The Atomic Mass Evaluation – An Example of Nuclear Physics Data for Fundamental Physics and Applications

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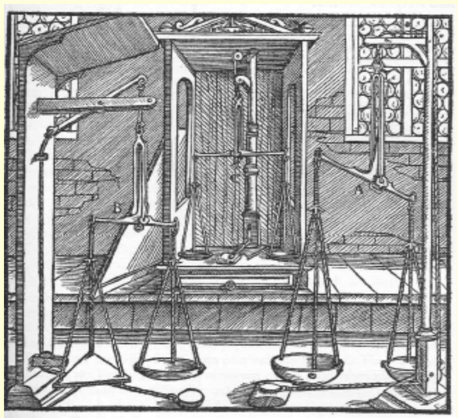

Balances from “De re metallica, Liber Septem”
G. Agricola, 1556

- Introduction
  Relative weights of the elements
- Isotopic masses
- Atomic mass evaluations
- The AAME project
- Application of atomic masses
- Nuclear astrophysics
- New developments in observation and calculations

LEBIT Penning trap

national nuclear data center

Nuclear Data Week at BNL
US Nuclear Data Program, November 4-6, 2009

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29: The bellows are burned, the lead is consumed of the fire; the founder melteth in vain:
for the wicked are not plucked away.
30: Reprobate silver shall men call them, because the LORD hath rejected them.

Jeremias, 6 ca. 600 B.C.E.

Nuclear data on isotopes, stable or radioactive, are needed in many fields:
• applications as e.g. tracer techniques or medical treatments
• nuclear technology
• astrophysics

Many nuclear structure effects manifest themselves already in the masses of the nuclear ground (and isomeric) states.

But one ought not forget that the importance of precise mass determinations does not begin with the detection of the first isotopes. This discovery solved a longstanding problem with the relative weight of the elements, going back to around AD 1800.
And according to historians of science, the use of precise balances by some alchemists was instrumental for the (slow) transition from alchemy to modern chemistry.
Chemical quantitative analysis was practised since antiquity (by e.g. craftsmen in metal-lurgy), but alchemists with their pending for esoteric philosophy were not interested in quantitative relationships. Around 1800, Richter, Proust, Dalton established stoichiometry and the Laws of Definite and Multiple Proportions.

As an explanation, Dalton reintroduced the atoms of Leukippos and Demokritos.

See also Ezekiel 22, 17-22 or Zechariah 13, 9

Table of the relative weights of the ultimate particles of gaseous and other bodies

Appended to
J. Dalton
“On the Absorption of Gases by Water and Other Liquids”
Memoirs and Proceedings of the Manchester Literary and Philosophical Society, Manchester, 1805, vol. 6, pp. 271-287

This paper was already presented orally in 1803.
It contains the first steps to the atomic hypothesis to explain the laws of definite and multiple proportions.
The first table of relative weights is appended without explanation of the methods applied.

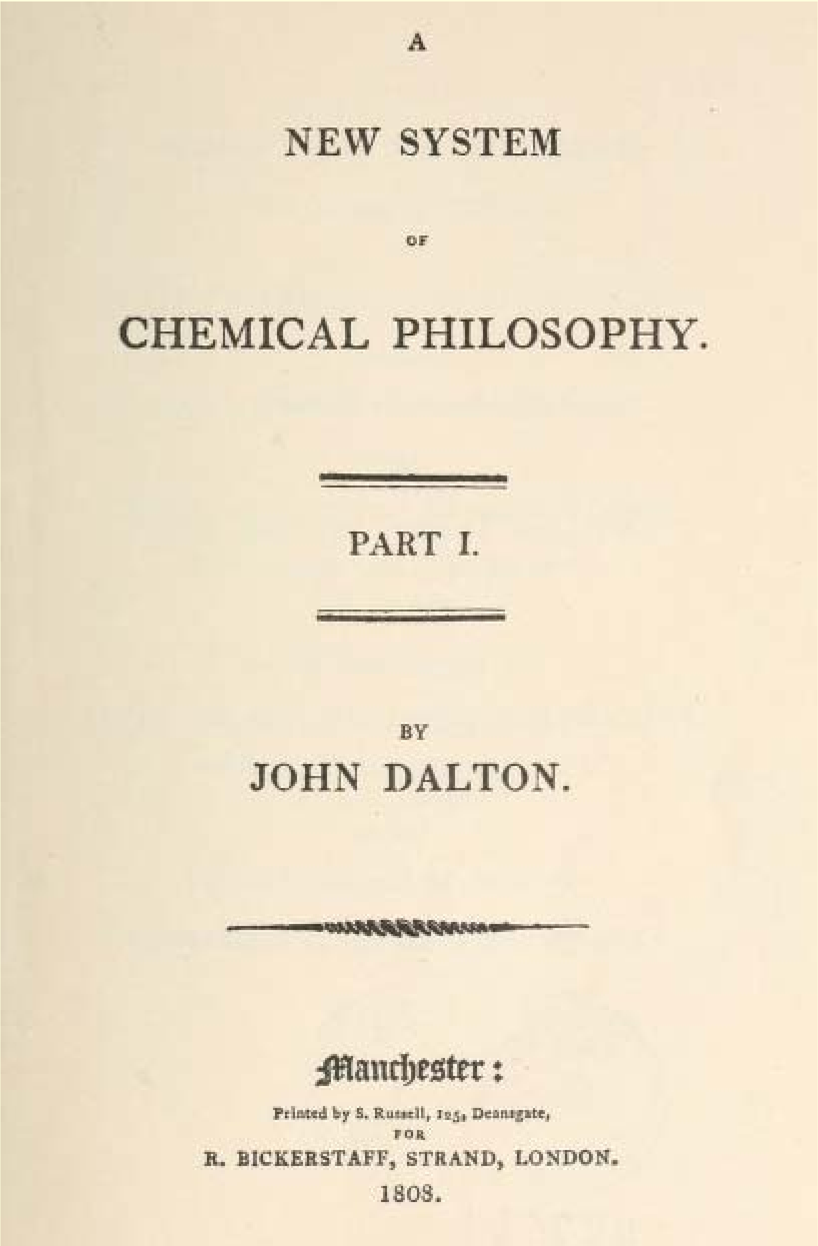
http://web.lemoyne.edu/~giunta/dalton52.html

TABLE

of the relative weights of the ultimate particles of gaseous and other bodies.

Hydrogen	1
Azot	4.2
Carbone	4.3
Ammonia	5.2
Oxygen	5.5
Water	6.5
Phosphorus	7.2
Phosphuretted hydrogen	8.2
Nitrous gas	9.3
Ether	9.6
Gaseous oxide of carbone	9.8
Nitrous oxide	13.7
Sulphur	14.4
Nitric acid	15.2
Sulphuretted hydrogen	15.4
Carbonic acid	15.3
Alcohol	15.1
Sulphureous acid	19.9
Sulphuric acid	25.4
Carburetted hydrogen from stag. water	6.3
Olefiant gas	5.3

John Dalton
A New System of Chemical Philosophy (1808)



A

NEW SYSTEM

OF

CHEMICAL PHILOSOPHY.

PART I.

BY

JOHN DALTON.

Manchester:

Printed by S. Russell, 125, Deansgate,

FOR

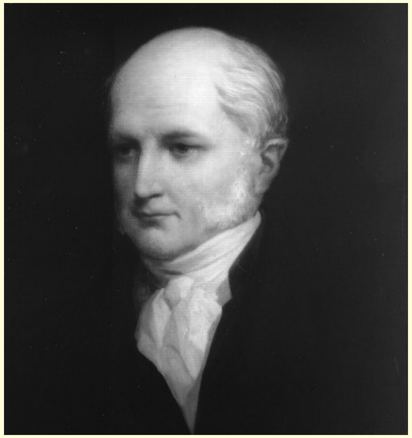
R. BICKERSTAFF, STRAND, LONDON.

1808.

http://www.archive.org/stream/newsystemofchemi01daltuoft

An ahead of time nucleosynthesis hypothesis?

In 1816, the physician Prout (and the chemist L. Meinecke) put forward the hypothesis that all relative weights of the elements are whole-number multiples of the weight of hydrogen.
[It is generally assumed, that he did not base this assumption on contemporary measurements, but on natural philosophy. He set the πρωτη νλη of the Greek philosophers synonymous with H.]



William Prout (1785-1850)

Some scientists in the 19th century assumed that "atoms" were composed of H atoms. Does anyone know, if they had speculated on nucleosynthesis by adding H on atoms?

In the following decades, chemists pushed the techniques to the limits in order to prove or disprove Prout's hypothesis (and advanced many ad-hoc "improvements").
Around 1860, relative atomic weights for 57 elements had been determined and they were one essential ingredient for the establishment of the "Periodic System" by Mendeleev and Meyer.

Remark: Still in the 20th century, isotopic masses were calculated from isotopic abundances and chemically measured elemental relative weights.

The periodic system of the elements

Based on chemical properties and the relative weights, in 1868/9 D.I. Mendeleev and L. Meyer developed the Periodic System of the Elements.

TABELLE II

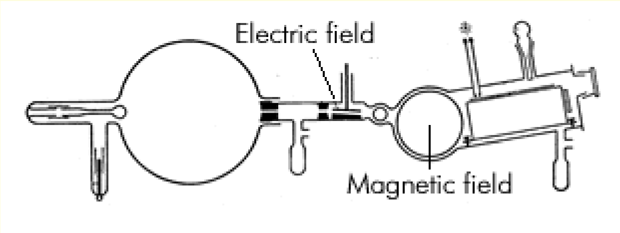
REIHEN	GRUPPE I. — R^2O	GRUPPE II. — RO	GRUPPE III. — R^2O^3	GRUPPE IV. RH^4 RO^2	GRUPPE V. RH^3 R^2O^5	GRUPPE VI. RH^2 RO^3	GRUPPE VII. RH R^2O^7	GRUPPE VIII. — RO^4
1	H = 1							
2	Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19	
3	Na = 23	Mg = 24	Al = 27,3	Si = 28	P = 31	S = 32	Cl = 35,5	
4	K = 39	Ca = 40	— = 44	Ti = 48	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 59, Cu = 63.
5	(Cu = 63)	Zn = 65	— = 68	— = 72	As = 75	Se = 78	Br = 80	
6	Rb = 85	Sr = 87	?Yt = 88	Zr = 90	Nb = 94	Mo = 96	— = 100	Ru = 104, Rh = 104, Pd = 106, Ag = 108.
7	(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 125	J = 127	
8	Cs = 133	Ba = 137	?Di = 138	?Ce = 140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er = 178	?La = 180	Ta = 182	W = 184	—	Os = 195, Ir = 197, Pt = 198, Au = 199.
11	(Au = 199)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
12	—	—	—	Th = 231	—	U = 240	—	— — — —

Figure 2.5 Dmitri Mendeleev's 1872 periodic table. The spaces marked with blank lines represent elements that Mendeleev deduced existed but were unknown at the time, so he left places for them in the table. The symbols at the top of the columns (e.g., R^2O and RH^4) are molecular formulas written in the style of the 19th century.

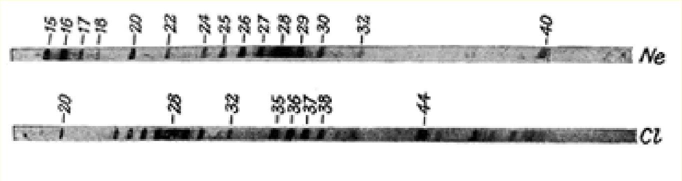
But, essential for the success was the preference of chemical similarities, the Law of Periodicity, which allowed to make testable predictions for unobserved elements.

Isomerism and mass formulas

- Prout's hypothesis was "philosophically" attractive and therefore scientists imagined amendments to stick to it.
- Sir William Crookes hypothesized 1871 that deviations from this rule indicate to "isotopes".
- J.J. Thomson / F.W. Aston observed 1912 with cathode rays, that Ne had two isotopes of mass 20 and 22.
- After the war, F.W. Aston measured isotopic masses .
- Based on these masses, Arthur Eddington explained 1920 the energy source of stars as fusion of H to He.



Aston's design for the mass spectrograph.

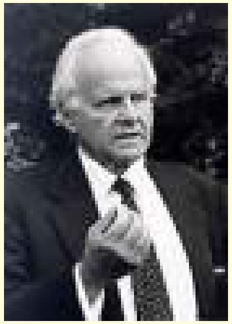


But isotopes important for astrophysics early on were not accessible to experiments.
Therefore, based on the liquid drop model C.F. v. Weiz-säcker *[Z. Physik 96 (1935) 431]* and H.A. Bethe and R.F. Bacher *[Rev. Mod. Phys. 8 (1936) 82]* developed a

semiempirical mass formula,

that served as basis for nucleosynthesis models for a long time, as the CNO- or Bethe-Weizsäcker-cycle:
C.F. v. Weizsäcker, *Z. Physik 39 (1938) 633* and
H. Bethe, *Phys. Rev. 55 (1939) 434*


Hans Bethe
1906-2005


Carl Friedrich von Weizsäcker 1912

Early Mass Compilatons/Evaluations

The more recent history of atomic masses can be found in: Georges Audi
"The history of nuclidic masses and of their evaluation"
International Journal of Mass Spectrometry 251 (2006) 85–94

An early (perhaps the first) attempt for a mass evaluation is
M.S. Livingston, H.A. Bethe, "Nuclear Physics: C. Nuclear dynamics, experimental"
Rev. Mod. Phys. 9 (1937) 245
XVIII. Nuclear masses; p. 366
The authors combined data from mass spectrometry and nuclear reaction and decay data up to ^{40}Ar.

In general, compilations of masses did not contain information on decay properties as half-lives or γ-transitions, and vice-versa. The only exception I know, is the 1949 „Isotopic Report" of Mattauch/Flammersfeld. In addition, it was updated by data from the US from a manuscript of the 1948 „Table of Isotopes".

In the early 1950's it was found that the many relations (direct and indirect) over-determined the mass value of many nuclides.
Aaldert H. Wapstra established a procedure using a least-squares method to solve this problem (still at the basis of the AME).
The first table of atomic masses using this method is dated 1955.

50 years of modern mass evaluations

A.H. Wapstra, Physica 21 (1955) 367 + 385; J.R. Huizenga, Physica 21 (1955) 410
F. Everling, L.A. König, J.H.E. Mattauch, A.H. Wapstra, Nucl. Phys. 18 (1960) 529
L.A. König, J.H.E. Mattauch, A.H. Wapstra, Nucl. Phys. 31 (1962) 18
R.R. Ries, R.A. Damerow, W.H. Johnson, Jr., Phys. Rev. 132 (1963) 1662 + 1673
J.H.E. Mattauch, W. Thiele, A.H. Wapstra, Nucl. Phys. A67 (1965) 1 + 32 + 73

After the retirement of Mattauch in 1965, the AMEs (as far as I know) were directed by Aaldert H. Wapstra.

A.H. Wapstra & K. Bos, At. Data Nucl. Data Tables 19 (1977) 175
A.H. Wapstra, G. Audi & R. Hoekstra, Nucl. Phys. A432 (1985) 185
G. Audi & A.H. Wapstra, Nucl. Phys. A 565 (1993) 66
C. Borcea, G. Audi, A.H. Wapstra & P. Favaron, Nucl. Phys. A 565 (1993) 158
G. Audi, A.H. Wapstra & M. Dedieu, Nucl. Phys. A 565 (1993) 193
G. Audi & A.H. Wapstra, Nucl. Phys. A 595 (1995) 409
G. Audi, O. Bersillon, J. Blachot & A.H. Wapstra, Nucl. Phys. A 624 (1997) 1
G. Audi, O. Bersillon, J. Blachot & A.H. Wapstra, Nucl. Phys. A 729 (2003) 3
A.H. Wapstra, G. Audi & C. Thibault, Nucl. Phys. A 729 (2003) 129
G. Audi, A.H. Wapstra & C. Thibault, Nucl. Phys. A 729 (2003) 337

The ***Future AME*** (2013 ?) is prepared on a broader, international basis including the Institute for Modern Physics, Lhanzou.

R.R. Ries et al., “Atomic Masses from Ga to Mo”, Phys. Rev. 132 (1963) 1662
R.A. Damerow et al.:”Atomic Masses from Ru to Xe”, Phys. Rev. 132 (1963) 1673

Doublet[a]	Mass difference[b] (u)	Error[c]
$C_7H_{12}-Ru^{96}$	0.186 304 6	38
$C_7H_{14}-Ru^{98}$	0.204 263 5	29
$C_7H_{15}-Ru^{99}$	0.211 442 8	30
$C_7H_{16}-Ru^{100}$	0.220 983 8	37

Backbone of evaluation:
Mass doublets measured with double-focusing mass spectrometers

Nuclear reaction and β-decay data are then combined with the masses of stable isotopes from the mass spectrometers.

Some mass doublet values from these papers are still part of the 2003 Mass Evaluation!

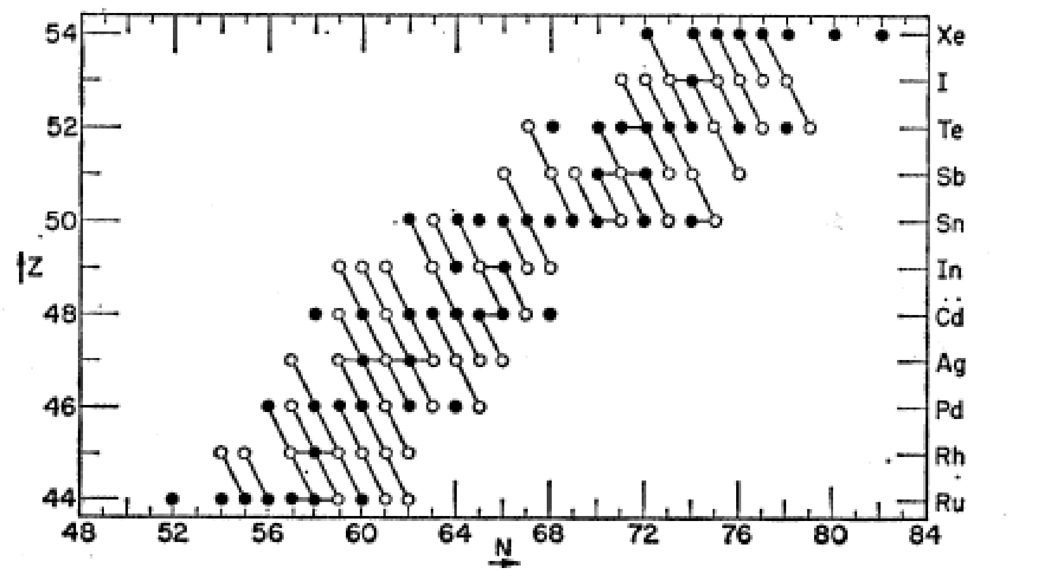


FIG. 2. Nuclear reaction and β-decay paths that were employed to calculate atomic masses of the radioactive isotopes. Solid circles represent stable nuclei, open circles represent radioactive nuclei, and connecting lines indicate nuclear reaction and β-decay mass differences.

Progress in mass measurements and evaluations

A=120

TABLE 9.1 (*continued*)

Nuclear binding energies and mass excesses			
	Binding Energy	Mass Excesses keV	Mass Excesses μMU
^{118}Sn	1004 737 ± 500	—56 522	—60 700 ± 500
^{118}Sb	999 856 ± 550	—52 424	—56 300 ± 550
^{119}Sn	1011 521 ± 500	—54 939	—59 000 ± 500
^{120}Sn	1020 764 ± 500	—55 814	—59 940 ± 500
^{120}Sb	1017 262 ± 500	—53 095	—57 020 ± 500
^{120}Te	1016 907 ± 500	—53 523	—57 480 ± 500
^{121}Sn	1026 943 ± 500	—53 625	—57 589 ± 500
^{121}Sb	1026 542 ± 500	—54 007	—58 000 ± 500
^{122}S[illegible]	[illegible]	[illegible]14	—57 900 ± 500
^{122}S[illegible]	[illegible]	[illegible]43	—56 320 ± 500
^{122}Te	1034 536 ± 500	—54 417	—58 440 ± 500

?

1u = ^{16}O/16

AME 1955

N	Z	A	EL	O	MASS EXCESS (KEV)	
72	48	120	CD	+A	-83981	30
71	49		IN	+	-85700	100
70	50		SN		-91101.8	3.5
69	51		SB		-88421	8
68	52		TE		-89404	21
67	53		I	-	-84000	200
66	[illegible]		[illegible]		[illegible]050	280
65	[illegible]		[illegible]		[illegible]640	320
64	[illegible]		[illegible]		[illegible]050	SYST

1u = ^{12}C/12

AME 1977

^{120}Ru	−50940#	800#				80#	ms
^{120}Rh	−59230#	600#				200#	ms
^{120}Pd	−70150	120				500	ms
^{120}Ag	−75650	70				1.23	s
^{120}Ag^m	−75450	70	203.0	1.0		371	ms
^{120}Cd	−83974	19				50.80	s
^{120}In	−85740	40			∗	3.08	s
^{120}In^m	−85690#	50#	50#	60#	∗&	46.2	s
^{120}In^n	−85440#	200#	300#	200#	∗&	47.3	s
^{120}Sn	−91105.1	2.5				STABLE	
^{120}Sn^m	−88623.5	2.5	2481.63	0.06		11.8	μs
^{120}Sn^n	−88202.9	2.5	2902.22	0.22		6.26	μs
^{120}Sb	−88424	8			∗	15.89	m
^{120}Sb^m	−88420#	100#	0#	100#	∗	5.76	d
^{120}Sb^n	−88346	8	78.16	0.05		246	ns
^{120}Sb^p	−86096	8	2328.3	0.6		400	ns
^{120}Te	−89405	10				STABLE	
^{120}I	−83790	18				81.6	m
^{120}I^m	−83717	18	72.61	0.09		228	ns
^{120}I^n	−83470	23	320	15		53	m
^{120}Xe	−82172	12				40	m
^{120}Cs	−73889	10			∗	61.2	s
^{120}Cs^m	−73790#	60#	100#	60#	∗	57	s
^{120}Cs^x	−73884	9	5	4		$R < 0.1$	
^{120}Ba	−68890	300				24	s
^{120}La	−57690#	500#				2.8	s
^{120}Ce	−49710#	700#				250#	ms

AME 2003 (NUBASE)

Atomic Mass Evaluation & NuBASE

AME 2003

November 18, 2003

3504 masses
3179 - ground-state masses
2228 experimental
951 estimations
325 - isomers
201 experimental
122 estimations

From the 2228 experimental masses have uncertainties

- 192 < 1 keV
- 1020 < 10 kev
- 231 < 100 keV
- 785 > 100 keV

Based on 7773 data, 374 not accepted:
6169 valid input data
4373 after compression by pre-averaging
887 added from systematic trends

“Primary” data:

- 1381 data representing 967 reactions and decays
- 414 mass spectrometric data

Backbone from least-square calculation:
System of 1381 equations for 847 parameters (“primary” masses)

This sample represents about half of the expected nuclides between the drip-lines.

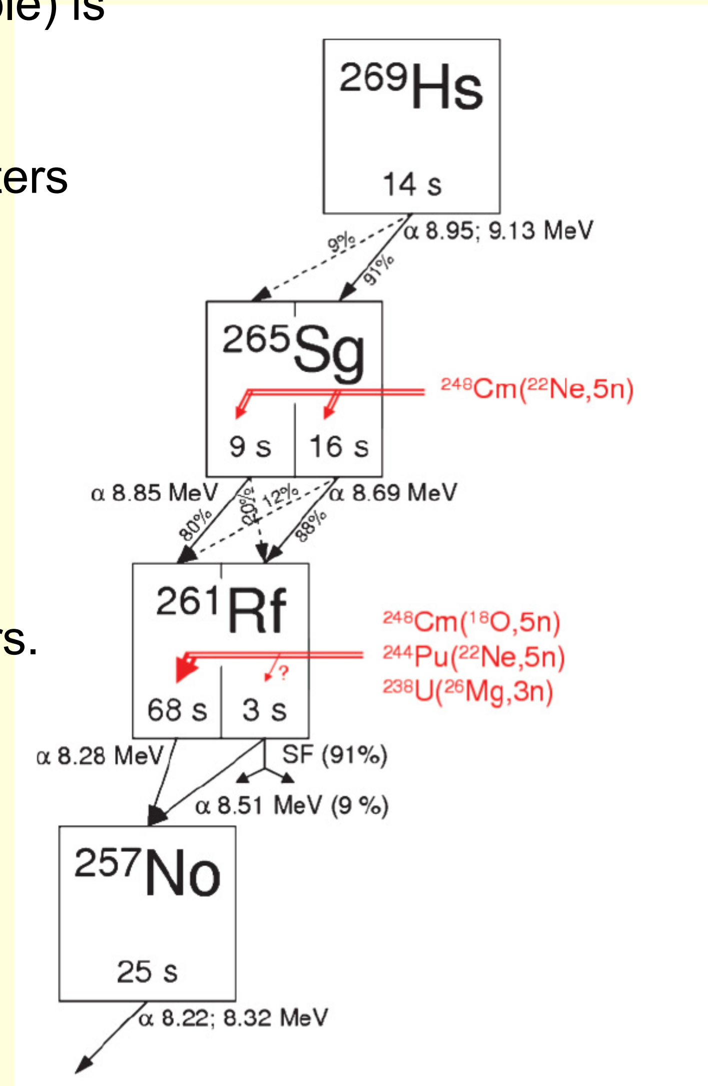
Progress in AME

	AME2003	2009 (approximate values)
Masses	3504	3555
Data points (total)	7773	13080‡
Mass-doublets		4390
Mass-triplets		220
Reaction data		8470
Not accepted	374	7130‡
After preaveraging	4373	4760
Mass adjustment		
“Primaries” equ. / unknowns	1381 / 847	1570 / 988
“secondaries	2770	2800
systematics	890	850

‡ These numbers include comment lines!

Incomplete Nuclear Structure Information

The superheavy isotope ^{277}Uub [^{277}Cp ?] (as an example) is connected by a cascade of α-decays to isotopes with known mass values: ^{245}Cm, ^{249}Cf, ^{253}Fm.
Nevertheless, the m.e. of ^{277}Uub and the decay daughters cannot be calculated unambiguously.
Summing up the measured Q_α does not yield the mass values, as initial and final energy levels are not known.
In the case of ^{261}Rf and ^{265}Sg, isomers have been observed, but their relative position is not known, nor if one is the ground state.
Other members of the cascade could also have isomers.



These isotopes were produced by heavy ion reactions which favour high-spin states.
Low-spin states are not populated, they might be the ground states.

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Düllmann, Türler, Phys. Rev. C77, 064320 (2008)

Importance of α,γ-coincidences

The detection of charged particles (as α or p) is possible even for very low production rates. In general, γ-rays deexciting excited states populated by α-particles could not be detected. The mass evaluators partly have introduced (unobserved) excited states based on systematics. In the case of the decay of ^{254}Lr, the 8460 keV α was supposed feeding a level at (190±150) keV.

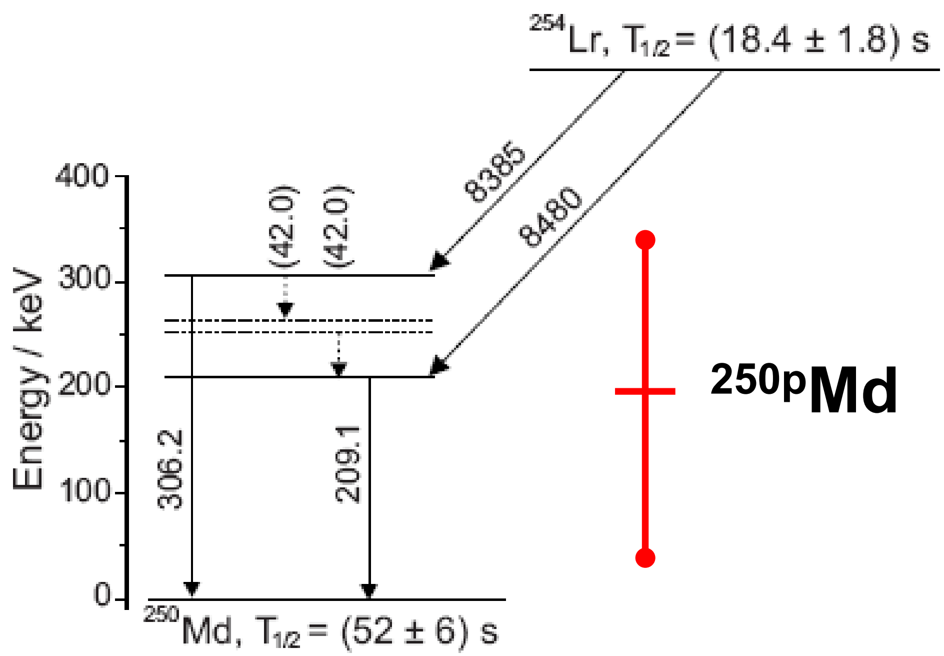


Fig. 2. Suggested decay scheme of ^{254}Lr. The placement of the 42.0 keV transition is uncertain. Energy values are given in keV.

Recent coincidence experiments allowed now to propose a partial decay scheme.

Also in the decay of ^{250}Md, an excited state in ^{246}Es at (350±200) keV was postulated. Only one γ-line of 152 keV was detected, not (yet) sufficient for proposing a scheme.

S. Antalic et al., EPJ A38, 219 (2008)

Progress in nuclear structure information

The proton decay of ^{146}Tm has been intensively studied in recent years.
Progress in experimental techniques results in changes of the decay scheme even before it was time to enter the data into the mass evaluation. And whereas in the older scheme all levels in ^{146}Tm and ^{145}Er were fixed, in the revised scheme, the high-spin states are floating.

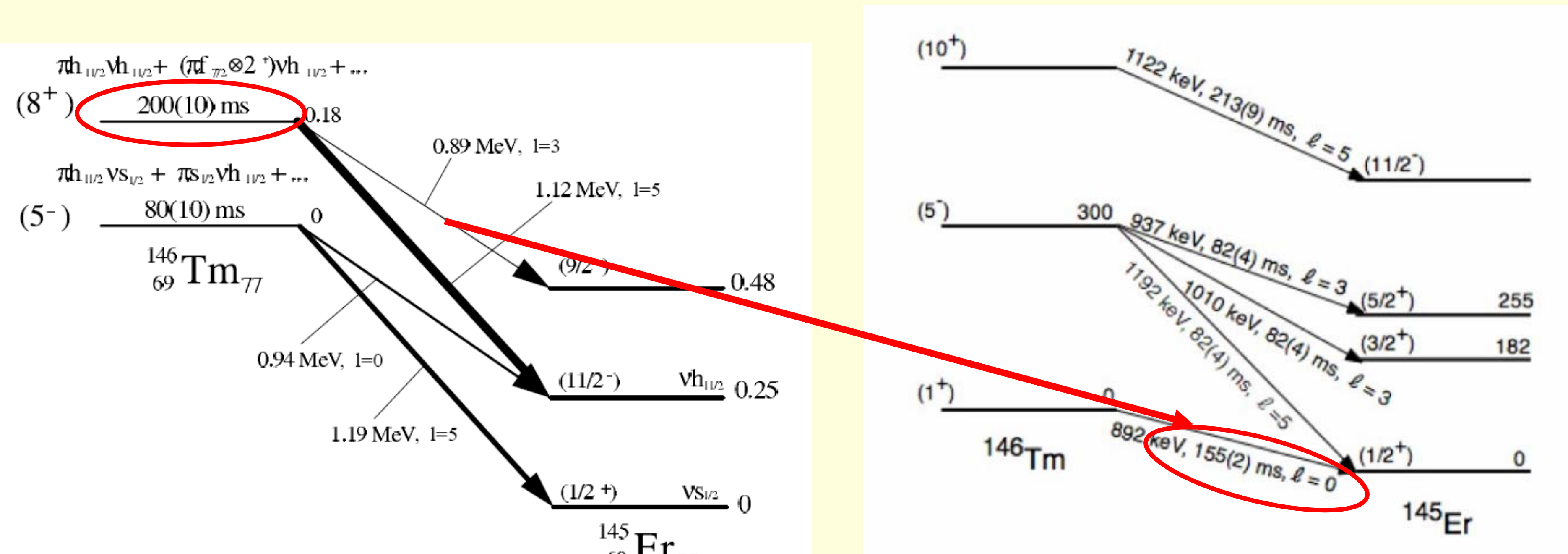


FIGURE 6. Proposed proton decay scheme for ^{146}Tm.

T.N. Ginter et al. 2003GI10

Cary N. Davids: 2007DAZU

Isolated regions

There are long α-decay chains observed for the heaviest isotopes.
Unfortunately, they often end in nuclides undergoing spontaneous fission, which have unknown masses.

These "islands" must be connected to the "mainland" by extra-polated masses guided by systematics.

Such "islands" exist also at lower masses. Here, chains end in isotopes with not measured EC/β+ energies.

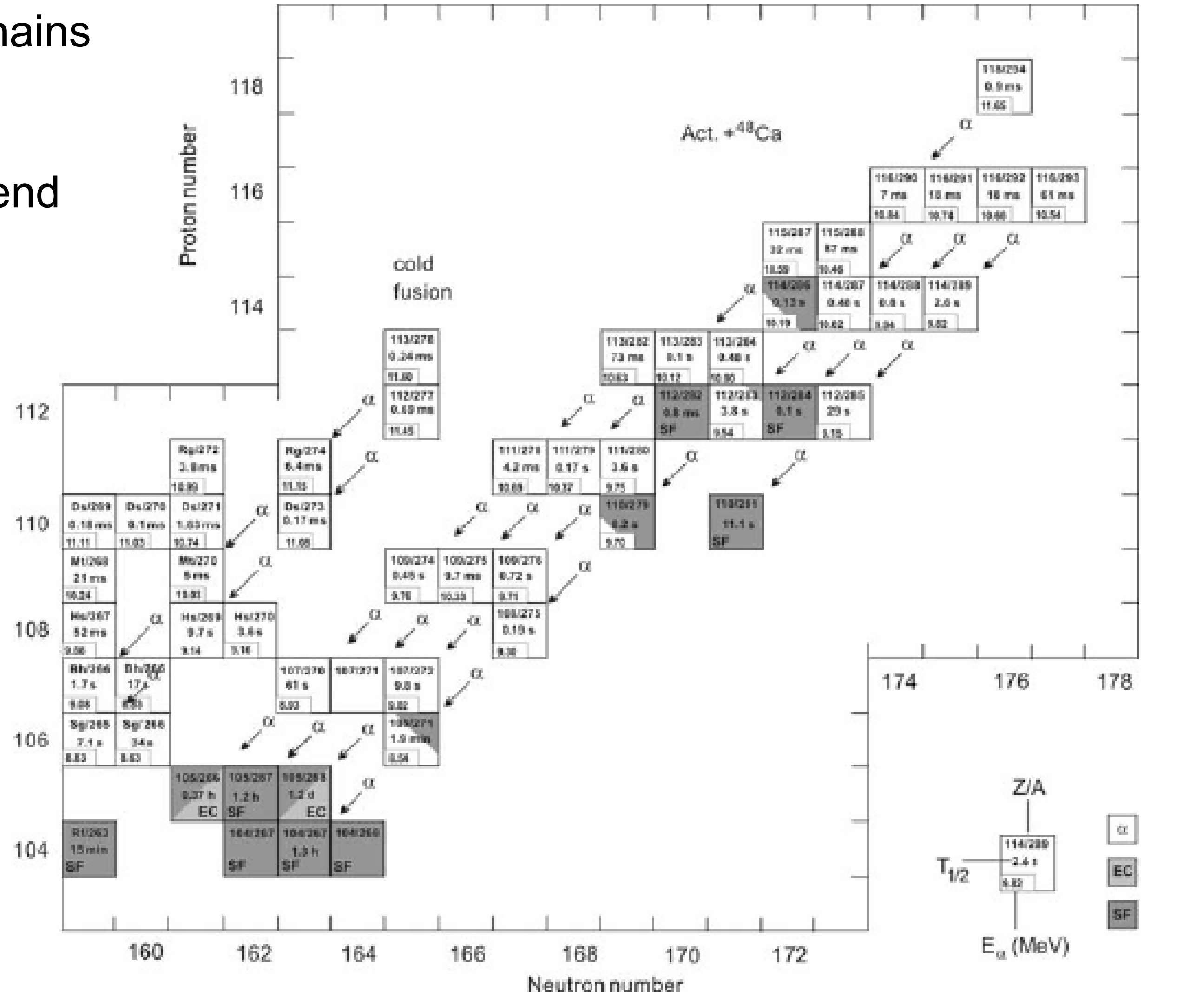


Figure 3. Chart of the heaviest nuclides. The squares contain the half-lives (without errors) and the maximum α-transition energy (E_α in MeV).

Yu.Ts. Oganessian / Nuclear Physics A 787 (2007) 343c–352c

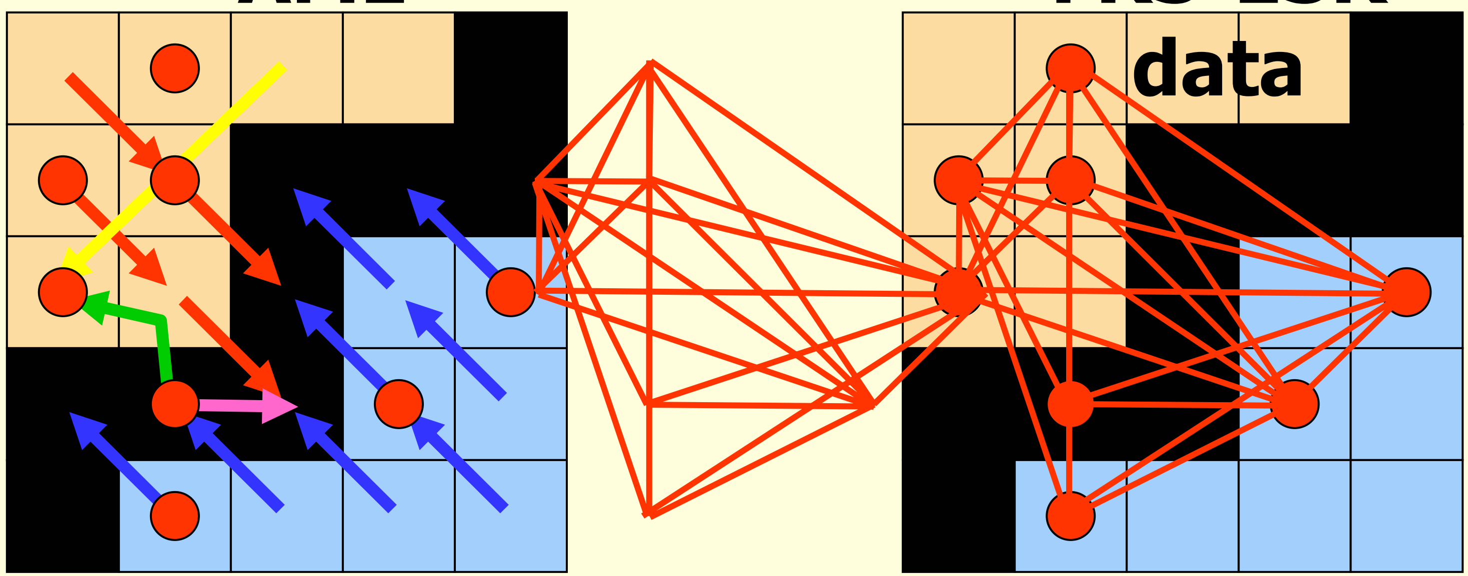
AAME – Advanced Atomic Mass Evaluation

- **Collect and evaluate experimental data on atomic masses (Q-values, excitation energies, lifetimes, etc.). Continuation of and improving the Atomic Mass Evaluation.**
- ***Maintaining the existing (e.g. Nucleus) and developing new tools (mass calculators, filters, extrapolations, etc.).***
- ***Creating and sustaining databases for experimental and theoretical data.***
- **Coordinating the information flow between different experimental and theoretical groups.**
- **Creating and/or maintaining the information exchange with other evaluation groups (NNDC, NuBASE, BrusLIB, etc.)**

Courtesy Yu.A. Litvinov

Advanced Atomic Mass Evaluation

- **AME**
- **FRS-ESR data**



- 1. Q-values: β-decays (β^+,β^-)
- 2. Q-values: α-decays
- 3. Q-values: reactions (p,n), (n,γ) etc.
- 4. direct measurements (traps, rings)

A. Wapstra, G. Audi, C. Thibault, NP A729 (2003) 129

- frequency correlations between all measured ESR data
- *Yu.A. Litvinov et al, NPA756 (2005) 3*

- **Combined Evaluation**
- *Yu.A. Litvinov, G. Audi et al., ILIMA Technical Proposal*

- **6169 input data**
- **~$2 \cdot 10^5$ input data / experiment**

Measured Mass Surface at FSR/ESR

Masses of more than 1100 nuclides were measured

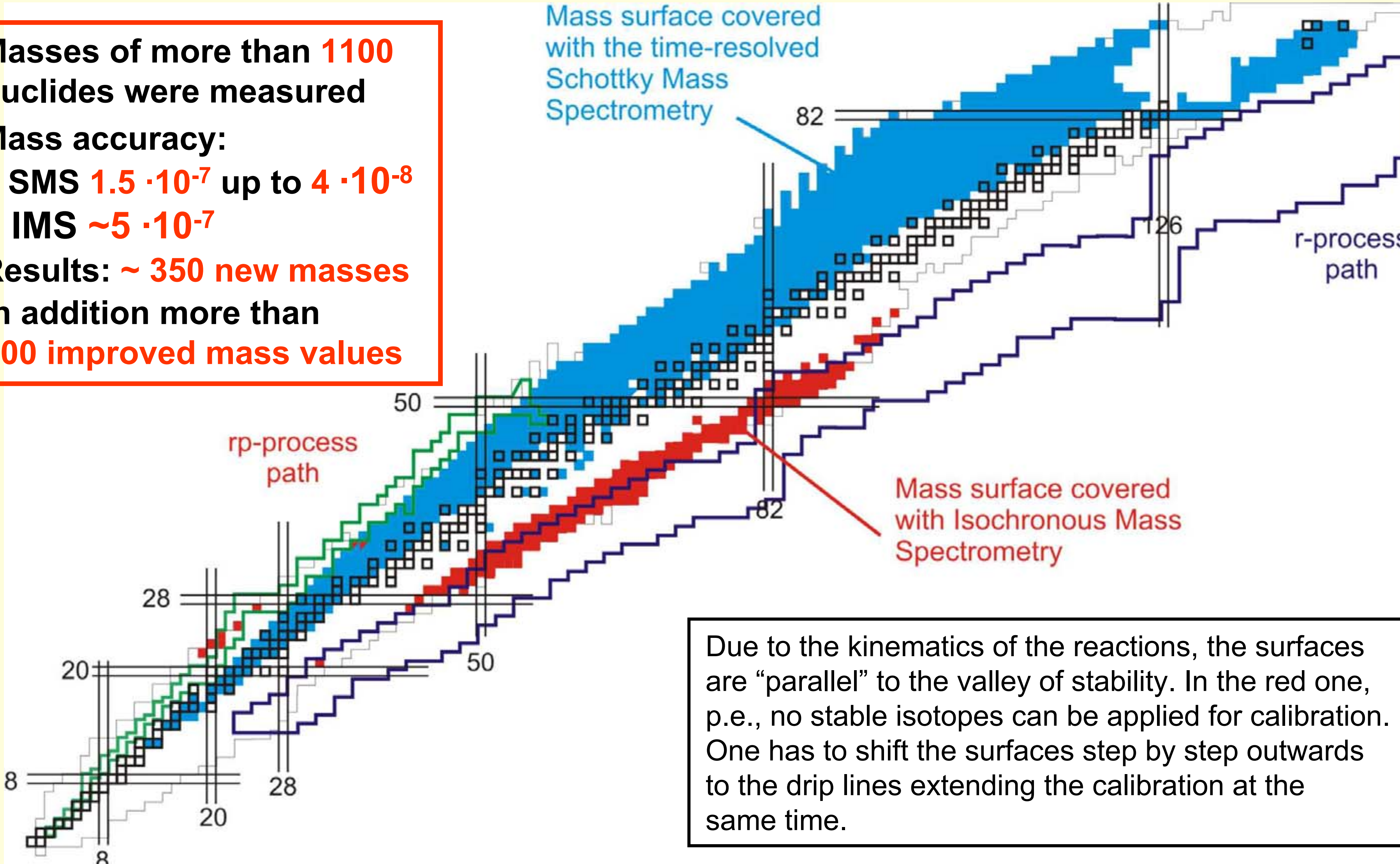
Mass accuracy:

SMS $1.5 \cdot 10^{-7}$ up to $4 \cdot 10^{-8}$

IMS $\sim 5 \cdot 10^{-7}$

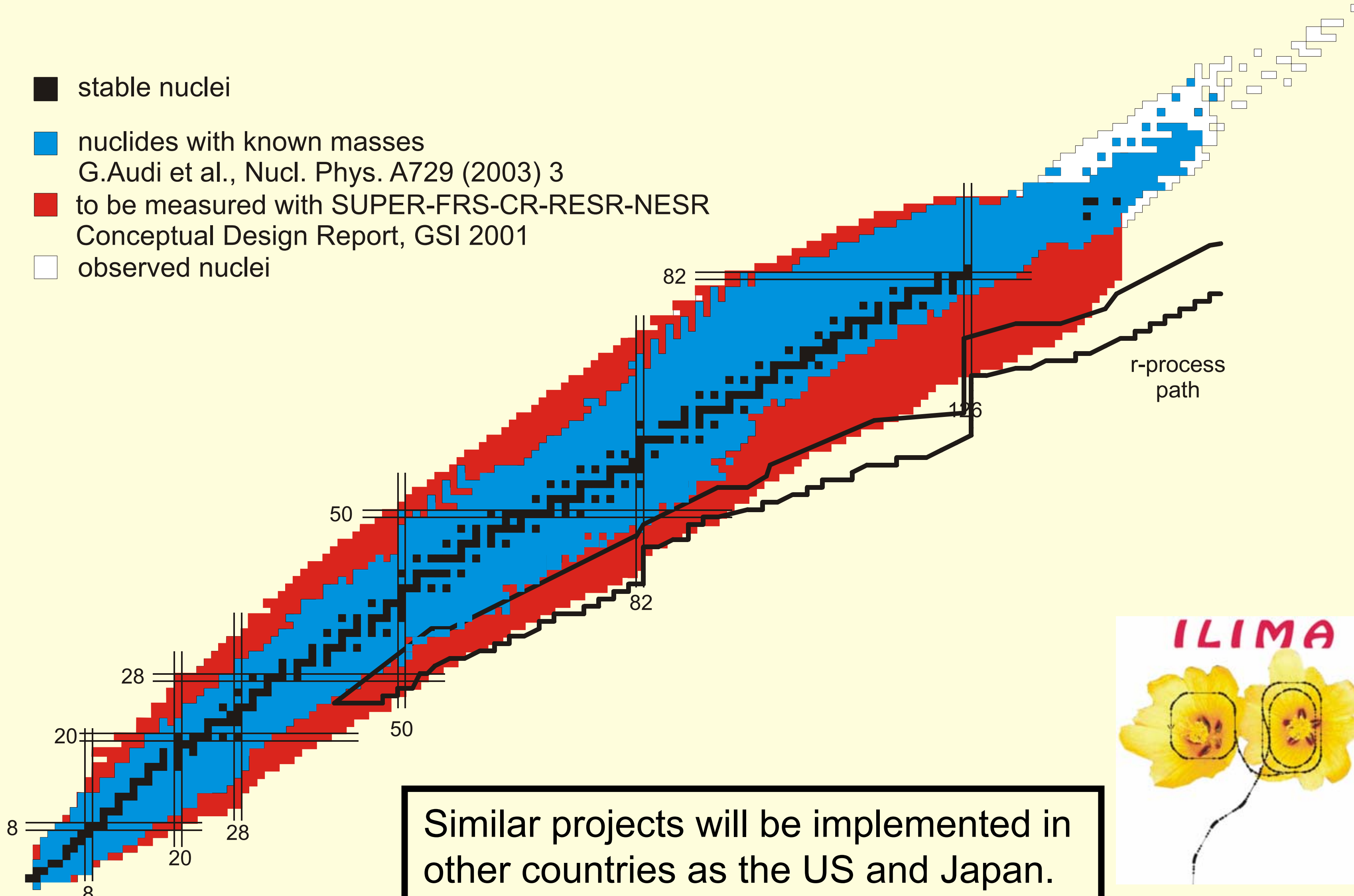
Results: ~ 350 new masses

In addition more than 300 improved mass values



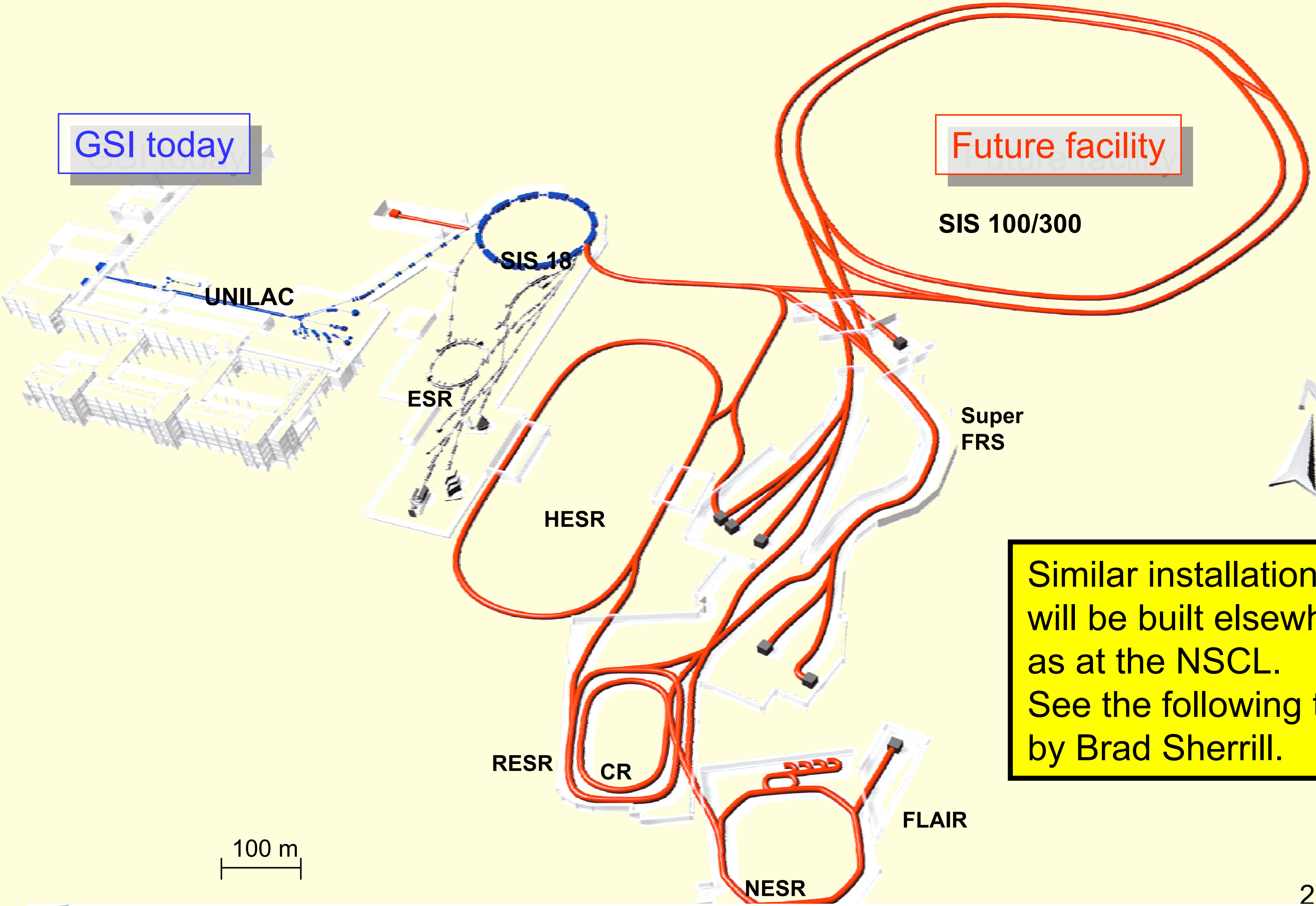
Due to the kinematics of the reactions, the surfaces are “parallel” to the valley of stability. In the red one, p.e., no stable isotopes can be applied for calibration. One has to shift the surfaces step by step outwards to the drip lines extending the calibration at the same time.

ILIMA: Masses and Halflives



Similar projects will be implemented in other countries as the US and Japan.

FAIR - Facility for Antiproton and Ion Research



Similar installations will be built elsewhere, as at the NSCL.
See the following talk by Brad Sherrill.

Might be a little smaller?

Combined compilations / evaluations

It seems to me that for quite a long time there existed several "communities" of scientists dealing each with different observables of the nuclides.
Even in the case of the masses of the (ground states) of isotopes, there were mainly two groups:

on the one hand the mass spectroscopists and on the other the reaction people.


Kernphysikalische Tabellen

Von

Professor Dr. J. Mattauch
Wissenschaftliches Mitglied des
Kaiser Wilhelm-Institutes für Chemie · Berlin-Dahlem

Mit einer Einführung in die Kernphysik

Von Dozent Dr. S. Flügge
Kaiser Wilhelm-Institut für Chemie · Berlin-Dahlem

As an example, Mattauch published in 1942 a booklet with lists of mass doublets and reaction Q-values and estimated masses up to the actinides. In his Isotopic Report of 1949, masses are only derived up to mass 41, he regarded the reaction values as too uncertain.

In the course of time, several compilations/evaluations were dedicated to only one observable, as e.g. magnetic moments, 2^+ excitation energies, etc.

A more complete picture of nuclides can be obtained by reviews as the Nuclear Data Sheets or the "handbooks" of the Table of Isotopes. The nuclear masses normally stayed aside.

Now, NUBASE combines masses of ground and longlived isomeric states with halflives, spins and parities.

An early form of NUBASE?

The Kaiser-Wilhelm-Institut für Chemie had issued yearly progress reports on masses since around 1934. After the war, J. Mattauch compiled a small booklet in honour of Hahn's 70th birthday. It comprised not only data on masses, but ,e.g., decay properties as half-lives. Seaborg had made available war-time data by sending the "Table of Isotopes" prior to publication.

SPECIAL ISSUE OF THE ZEITSCHRIFT FÜR NATURFORSCHUNG

ISOTOPIC REPORT

Tabular Survey of the Properties of Atomic Nuclei
as known till the end of 1948

By

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Direktor des Kaiser Wilhelm-Instituts für Chemie, Tailfingen (Württbg.)
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and

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Dozent an der Universität Tübingen

SONDERHEFT DER ZEITSCHRIFT FÜR NATURFORSCHUNG

ISOTOPENBERICHT

Tabellarische Übersicht der Eigenschaften der Atomkerne,
soweit bis Ende 1948 bekannt

Von

JOSEF MATTAUCH
Direktor des Kaiser Wilhelm-Instituts für Chemie, Tailfingen (Württbg.)
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In the following decades, mass evaluations normally contained only masses.

Br isotopes in the 1949 Isotope Report

Z	Symbol	A	N	I	Häufigkeit Abundance %	Klasse Class	T ½ oder/or Spin i h/2π	Zerfall Decay	Energie der Strahlung in MeV / Energy of radiation in Mev: β oder μ in Kernmagnetonen or μ in nuclear magnetons	γ oder/or Q 10^{-24} cm²
1	2	3	4	5	6	7	8	9	10	11
35	Br	75	40	5	—	A	1,7 h *W 81;*	K[4,4], β+ [1] *W 81;*	1,6 (abs) *W 82;*	keine *W 81;*
		84	49	14	—	A	30 ± 5 m *H 19 a;*	β−	4,5 (abs) *B 118; B 117*	γ *P 61;*
		85	50	15	—	A	3,0 ± 0,5 m *H 19 a;*	β−	—	—

^{84}Br

ΔE MeV Mev	M—A 10^{-3} ME 10^{-3} MU	Erzeugt durch Produced by			
12	13	14			15
—	—	^{74}Se (d, n); *W 81 (1)*	^{74}Se (p, γ); *W 81 (1)*		^{75}Br
—	—	U (n, Sp.); *D 23, H 11, H 14, H 12, H 19 a, B 118, M 92*	Th (n, Sp.); *P 12*	^{87}Rb (n, α); *B 117*	^{84}Br
—	—	U (n, Sp.); *H 13 a*			^{85}Br

The data on masses and reactions were in separate tables.

Table of Isotopes

REVIEWS OF

MODERN PHYSICS

VOLUME 20, NUMBER 4 OCTOBER, 1948

Table of Isotopes

G. T. SEABORG AND I. PERLMAN

Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California

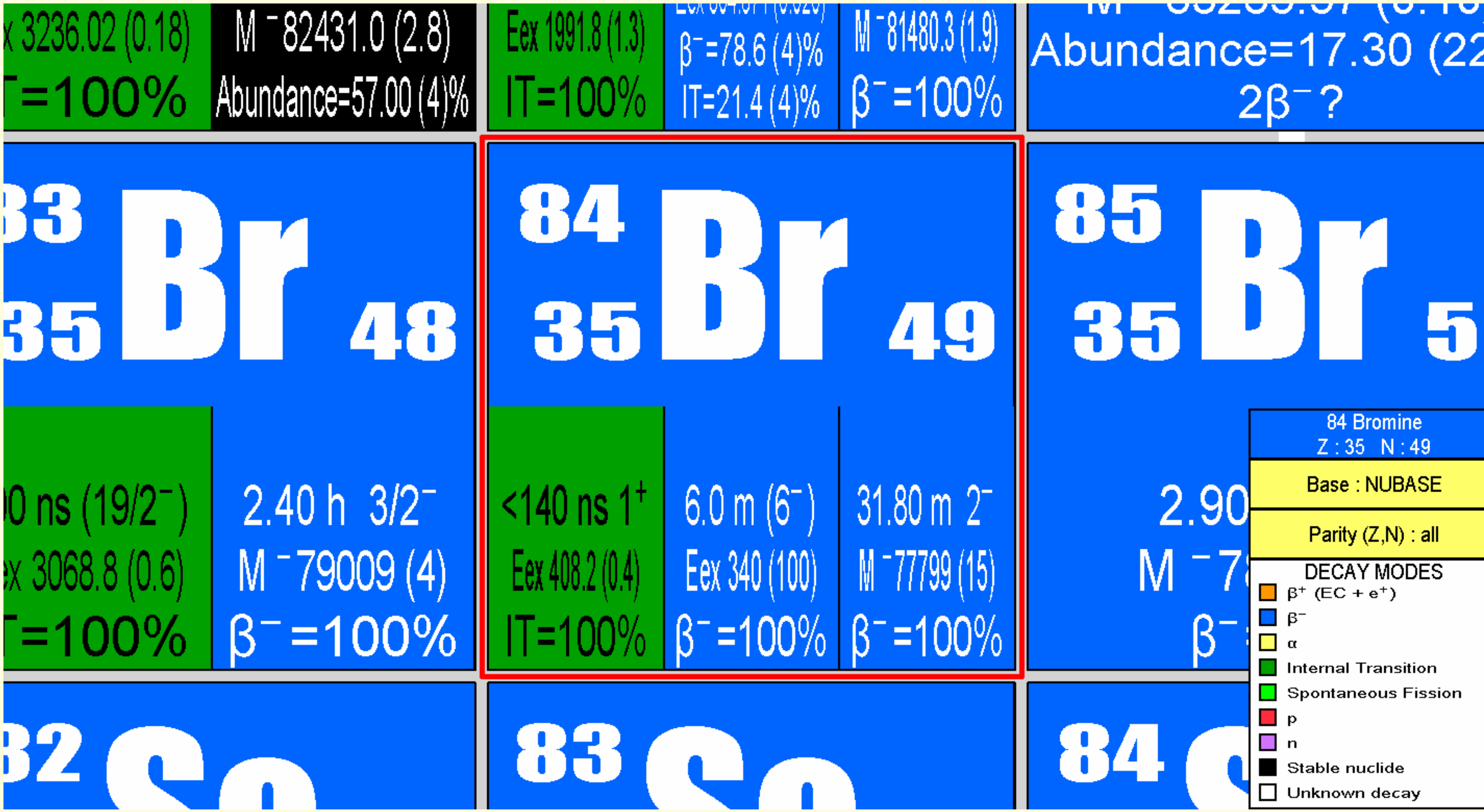
Table of Isotopes—*Continued*

Isotope Z	Isotope A	Class	Percent abundance	Type of radiation	Half-life	Energy of radiation in Mev: Particles	Energy of radiation in Mev: γ-rays	Produced by
	Br^{84}	A		β^-,γ	30 min.(S35); 33 min.(K104,K111)	5.3(K111) abs. Al; 4.5(B30) abs.		Rb-n-α(B29) U-n(D6,H22,H57, M9,S35,B29, K104), Se^{84} β^--decay(E111) Th-n(P12,B101) Bi-d(P104)

G.T. Seaborg and S. Perlman, Rev.Mod.Phys. 20 (1948) 585

From the first edition onwards (J.J. Livingwood and G.T. Seaborg, Rev.Mod.Phys. 12 (1940) 30), the Tables of Isotopes were intented as handbooks for immediate use in identification and radiotracers. So there was no information on masses and at the beginning only artificialy produced isotpes were compiled.

NUBASE 2003



http://www.nndc.bnl.gov/amdc/jvnubase/jvNubase_en.html

^{84}Br in NDS

^{84}Br Levels

Cross Reference (XREF) Flags

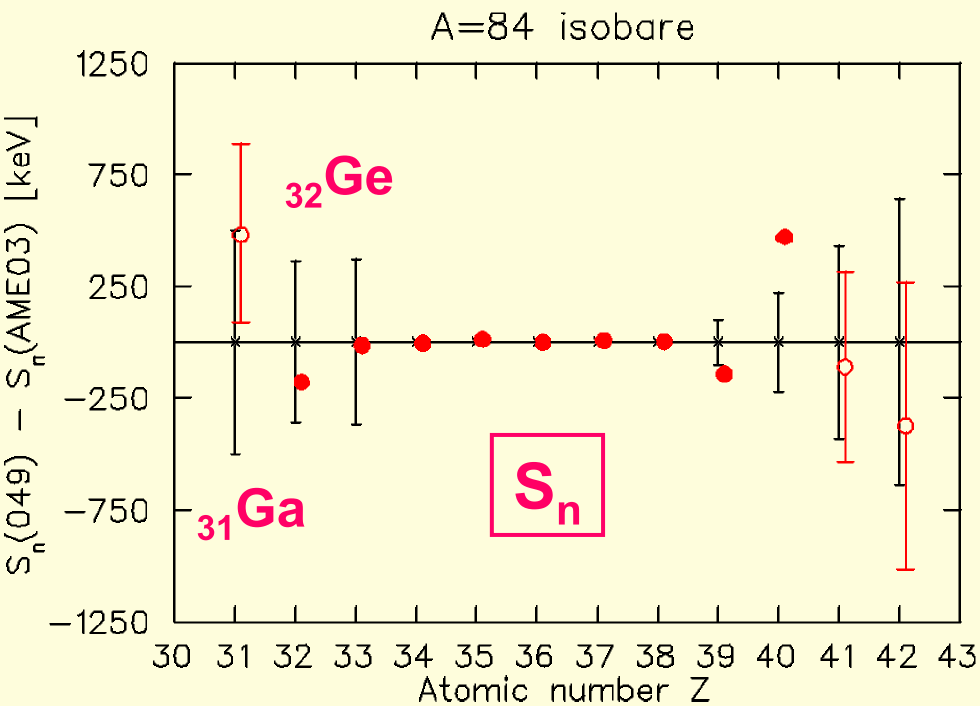
A ^{84}Se β^- Decay
B ^{208}Pb(^{18}O,Xγ)

E(level)	Jπ	XREF	$T_{1/2}$	Comments
0.0	2−	A	31.76 min *8*	%β^-=100. μ=1.9 *7* (1992Pr06). Jπ: shape of β spectrum of transition to 0+ is that expected for a first-forbidden unique transition (1970Ha21); possible configuration=$\pi 1f_{5/2}{}^3 \otimes \nu 1g_{9/2}{}^{-1}$ (1970Ha21). $T_{1/2}$: from weighted average of 31.7 min *2* (1960Sa05), 31.80 min *8* (1957Jo21) and 31.6 min *2* (1956Fi36). Others: 32 min (1951Du03), 33 min (1950Ka02), 30 min (1943Bo02,1943Bo01), 30 min (1940St03), 40 min (1939Do02), 30 min (1939Ha14). μ: from $\gamma(\theta$,H,t) (1992Pr06). See also 2005St24 compilation.
320 *100*	(6)−	B	6.0 min *2*	%β^-=100. %IT: no IT decay from this level has been observed, probably <0.1%. E(level): from difference in Q(β^-) values for the two activities (1970Ha21). Jπ: log *ft*=5.1 to 5−. Jπ=4− is not likely as E2 transition to 2− g.s. would be expected to be fast and 5− is less likely as B(M3)(W.u.) for %IT<0.1 would be smaller than for any other M3 transition in this region. Possible configuration=$\pi 1p_{3/2}{}^{-1} \otimes \nu 1g_{9/2}{}^{-1}$ configuration (1970Ha21). $T_{1/2}$: from 1960Sa05.
408.2 *4*	1+	A	<0.14 μs	Jπ: log *ft*=4.0 from 0+. $T_{1/2}$: from $\beta\gamma$(t) (1970Ei02).

Workshop ENSDF-2009
Nuclear Structure & Decay Data Evaluators
April 2009, Bucharest-Magurele, Romania

D. Abriola et al., NDS 110 (2009) 2815 – 2943

Data for r-process calculations

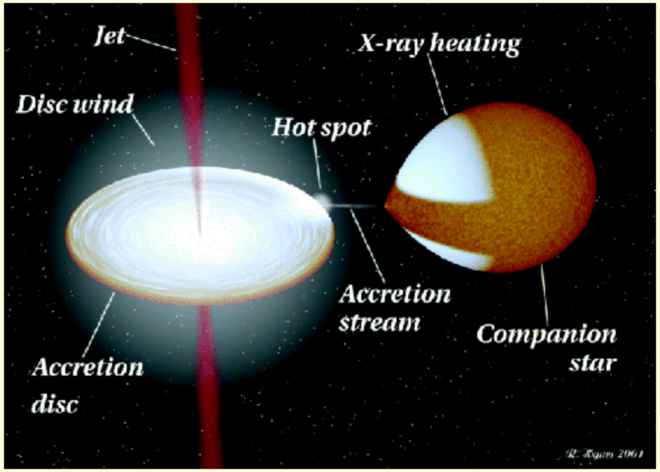


In the following, I compare the AME03 with the 2009 intermediate evaluation 2009AuZZ.

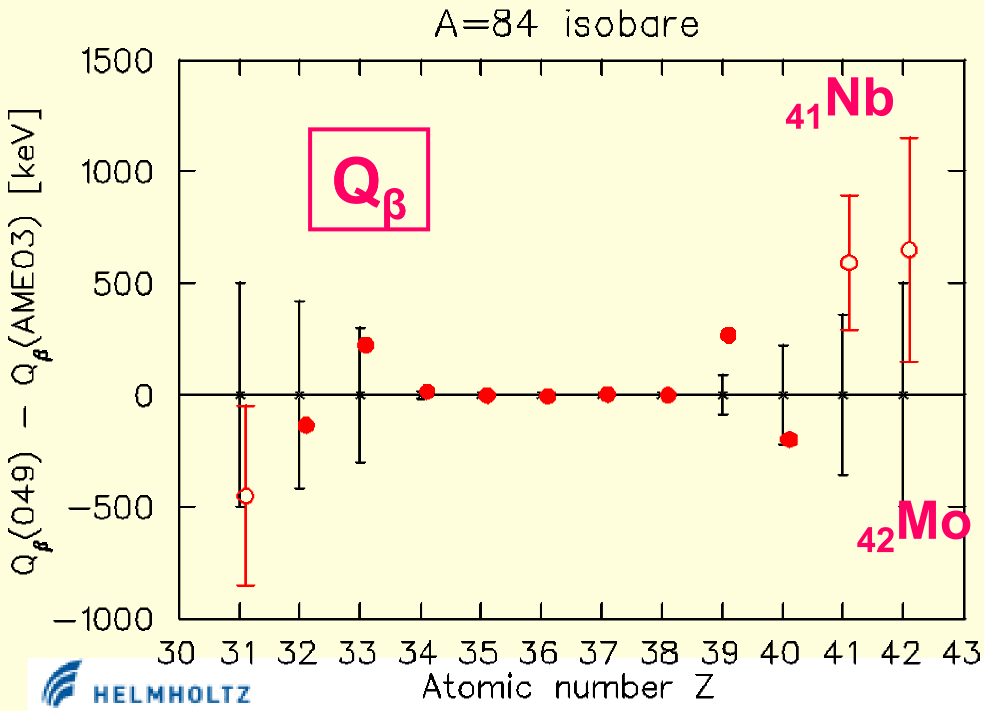
In r-process calculations, the S_n-values determine the r-process path and the Q-values via the decay constants the final abundances of the isotopes.
Unfortunately, high-precision mass values are in general not (yet) available for very neutron-rich isotopes.
For the S_n/S_{2n} below, the uncertainty is lowered from ~5 to ~0.05 %.

^{84}Ga	Q_β(Ga)	S_n(Ge)	S_{2n}(Ge)	$T_{1/2}$	P_{1n}	P_{2n}
	[keV]	[keV]	[keV]	[ms]	[%]	[%]
2003	14140# ±500#	5420# ±360#	8770# ±390#	112	41	7
2009	13688# ±400#	5243 ±4	8876 ±4	147	72	5

Near the proton dripline

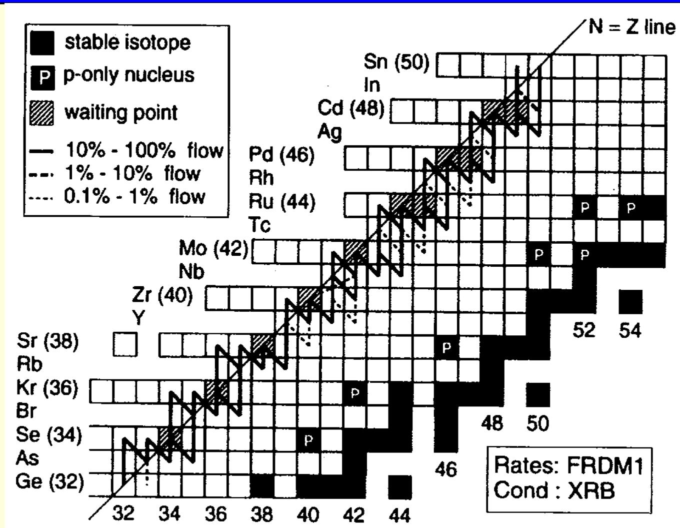


The **r**apid-**p**roton capture-process (rp-process) proceeds close to the proton drip-line with scarce information. The decrease of the radiated energy in the X-ray burst is influenced by the half-lives of the β-decays back to stablity.

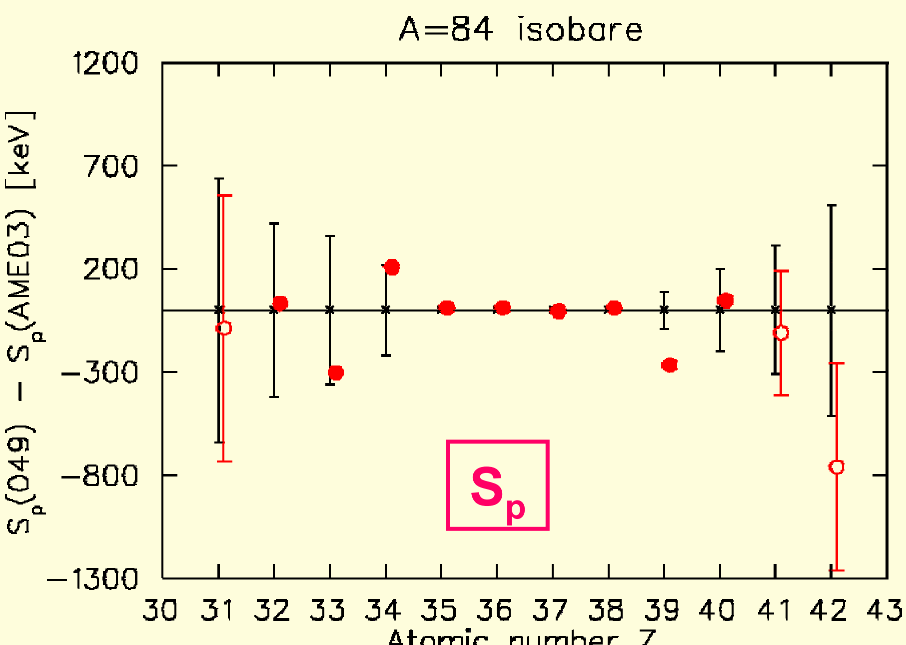


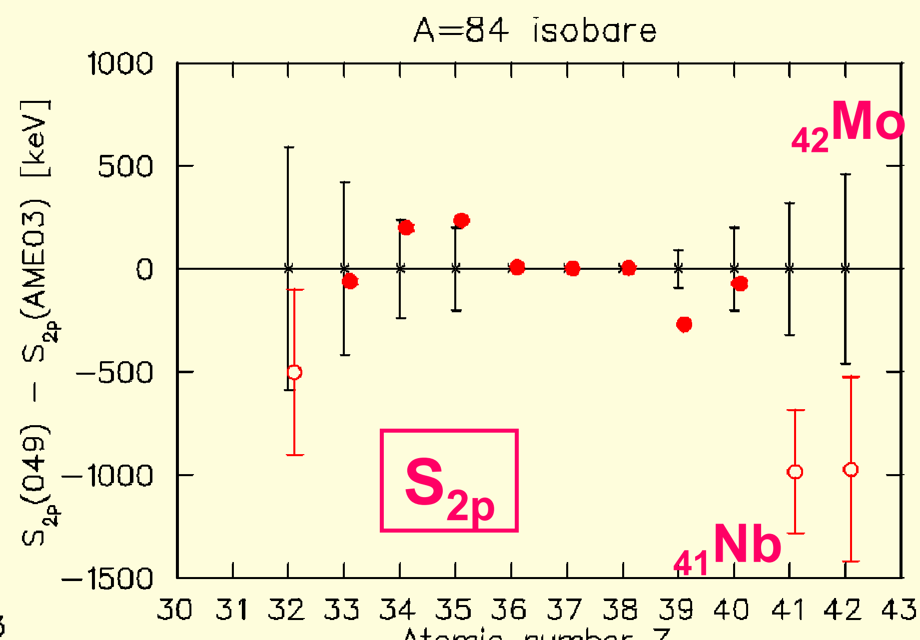
		Q_β	$T_{1/2}$
		[keV]	[ms]
^{84}Nb	2003	9610# ±360#	570
	2009	10200# ±300#	403
^{84}Mo	2003	6070# ±500#	4040
	2009	6719# ±500#	2019

Isotopes for rp-process calculations



One- and two-proton separation energies near the proton-dripline determine the rp-process path, especially up to which elements it can proceed.





Mass-derived quantities in NDS

At the top of each isotope are listed Q(β⁻), S(n), S(p) and Q(α) values from the Mass Evaluations (often outdated). In the case of the β⁻-unstable ^{84}Br, OK.

$^{84}_{35}\mathrm{Br}_{49}$–1

Adopted Levels, Gammas

Q(β⁻)=4629 *15*; S(n)=6875 *16*; S(p)=9759 *15*; Q(α)=–8065 *28* 2009AuZZ.
Values in 2003Au03 are: Q(β⁻)=4632 *14*, S(n)=6862 *15*, S(p)=9748 *15*, Q(α)=–8065 *28*.
^{84}Br evaluated by B. Singh.

But ^{84}Sr is stable against β-and α-decay. So why listing Q(β⁻) and Q(α)?

$^{84}_{38}\mathrm{Sr}_{46}$–1

Adopted Levels, Gammas

Q(β⁻)=–6757 *5*; S(n)=11923 *7*; S(p)=8867.5 *27*; Q(α)=–5181.6 *16* 2009AuZZ.
Values in 2003Au03 are: Q=–6490 *90*, S(n)=11920 *11*, S(p)=8858 *7*, Q(α)=–5176 *4*.
^{84}Sr evaluated by B. Singh, A. Negret, and K. Zuber.

Ref. 2009AuZZ lists Q(2β⁻)-values, but ^{84}Sr is unstable against 2β⁺-decay:
Q(2β+)[Z,N] = – Q(2β⁻)[Z–2,N+2]

$^{84}_{41}\mathrm{Nb}_{43}$–1

Adopted Levels, Gammas

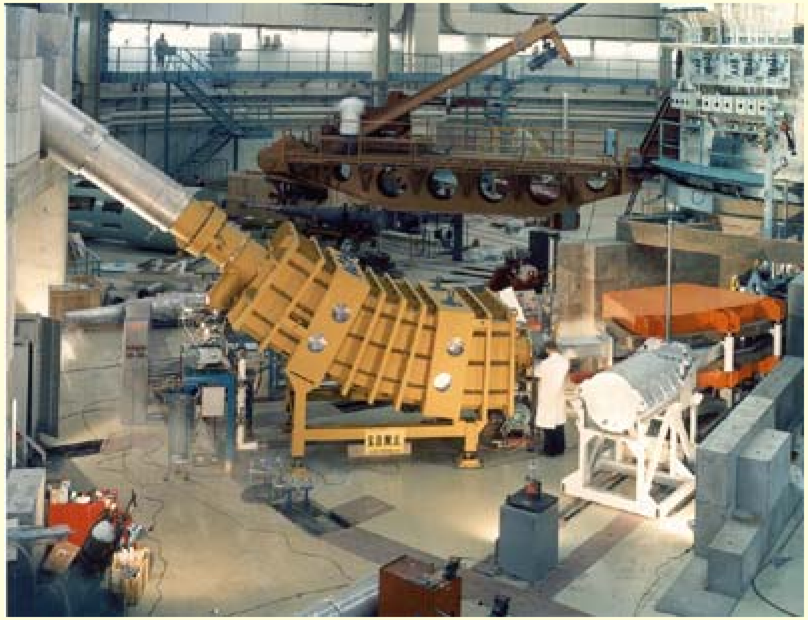
Q(β⁻)=–6720 *SY*; S(n)=10880 *SY*; S(p)=2600 *SY*; Q(α)=–2500 *SY* 2009AuZZ.
ΔQ(β⁻)=500, ΔS(n)=420, ΔS(p)=ΔQ(α)=300 (2009AuZZ).
Q(εp)=3700 *300* (syst,2009AuZZ).
The values in 2003Au03 are: Q(β⁻)=–6070 *500*, S(n)=10990 *430*, S(p)=2710 *310*, Q(α)=–3090 *350*, Q(εp)=3160 *300*; all from systematics.
^{84}Nb nuclide evaluated by D. Abriola and M. Galan.

^{84}Nb is unstable against β⁺-decay:
Q(β⁺)[Z,N] = Q(β⁻)[Z–1,N+1]

Applications of nuclear physics data

At the start of my scientific work in experimental nuclear physics, we were collecting data on nuclear fission and the properties of fission products.

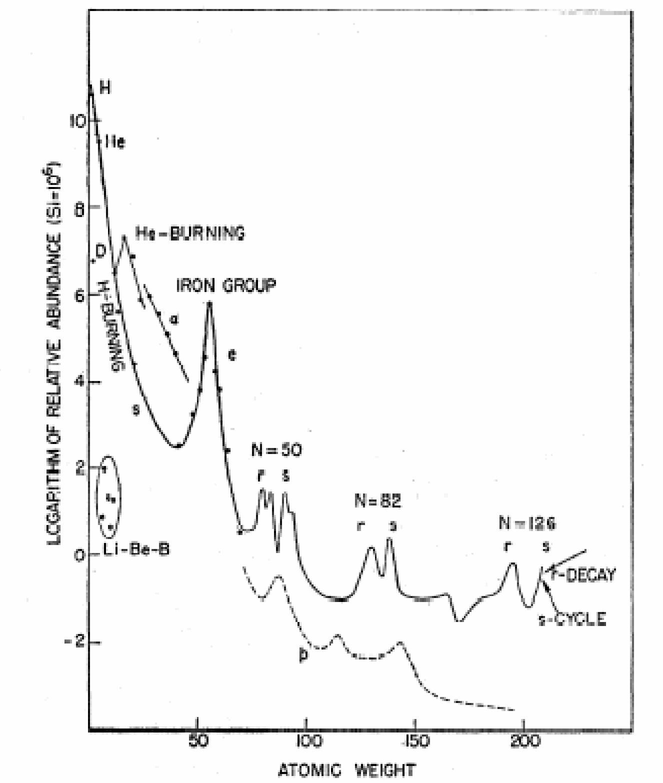
Young and idealistic, we were convinced that our data would make the operation of nuclear power plants more secure.
But the essential data had been obtained long before.
And when (at least in Germany) people did not want any longer “Atomreaktoren”, the funding was reduced. One consequence was that Kernforschungszentrum Karlsruhe ceased the work on the NDS.
In the following, we applied our data in (nuclear) astrophysics which does not sound as dangerous to the public.



Construction of the LOHENGRIN at ILL

It is our obligation as scientists not to keep our findings for us,
but one ought not be obliged for funding to only argue with applications,
fundamental physics is a field in its own right,
and often leads to unforeseen applications.

Since the end of the 50's, there exist successful theories of post-Big-Bang nucleosynthesis, as the r-process.



Suess and Urey
„Abundances of the Elements"
(Rev. Mod. Phys. 28 (1956) 53)

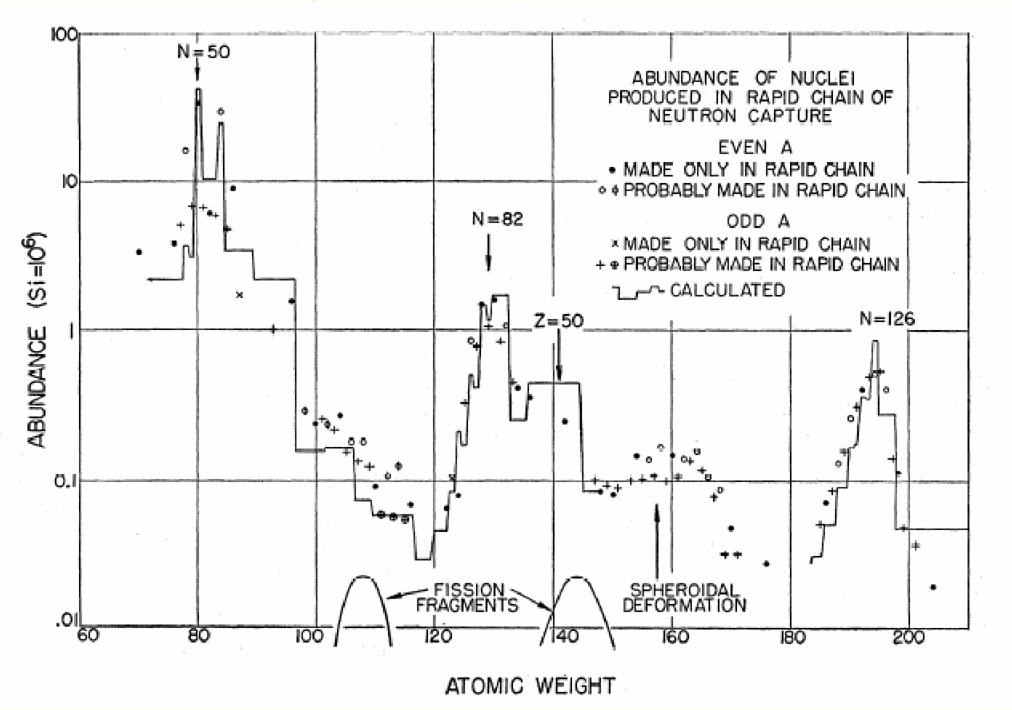


Fig. VII,3 of B^{2}FH: Classical static r-process calculation compared to observed abundances of Suess and Urey.

B^{2}FH concluded back in 1957 that for the r-process a
„reasonable but not exact agreement with observed abundances is obtained".

A fine example of British understatement!
Quite some work had (and still has) to be invested to get better results.

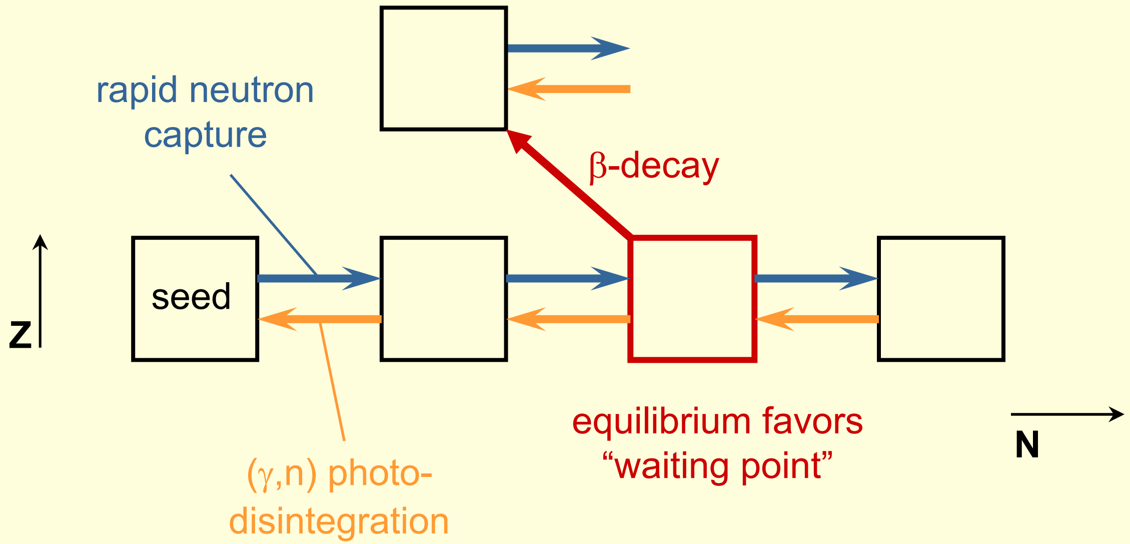
Classical approach of the r-process

Waiting point approximation

assumes

- (n,γ) $\leftrightarrow$ (γ,n) equilibrium within isotopic chain, and
- β-flow equilibrium

  β-decay of nuclei from each Z-chain to (Z+1) is equal to the flow from (Z+1) to (Z+2)



The nucleus with maximum abundance in each isotopic chain must wait for the longer β-decay time scales.

Good approximation for parameter studies, **BUT** steady-flow approximation is not always valid.

Courtesy Marialuisa Aliotta, Edinburgh

The “waiting-point” approximation

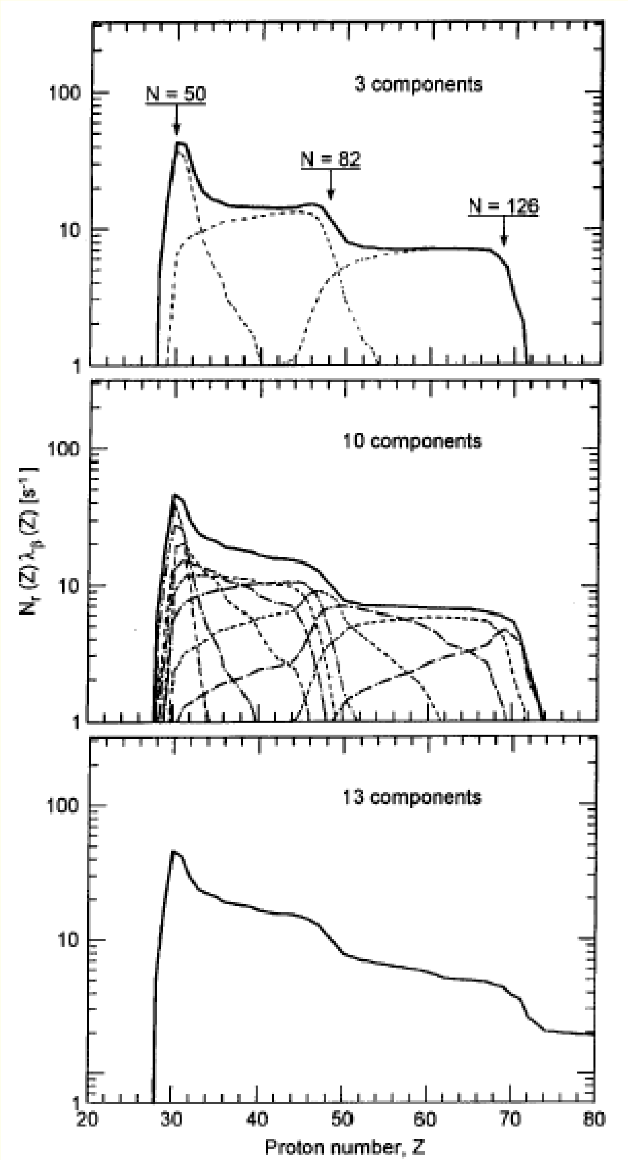
B²FH had developed “simplifying” concepts to reduce the mathematical framework and the nuclear-structure input to a manageable size for the early computers.

Rates for neutron capture and photodisintegration are related by the concept of detailed balance (invariance of physical laws under time-reversal), omitting the need for neutron-capture rates. The “waiting-point” concept (beta flow and $(\gamma,n)\leftrightarrow(n,\gamma)$ equilibrium) reduced the problem to a simple product:

$$Y(Z)\cdot\lambda_{\beta}(Z) = \text{const.}$$

We found out that there does not exist one constant for the whole range, but that the concept nevertheless is a good approximation between neutron magic numbers.

As an example, Wolfgang Hillebrandt had predicted the half-life of ^{130}Cd prior to our experiment at CERN.



Nuclear-data needs for the classical r-process

- **β-decay properties**

  $T_{1/2} \Rightarrow$ r-process progenitor abundances, $N_{r,prog}$

  $P_n \Rightarrow$ smoothing $N_{r,prog} \xrightarrow[\text{freeze-out}]{\beta\text{-decay}} N_{r,final}$ ($N_{r,\odot}$)

- **nuclear masses**

  S_n-values $\Rightarrow$ r-process path
  Q_β, S_n-values $\Rightarrow$ theoretical β-decay properties, n-capture rates

- **neutron capture rates**

  $\sigma_{RC} + \sigma_{DC} \Rightarrow$ smoothing $N_{r,prog}$ during freeze-out

- **fission modes**

  SF, βdf, n- and ν-induced fission
  $\Rightarrow$ "fission (re-) cycling"; r-chronometers

- **nuclear structure development**

  - level systematics
  - "understanding" β-decay properties
  - short-range extrapolation into unknown regions

HEW scenario of type II supernovae

Nowadays with the much advanced computing power already available with desktops, one can give up most of the simplifying assumptions and calculate large networks of reactions (not yet coupled to hydrodynamics). One unexpected result was that the seed composition for an r-process is far from the classical ^{56}Fe, consisting of neuron-rich isotopes in the A ≈ 100 region, speeding up the process considerably. And in addition, the light classical r-process nuclei are not formed by n-capture, but by charged particle reactions, demanding additional new processes (as LEPP).

K. Farouqi et al. / Nuclear Physics A 758 (2005) 631c–634c

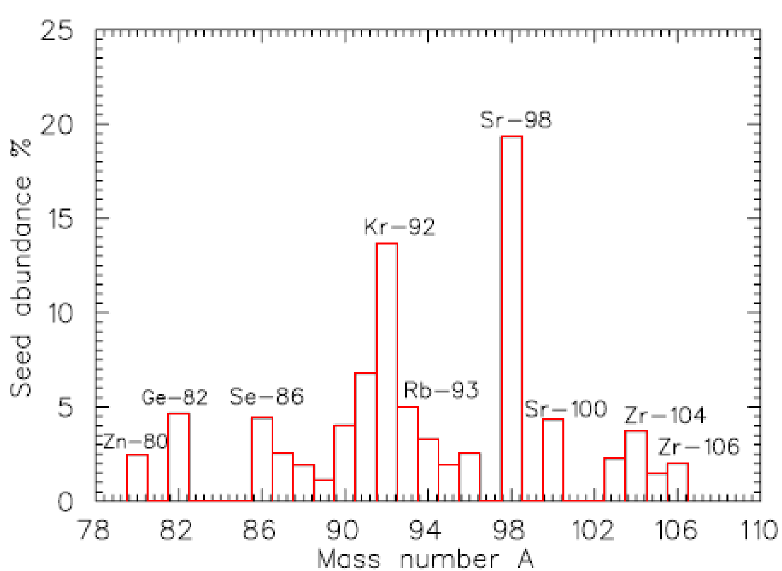


Figure 1. Typical r-process seed distribution after an α-rich freezeout

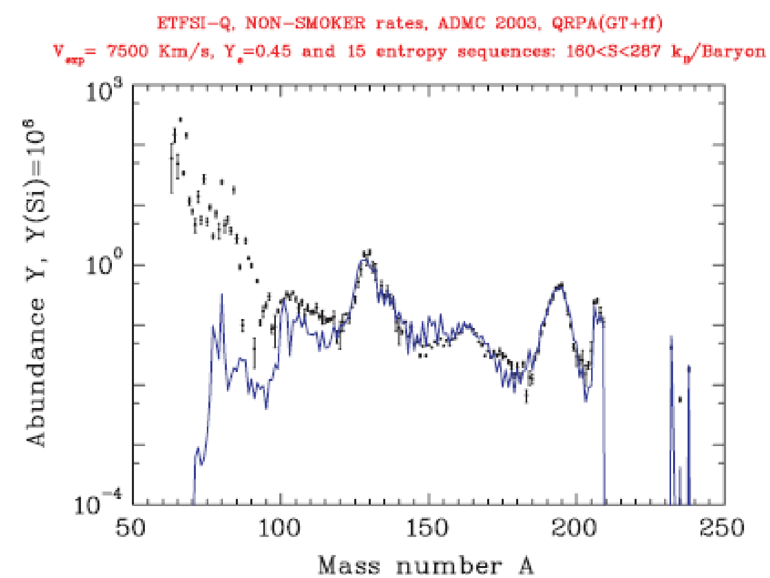
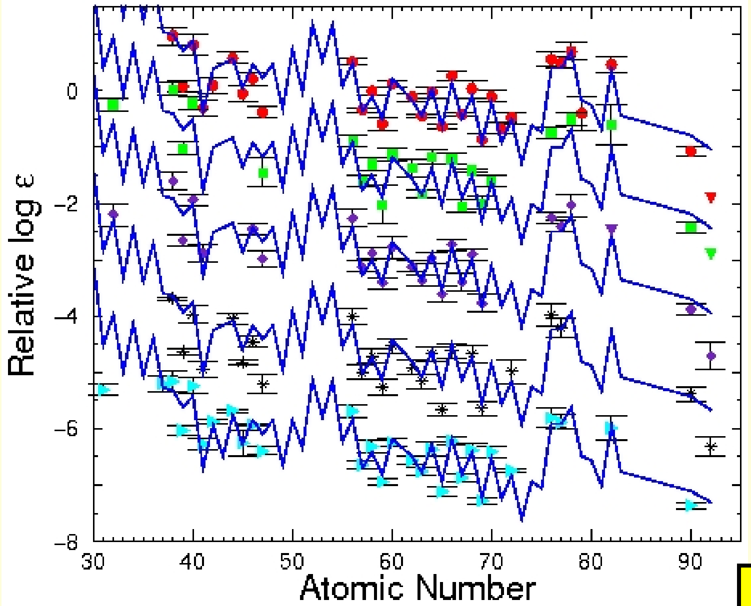


Figure 2. Comparison of the $N_{r,\odot}$ distribution (data points; Käppeler et al. 1989) with predicted isotopic abundances (solid line) from a weighted superposition of 15 HEW entropy components in the range $160 \leqslant S \leqslant 287$. For further details and discussion, see the text.

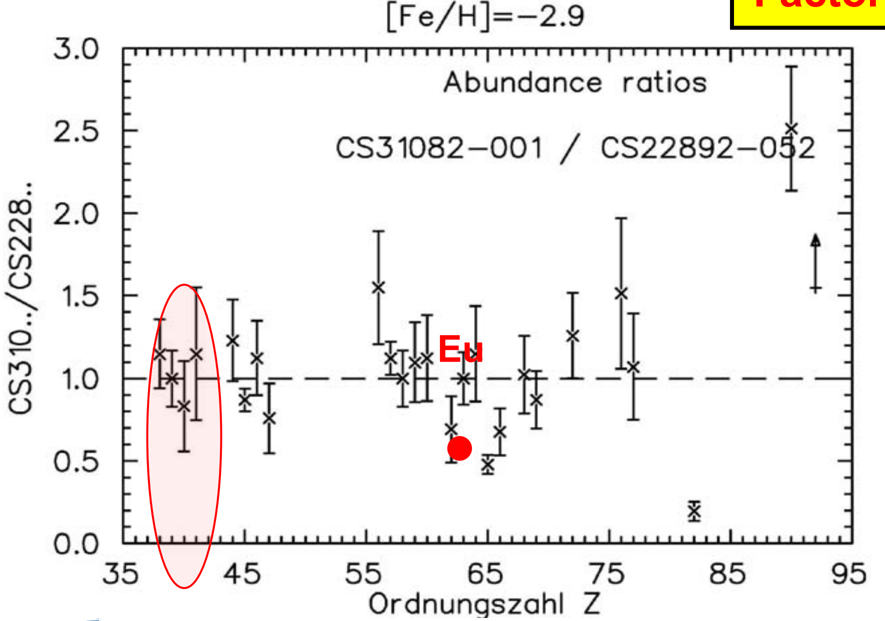
Observations: Selected UMP halo stars

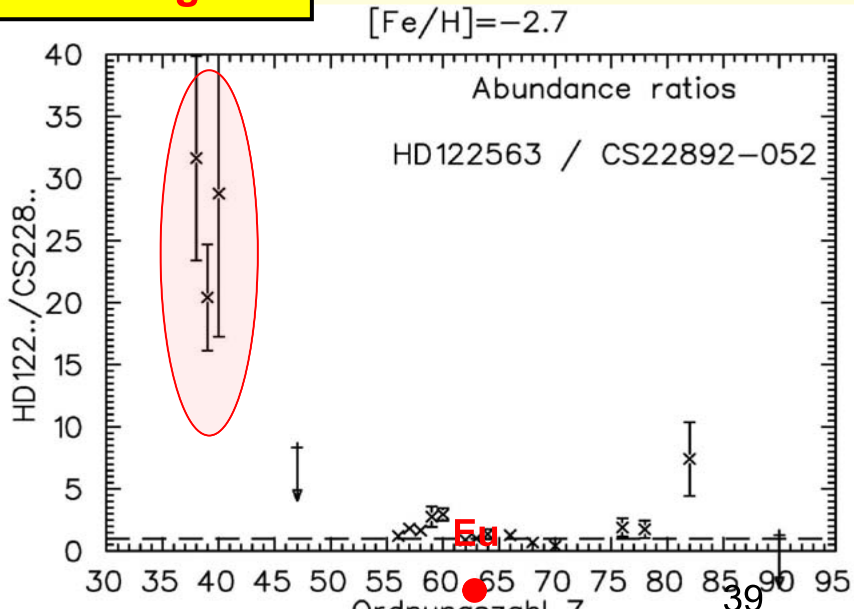


There are first indications from observations of UMP Halo stars. The 5 typical examples figured in this small plot show no evident deviations.

But is there the same abundance pattern at the **upper end** and at the **lower end ???**.

Factor 25 for LEPP region !





Mathematical artefacts?

The solar system r-process abundances had been reproduced with the old simplified calculations satisfactorily over the whole range from A≈80 up to the actinides (see left figure). The network calculations revealed that (at least for the low-A region) this was more mathematics than physics (see right figure).

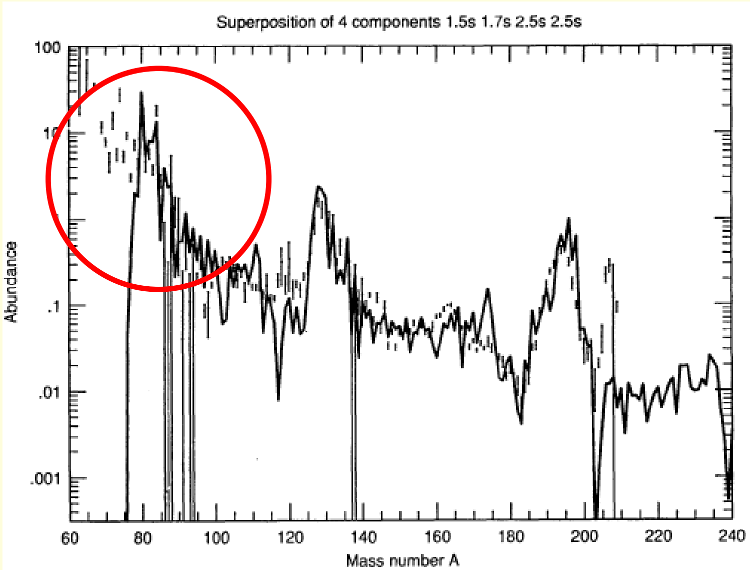
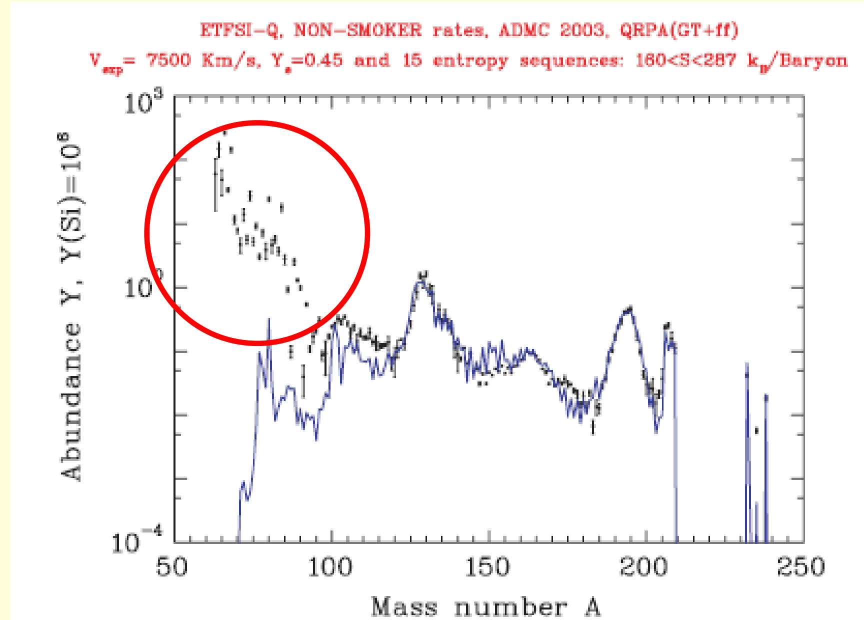


FIG. 18.—Same as Fig. 17, but with an additional component superposed which leads to an r-process path far enough from stability so that during 1.5 s even nuclei beyond the $A \simeq 195$ peak are produced. Stable Pb and Bi isotopes will get (large) contributions from alpha-decay chains. Times are t = 1.5 s, 1.7 s, 2.5 s, and 2.5 s.



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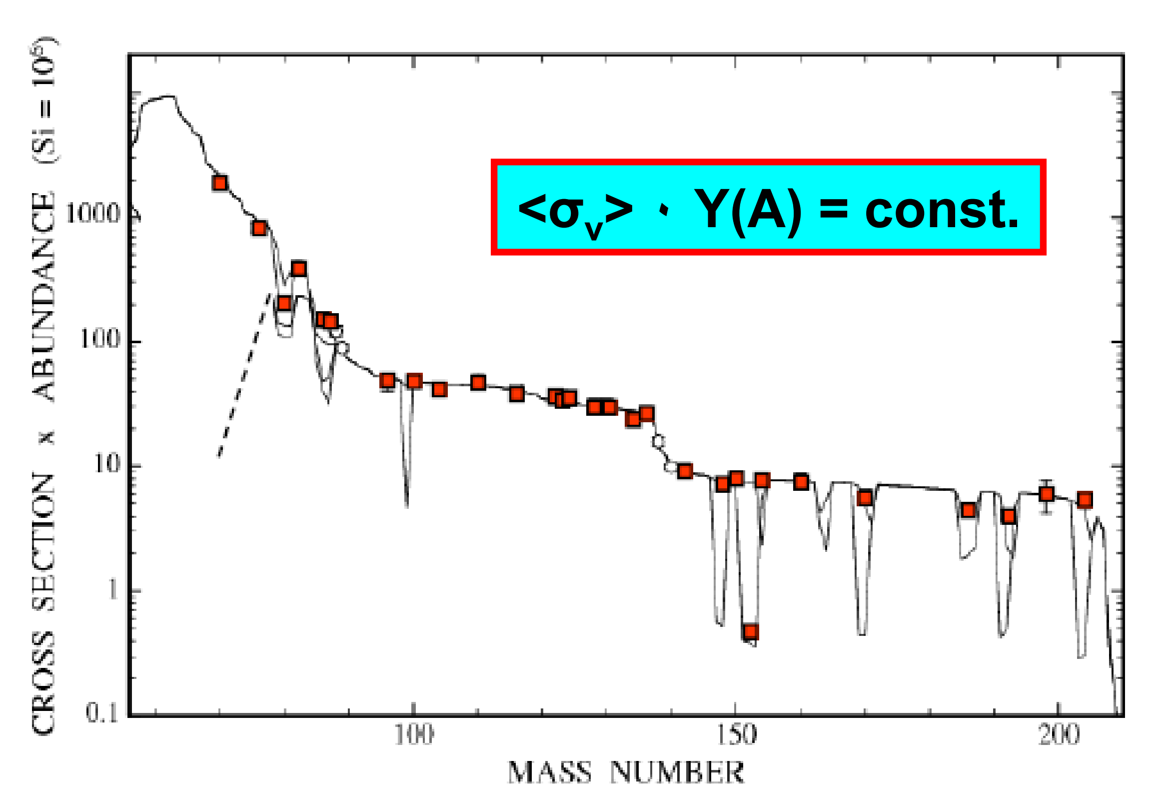
The classical s-process

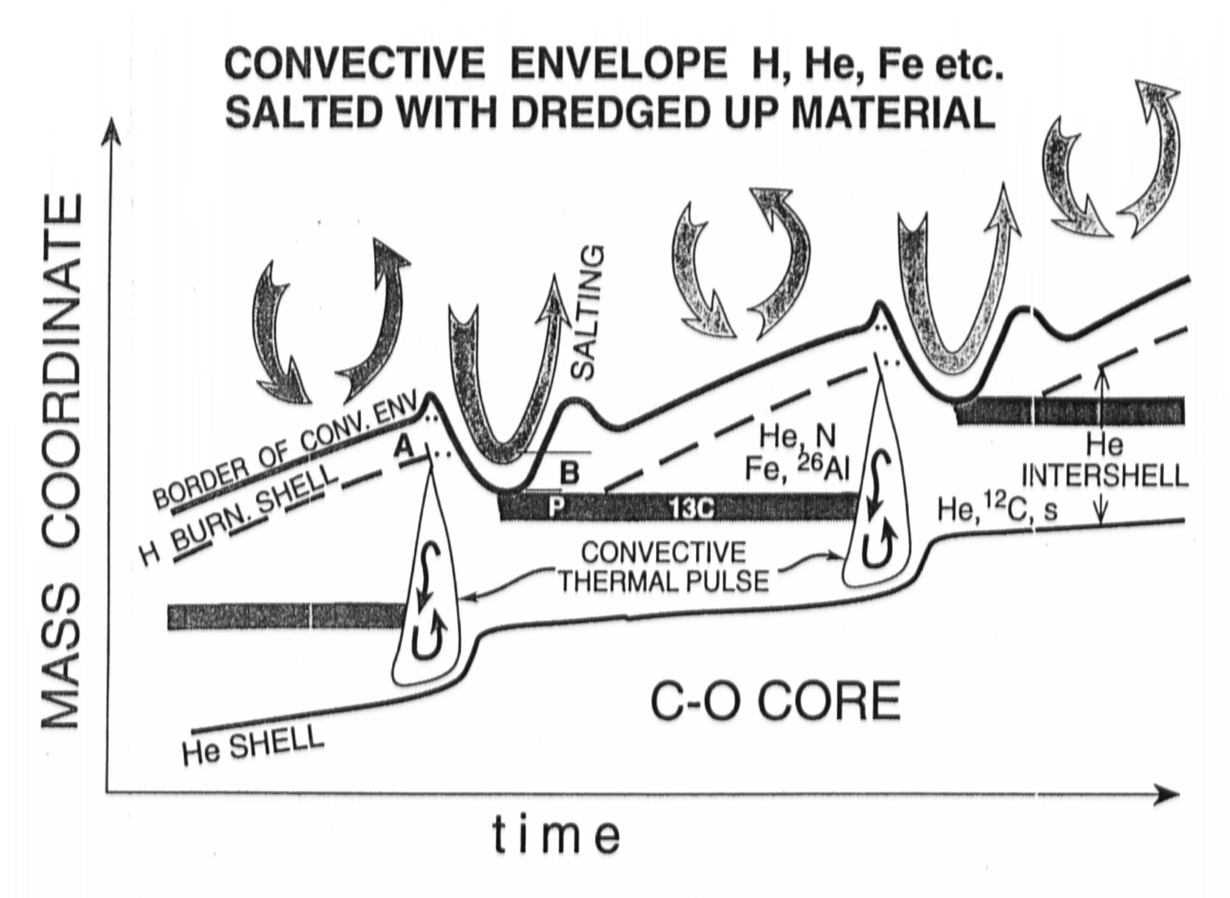
The “classical” description of the 2 processes responsible for the formation of the elements beyond Fe both add neutrons to Fe-seed nuclei.
From the viewpoint of nuclear input data, the s-process seemed to be “totally” understood (at least compared to the r-process), as the path follows the neutron-rich edge of the valley of β-stability with stable or long-lived isotopes accessible to experiments.



Courtesy: Franz Kaeppeler 2007

The s-process in Red Giant stars

The classical model was not directly related to an astrophysical scenario. Contrary to the case of the r-process, it is now common agreement that the s-process takes place in the AGB (Asymptotic Giant Branch) phase in the evolution of Red Giant Stars.
The new models intend to follow the evolution of the star, providing the astrophysical conditions underlying the nuclear reactions.



This leads to new demands on data for the charged particle and neutron-capture reactions.

Most demanding is the description of the neutron sources, ^{22}Ne(α,n) and ^{13}C(α,n).
In the He-burning shell, there is no ^{13}C. It must be synthesized by proton-capture, by protons mixed by convection from outer shells.

Acknowledgements

Over the years, I collaborated with many colleagues in the fields of nuclear structure work and the related field of nuclear astrophysics.

I hesitate to write down names, not to offend someone by an incomplete list.

Therefore, a few very long-time friends and more recent collaborators shall be mentioned as representatives for all the other ones:

- Karl-Ludwig Kratz
- Peter Möller
- Friedrich-Karl Thielemann

- The IKP II group at GSI, which connects me back to my scientific origins.

- Georges Audi and the atomic mass evaluators.

- All the evaluators who joint efforts to update the A=84 NDS in this spring.