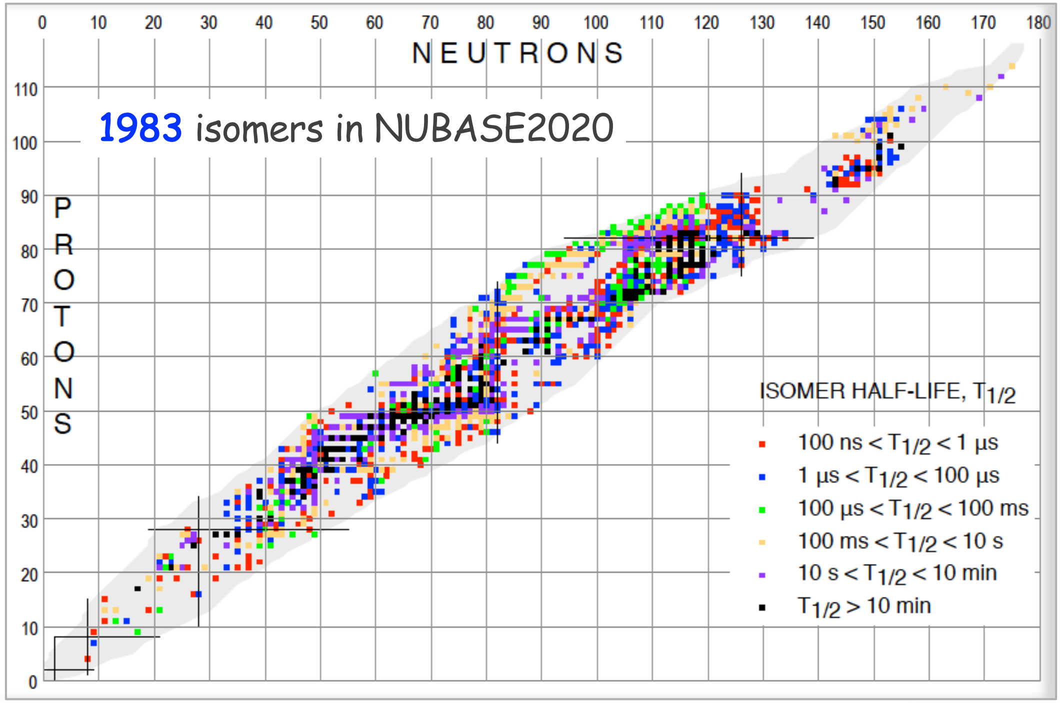
The NUBASE2020 evaluation of nuclear physics properties**

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]

⇒ complete, up-to-date & reliable information about the basic NP properties for gs & isomers

^{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 ∗∗



⇒ masses (Ex) for isomers 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

AME & NUBASE cover majority of nuclear properties needed in astrophysics simulations -> widely used in all Astro libraries

Value of Evaluation – example $^{69,69m}Co$

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

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)	D
^{67}Fe	394(9)	$(1/2^-)$	0.797874190(8)	−45709.1(3.8)	−45610(270)	
^{69}Co	180(20)	$7/2^-$#	0.821649141(428)[a]	−50383(44)	−50280(140)	
^{69}Co^m	750(250)	$1/2^-$#	0.821651504(291)[a]	−50207(36)	−49780(240)#	
^{70}Co[b]	508(7) [50]	$(1^+, 2^+)$ [50]	0.833615937(21)	−46525(11)	−46430(360)#	

…publication

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

1

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)]

erratum …

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)#

PHYSICAL REVIEW C **97**, 014309 (2018)

2

Precision mass measurements of neutron-rich Co isotopes beyond $N = 40$

Ion	Reference	Frequency ratio	Mass (u)	ME (keV)	AME2016 (keV)	ΔME (keV)
$^{68}Co^{2+}$	$^{16}O^{18}O^{+}$	1.000 641 552(70)	67.944 559 2(48)	−51 642.8(4.4)	−51 930(190)	290(190)
	$^{34}S^{+}$	0.999 870 11(12)	67.944 559 3(82)	−51 642.6(7.6)		290(190)
$^{69}Co^{2+}$	$^{39}K^{+}$	1.130 267 90(24)	68.946 093(15)	−50 214(14)	−50 280(140)	66(140)

claimed to be ^{69}Co, but it is actually ^{69m}Co

- ^{69}Co – 100% influence from 1
- ^{69m}Co – 93% influence from 2 and 7% influence from 1

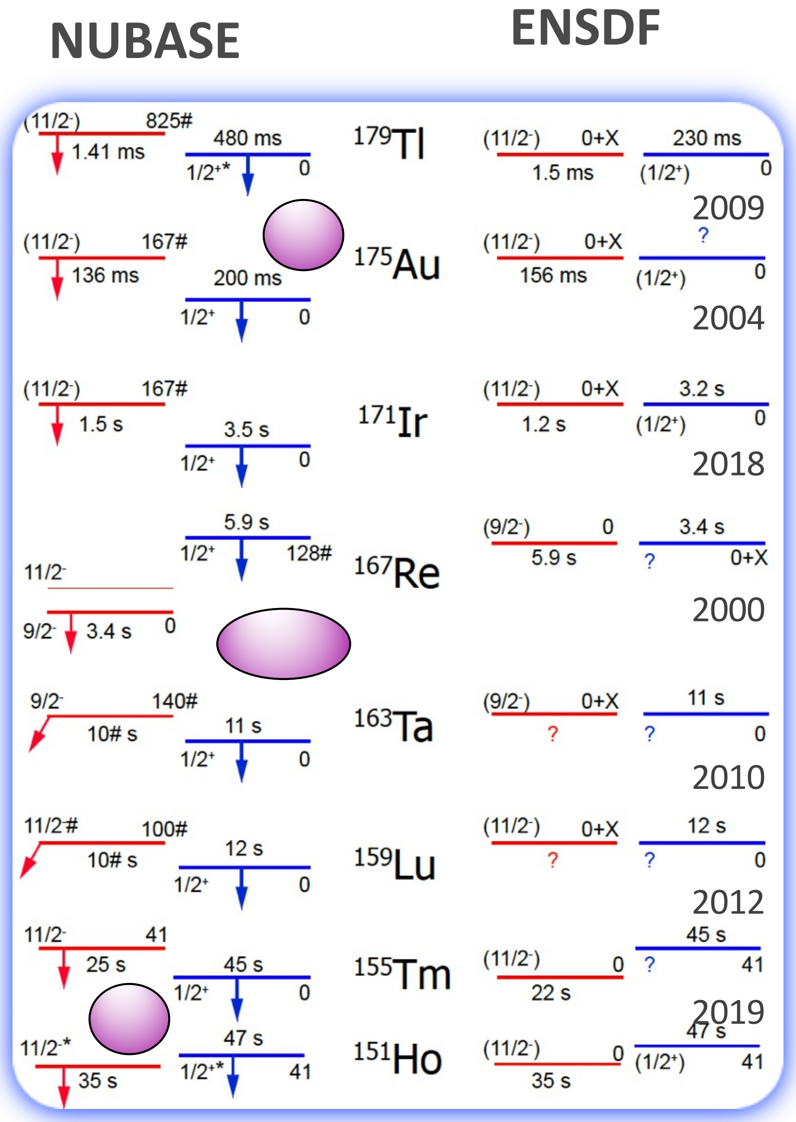
Example: A=179 decay chain

⇒ENSDF in principle contains the needed nuclear structure information, BUT
- increasingly outdated
- non-uniform in quality and coverage
- differences in polices

<u>Comparison between NUBASE & ENSDF</u>

⇒resolving ground states & isomers
- excitation energies
- lifetimes, e.g. ^{175}Au & ^{167}Re
- ordering of the states – e.g. ^{155}Tm

⇒consistent Jπ assignment
- shape changes



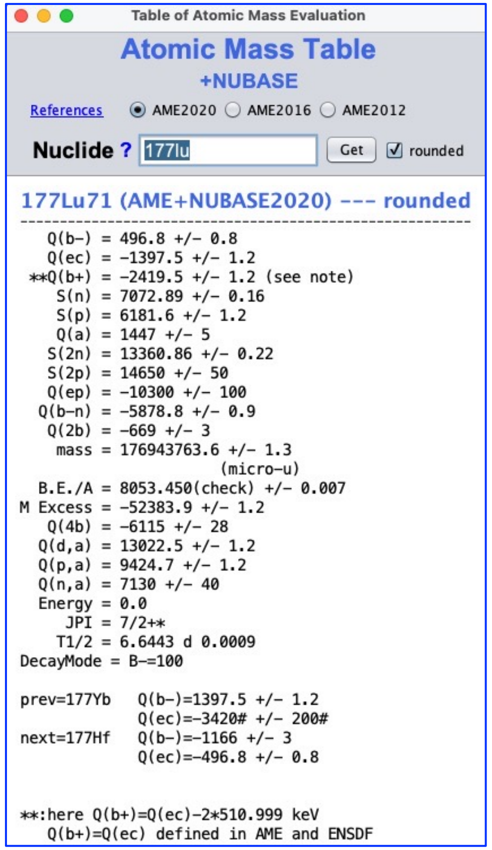
Where to find the data

pdf & ascii
covariances

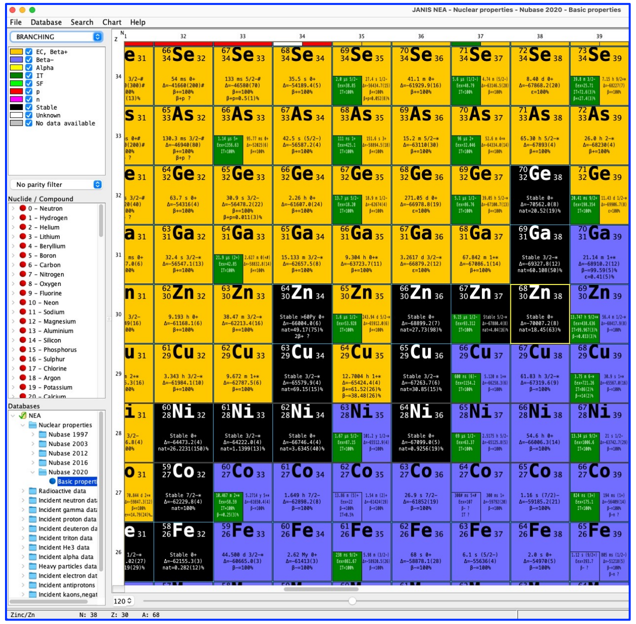
https://www.anl.gov/phy/atomic-mass-data-resources (ANL)
https://amdc.impcas.ac.cn/web/nubcleus%202_en.html (IMP)
https://www-nds.iaea.org/amdc/ (IAEA)

JAVA-AME
J. Chen

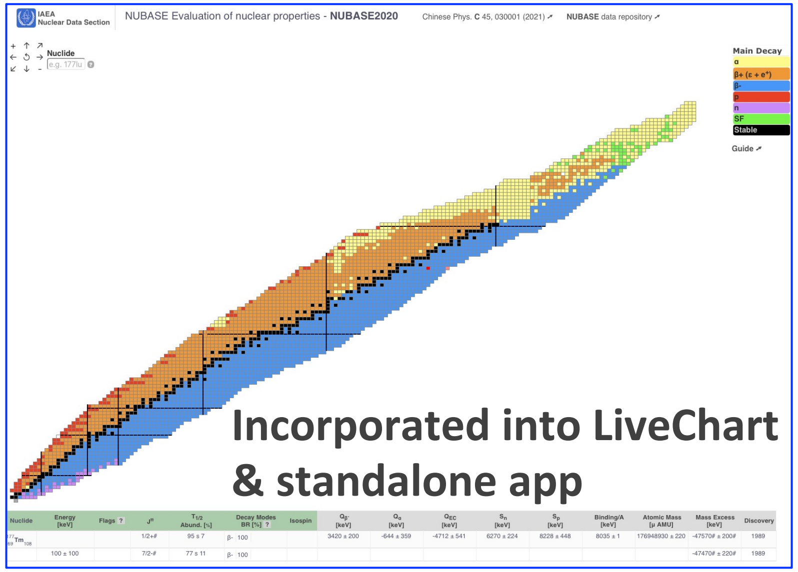
stand-alone & www



JANIS
NUBASE1997-2020
Nicolas Soppera



NUBASE2020
Marco Varpelli



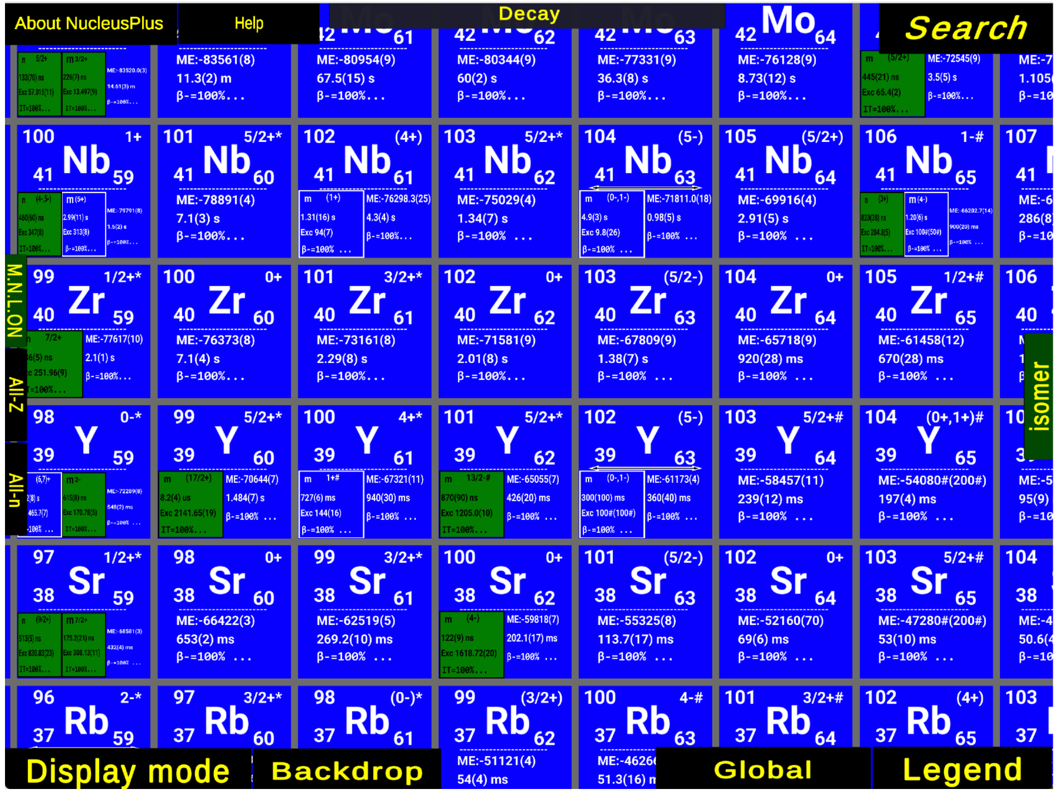
Incorporated into LiveChart & standalone app

New dissemination platforms

https://amdc.impcas.ac.cn/web/nubcleus%202_en.html (IMP)

Nucleus++: a new tool bridging AME and NUBASE for advancing nuclear data analysis

Jin-Yang Shi[1,2] · Wen-Jia Huang[3,2] · Meng Wang[2] · Xin-Liang Yan[2] · David Lunney[4] · Georges Audi[4] · Filip G. Kondev[5] · Sarah Naimi[4] · Rikel Chakma[5]



Desktop Applications

macOS

Windows

Mobile Applications

iPhone & iPad

Android

Next AME & NUBASE Updates

- historically - A. Wapstra (since 1948), G. Audi (since 1985) & others
- since 2006 a collaboration effort between ANL, IJCL & IMP

⇒ followed a 4 years publication interval - 2012, 2016, 2020 …

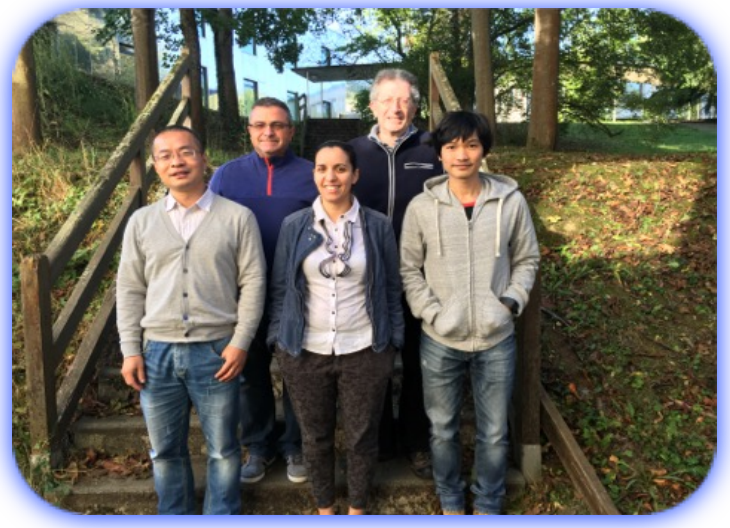
- next tables were planed for 2024 -> aiming at mid 2026

⇒ relatively small effort – 4 part-time staff (~1 FTE total) & 1 full time post-doc

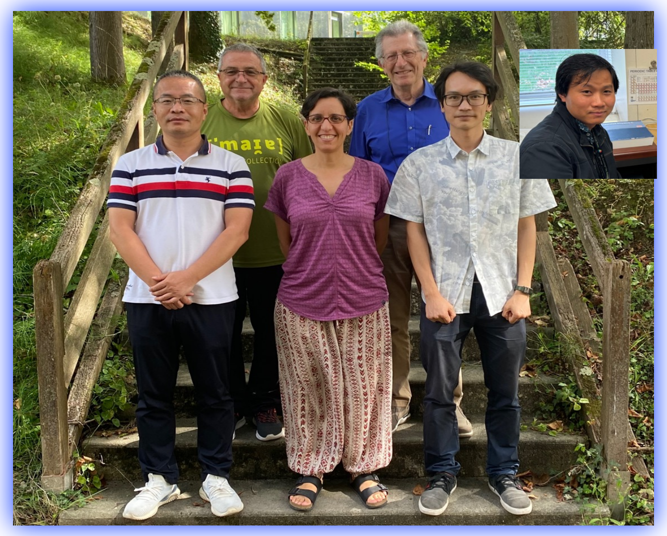
- maintaining the expertise, currency & quality

2013

2016

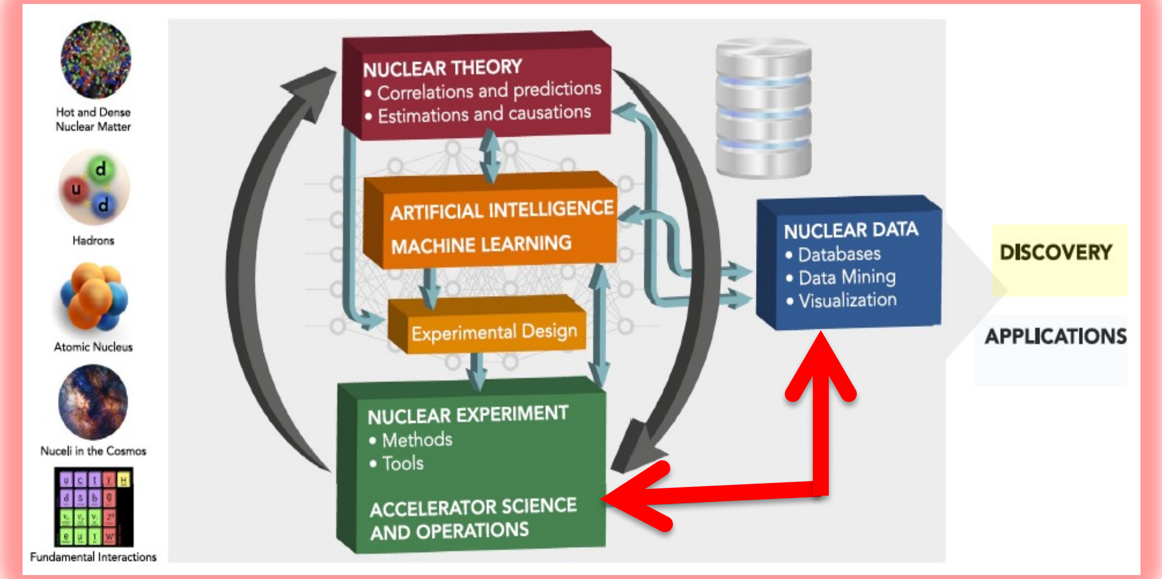


2023



Rikel Chakma
post-doc @ANL

Role of Evaluated Nuclear Data



Rev. Mod. Phys. 94 (2022) 031003

⇒ **Role of Nuclear Data:** collect experimental results, assess the data and provide recommended (best) values for all nuclear properties

⇒ **Essential Requirements:** comprehensive, complete, up-to-date & reliable

Value of the evaluated data

- archival of all experimental data - both published and unpublished - planning & executing new experiments, their analysis, interpretation & publication of the results
- resolve differences between overlapping and contradictory results
- identify and stimulate needs for new experiments
- beneficial to nuclear theory development
- input to specialized astro libraries and codes
- beneficial to many applied areas, e.g. nuclear medicine, nuclear energy, national security, etc.