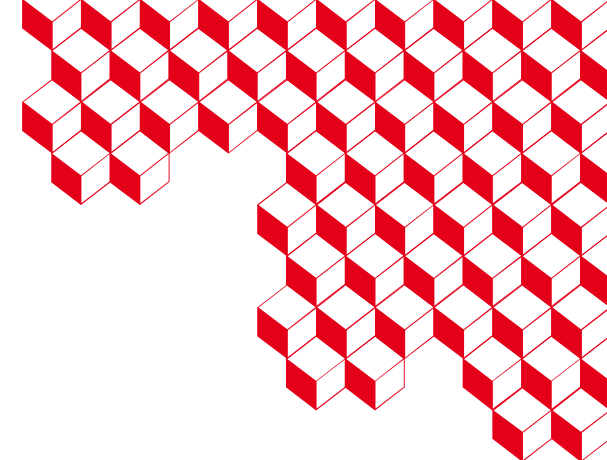




Applications of Nuclear Physics in Everyday Life

Sylvain Leblond

CEA LIST-LNHB



Who am I? (does it matter?)



A permanent researcher working at CEA Saclay (near Paris)

Studies

■ Bachelor	Paris-Sud XI, Paris	Physics	2009 - 2011
■ Master	Université de Caen, Caen	Subatomic Physics	2011 - 2012
■ Ph.D.	LPC, Caen	Nuclear structure	2012 - 2015

Searching for job

■ Post-doc	HKU, Hong-Kong	Nuclear structure	2016 - 2017
■ Post-doc	CEA, Paris	Dismantlement	2017 - 2019
■ Post-doc	GANIL, Caen	Nuclear structure	2019 - 2020

Current position

■ Permanent research	LNE-CEA/LNHB, Paris	Radionuclide metrology	2020 - today
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Today's content

- 1. Overview of Nuclear Physics applications**
- 2. The use of Nuclear Data for applications**
- 3. Radionuclide metrology**
- 4. Dismantling Applications: example of recent technical developments**



1 ■ An overview of applications

What are we (not) going to talk about today?

At the origin: discovery of new radiations

- Discovery of ionizing radiation (1895)
 - Röntgen was investigating the external effect of electric discharge in a vacuum tube
 - He noticed that a tube hidden behind a cardboard was causing fluorescent effect on specific surfaces
- Discovery of Radioactivity (1896)
 - Becquerel was studying phosphorescence of material
 - Due to bad weather, some uranium salt was left on a photographic plate in a closet
 - In order to have a reference measurement Henri Becquerel decided to reveal the plate...
 - Later on the same year, Marie Sklodowska Curie confirms that the radiation exist regardless of the physical form of the uranium



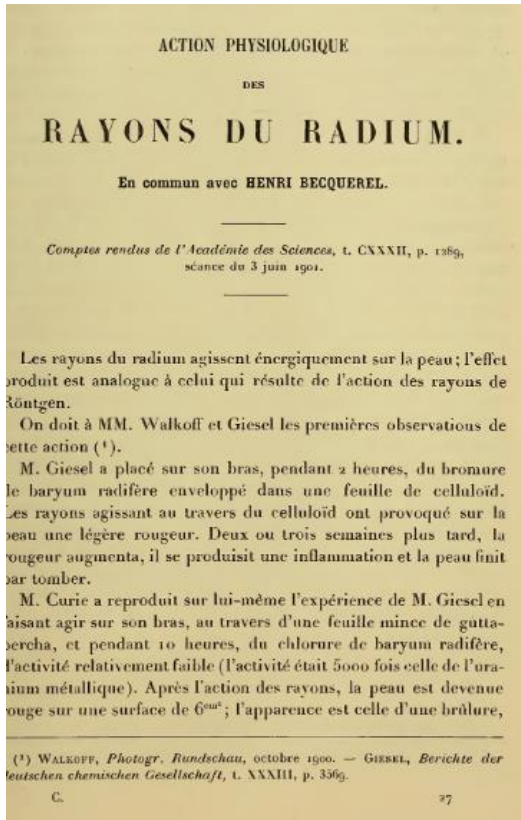
Wilhelm Röntgen, 1895 — Wikimedia Commons



Henri Becquerel, 1896 — Wikimedia Commons

Applications are quickly developed

Medical treatment (1901)



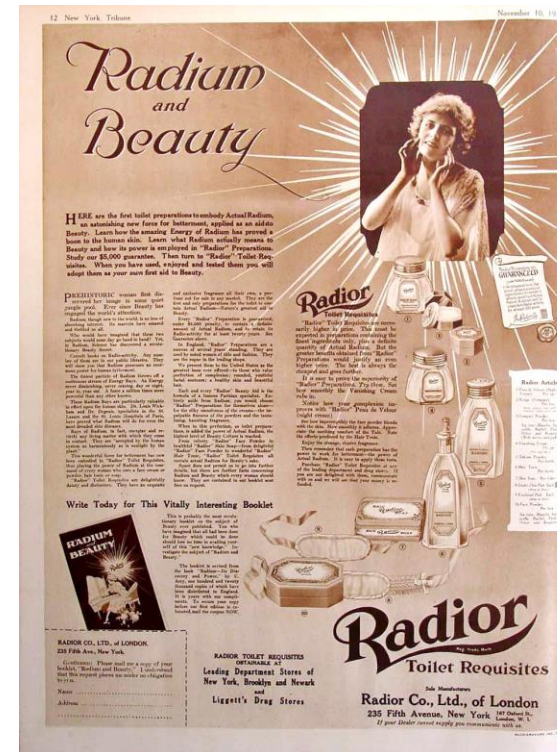
Comptes rendus de l'Académie des Sciences (CXXXII, p. 1289-1291) 1901

Radioactive watch (1917)



Ingersoll, 1917 — Wikimedia Commons

Radioactive cosmetic (1918)



Radium cosmetics, 1918 — Wikimedia Commons

Radioactive water dispenser (1930)



Van Der Meulen Christofle, 2024 — Wikimedia Commons (CC0)

Today's fields of application

Food and agriculture



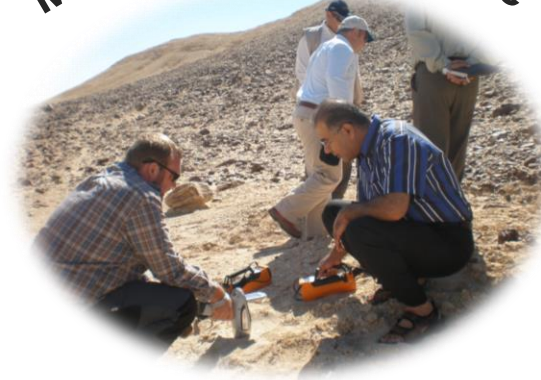
Jérémy Toma, 2016 — Wikimedia Commons (CC BY-SA 4.0)

Space industry



SAC-A satellite, 1998 — NASA

Mining & Earth Science



Uranium exploration, Jordan, 2009 — NucleaX / Wikimedia Commons (CC BY-SA 4.0)

Culture & History



Shonagon / Wikimedia Commons (CC0)

Medicine



Ptrum16 / Wikimedia Commons (CC BY-SA 4.0)



Manufacturing Industry

CEphoto, Uwe Aranas — Wikimedia Commons (CC BY-SA 3.0)



Domestic Security

Mobile VACIS, 2010 — CBP Photography / Wikimedia Commons

Energy production



Kalinin Nuclear Power Plant, 2025 — Vsatinet / Wikimedia Commons (CC BY-SA 4.0)

Applications and radiation usage



Main objectives	Physical mechanisms involved	Application examples
Imaging	Transmission, scattering, attenuation	Medical radiography, tomography (pyramid, volcano)
Cleaning & treating	Energy deposition, ionization	Radiotherapy, sterilization of food or medical instrument, insect pest control
Material modification	Nuclear reaction, activation	Induced mutation on crops, Radiation-induced polymerization, Isotope production
Characterization	Nuclear decay	Radiotracers, Radiocarbon dating

Today's course content

- The goal of this course is not to give you an extensive presentation of all the applications related to Nuclear Physics
- The course aims at giving you some basic knowledge that would help you to better apprehend most of the encountered applications
- We will discuss
 - Nuclear Data
 - Metrology in Nuclear Physics
 - Dismantlement of any Nuclear Facility



2 ■ Nuclear Data

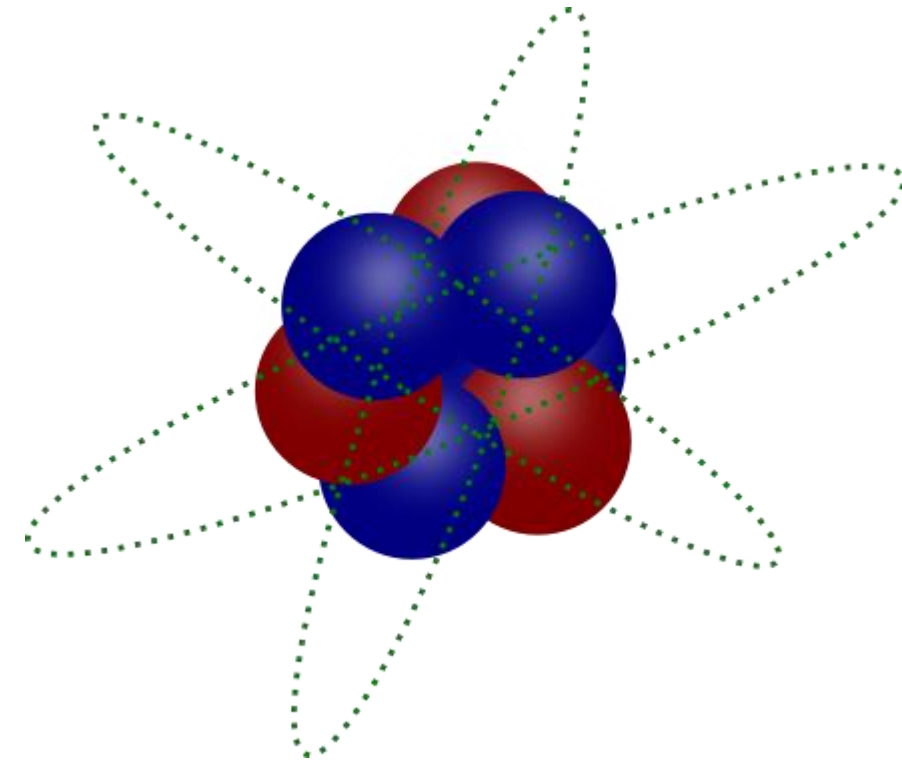
If I want to make a calculation which data should I take?

About Nuclear Data

- 1. What are nuclear data?**
- 2. Presentation of the main databases**
- 3. The Decay Data Evaluation Project**
- 4. Reminders on decay processes**
- 5. Example of the ^{137}Cs half-life evaluation**

At the origin of our understanding...

- The atomic nucleus: a most complex quantum system
 - Three types of particles
 - Proton
 - Neutron
 - Electron
 - Three interactions
 - Electromagnetic
 - Strong
 - Weak
- Theoretical predictions and measurements are difficult to perform
- Many questions remain open regarding
 - Internal structure
 - Decay properties
 - Reactions



Our description of the atomic nucleus is still incomplete and evolves continuously

A wide variety of information

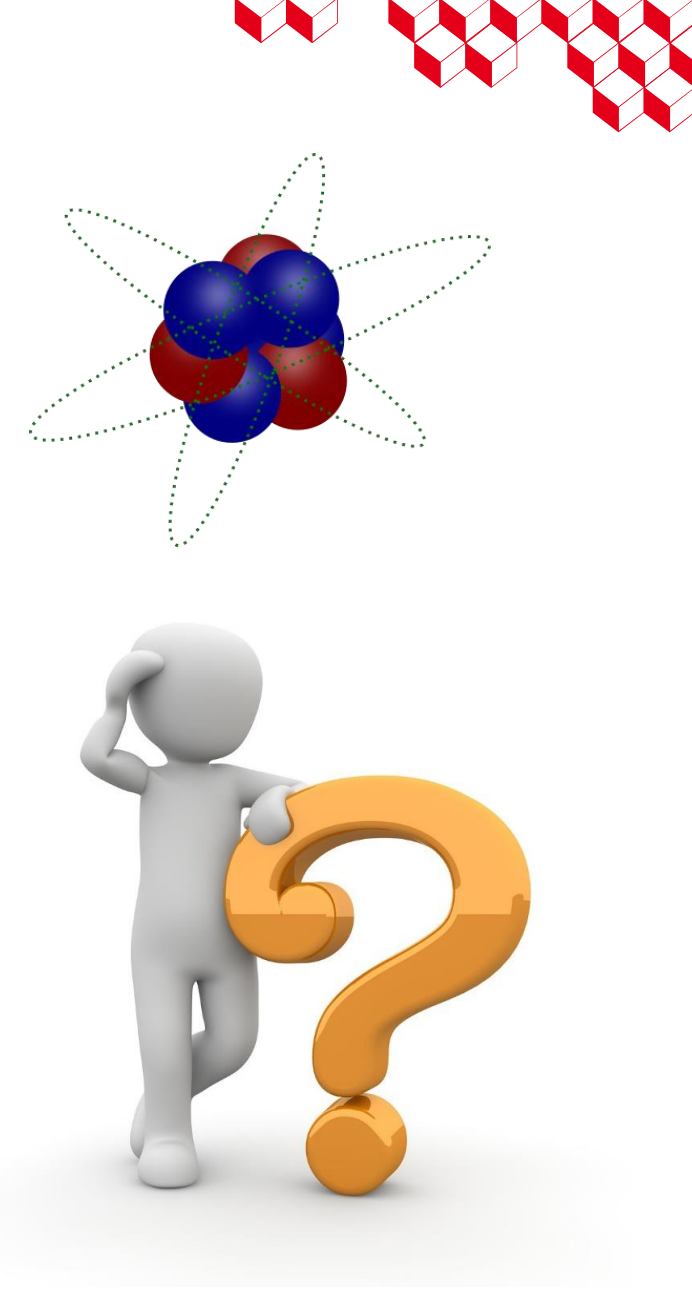
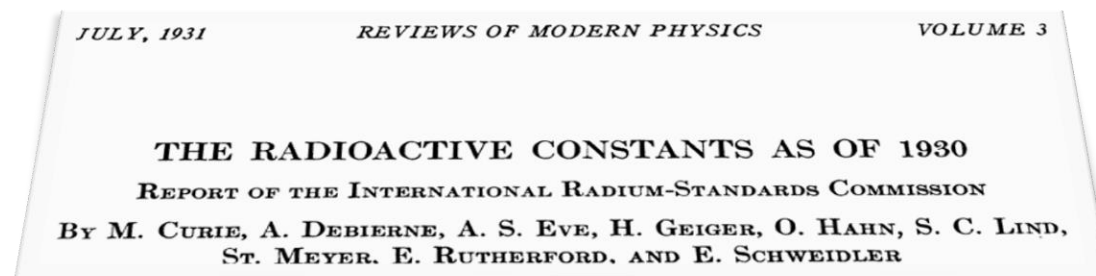
- From theory
 - Wave function
 - Quantum number (Spin-parity)
 - Level energy
 - Transition probability
 - ...
- From experiments
 - Mass
 - Half-life
 - Emission energy and intensity
 - Cross-section
 - Angular distributions
 - ...

How do we ensure the overall consistency
of these different information?

The advent of nuclear data

Which data should be trusted?

- Nuclear database: a critical need
 - Reliable and unbiased analysis
 - Coherence between information
 - Robust uncertainty estimation
- First international recommendation of nuclear data in 1931



Nuclear data nowadays



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

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. Kondev⁶ G. Audi (欧乔治)³ S. Naimi⁷



Evaluated Nuclear Data File (ENDF)

ENDF ENDF/B-VIII.0 released February 2, 2018

JEFF-3.3  **NEA**
NUCLEAR ENERGY AGENCY

The Joint Evaluated Fission and Fusion File (JEFF) is an evaluated library produced via an international collaboration of NEA Data Bank participating countries.

About Nuclear Data

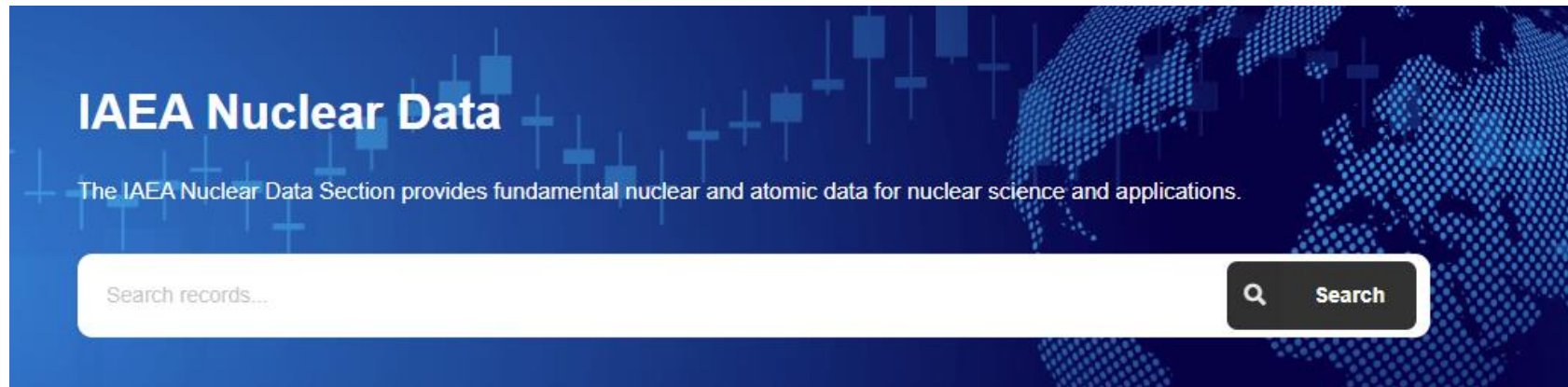
1. What are nuclear data?
2. Presentation of the main databases
3. The Decay Data Evaluation Project
4. Example of the ^{137}Cs half-life evaluation

Wide variety of databases

- There has never been not a single unified database containing all the information relevant to Nuclear Physics.
- Several different databases have been developed independently following the initiative of various communities
- Over the course of the years, the number of databases have been reduced to several large databases
- As of today, most of databases belong to one of the following categories:
 - Atomic Mass
 - Nuclear structure
 - Nuclear Reaction
 - Decay data

Where to find nuclear data?

- The majority of Nuclear Databases can be found through the Nuclear Data Section from the IAEA :
<https://www-nds.iaea.org/>



Atomic Mass Evaluation

- Performed by the Atomic Mass Data Center
- Published regularly since 1955
 - Latest version in 2020 (2026 expected)
- Provide
 - Atomic Mass
 - Mass excess
 - Binding energy per nucleon

$$ME \left({}^A_ZX \right) = [m({}^A_ZX) - A \cdot u] \cdot c^2$$

$$\frac{B({}^A_ZX)}{A} = \frac{(Z \cdot m(p) + (A - Z) \cdot m(n) - m({}^A_ZX)) \cdot c^2}{A}$$

Wapstra, A. H.
1955

Physica XXI
367 – 384

ISOTOPIC MASSES I. $A < 34$

by A. H. WAPSTRA

Instituut voor Kernfysisch Onderzoek, Amsterdam, Nederland

Chinese Physics C

NUCLEAR PHYSICS • OPEN ACCESS

The AME 2020 atomic mass evaluation (II). Tables, graphs and references*

Meng Wang (王猛), W.J. Huang (黄文嘉), F.G. Kondev, G. Audi (欧乔治) and S. Naimi

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[Chinese Physics C, Volume 45, Number 3](#)

Citation Meng Wang et al 2021 *Chinese Phys. C* 45 030003

DOI 10.1088/1674-1137/abddaf

How is AME evaluated?

- Mostly based on experimental measurements
 - Mass
 - Q-value
- For unknown / poorly known nuclei: Trends from the Mass Surface
- Details given in Chinese Physics C

PAPER • OPEN ACCESS

The **AME** 2020 atomic mass evaluation (I). Evaluation of input data, and adjustment procedures*

W.J. Huang (黄文嘉), Meng Wang (王猛), F.G. Kondev, G. Audi (欧乔治) and S. Naimi

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[Chinese Physics C, Volume 45, Number 3](#)

Citation W.J. Huang *et al* 2021 *Chinese Phys. C* **45** 030002

DOI 10.1088/1674-1137/abddb0

How AME data look like?

- A large table in pdf or text format

Chinese Physics C Vol. 45, No. 3 (2021) 030003

Table I. The 2020 Atomic mass table (Explanation of Table on p. 030003-5)

N	Z	A	Elt.	Orig.	Mass excess (keV)		Binding energy per nucleon (keV)		Beta-decay energy (keV)			Atomic mass μu	
1	0	1	n		8071.3181	0.0004	0.0	0.0	β^-	782.347	a	1 008664.9159	0.0005
0	1		H		7288.97106	0.00001	0.0	0.0		*		1 007825.03190	0.00001
1	1	2	H		13135.72290	0.00002	1112.283	a		*		2 014101.77784	0.00002
2	1	3	H		14949.81090	0.00008	2827.265	a	β^-	18.592	a	3 016049.28132	0.00008
1	2		He		14931.21888	0.00006	2572.680	a		*		3 016029.32197	0.00006
0	3		Li	-pp	28670#	2000#	-2270#	670#	β^+	13740#	2000#	3 030780#	2150#

Evaluated and compiled Nuclear Structure Data File

- From International Network of Nuclear Structure and Decay Data Evaluators (AIEA)
 - Hosted by the National Nuclear Data Center (Brookhaven)
 - Based on experimental data (decay & reactions)
- Published regularly since mid 1960s
 - In Nuclear Data Sheets
 - Organized along Mass chain
- Provide structure information on
 - Adopted levels
 - E , J^π , $T_{1/2}$...
 - Adopted gamma
 - E_γ , I_γ , Multipolarity...

Nuclear Data Sheets for $A = 84^*$

R. L. AUBLE

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

Abstract: Nuclear structure information from radioactive decay studies and nuclear reactions pertaining to mass 84 nuclei are compiled, and adopted level schemes are presented. It was found that there are relatively few data for several of these nuclei and, therefore, all data and adopted values for ^{84}As , ^{84}Se , ^{84}Kr and ^{84}Sr are presented in the Summary Sheets. There are no separate Data Sheets for these nuclei.

Many levels have been populated in ^{84}Sr and, to a lesser extent, in ^{84}Kr from the decay of ^{84}Y and ^{84}Br , respectively. However, the properties of most of these levels, other than their energies and gamma-decay modes, are unknown. There also appears to be some uncertainty as to placement of the highest energy beta transition observed in the decay of ^{84}Y . Only two excited states have been studied in each of the odd-odd nuclei, ^{86}Br and ^{86}Rb , one of them being a long-lived metastable state in each case. The decay of $^{86\text{m}}\text{Rb}$ is rather interesting since, if the presently adopted gamma-ray intensities and decay scheme are correct, a large $E4/M3$ or $M4/E3$ mixing ratio is indicated for one of the transitions.

The adopted level properties are based on data received through July 1970. Data from a recent study of ^{84}Rb have been added in proof.

Acknowledgments: The compilers wish to thank Drs. J. Eidens, H. C. Griffin, P. del Marmol, A. C. Rester, and N. G. Zaitseva for their reviews of a preliminary version of this compilation.

NDS 5, issue 2, page 190 (1971)

How is it evaluated?

- Mostly using experimental data
 - Level
 - Gamma energy, intensity
- Rely on several calculation codes
 - Brlcc (conversion coefficients)
 - BetaShape (mean energy, energy distribution)
- Procedure & guidelines
 - Available in a dedicated report

https://www.nndc.bnl.gov/ensdf/evalcorner/pdfs/Evaluators_Guidelines_2021_V2.pdf

Approved for public release. Distribution is unlimited

ORNL/TM-2022/1835

Guidelines for Nuclear Structure Evaluators



Murray J. Martin (ORNL/UTK)

4/26/2021

ENSDF Format

- Based on a 80 column text file
 - Designed to be read by punched card reader
 - Defined in the ENSDF manual

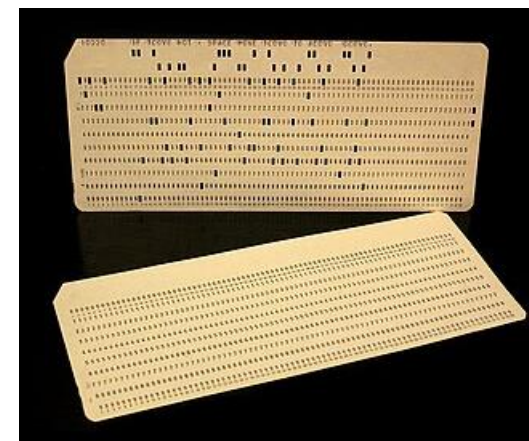
Evaluated Nuclear Structure Data File

A Manual for Preparation
of Data Sets

Jagdish K. Tuli

February, 2001

- Not the easiest to read / interact with at first...
- Currently being updated on a more modern format



IBM-style punched cards — José Antonio González Nieto / Eyesinthefire, 2026 —
Wikimedia Commons (CC BY 4.0)

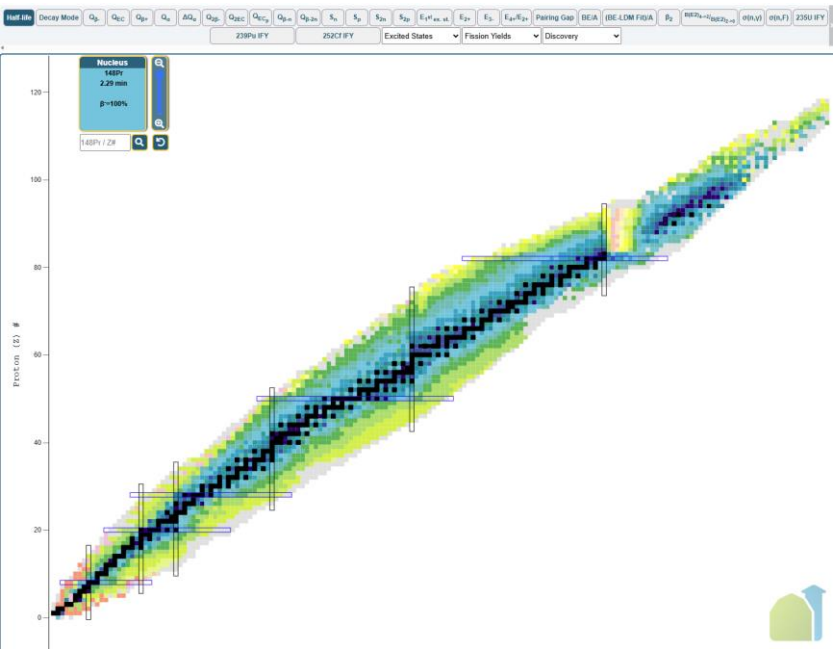
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137CS      ADOPTED LEVELS, GAMMAS                                07NDS      200709
137CS  H TYP=ERR$AUT=J. Tuli$DAT=17-Dec-2007$COM=fixed typos noted by PNPI$
137CS  H TYP=FUL$AUT=E. BROWNE, J. K. TULI$CIT=NDS 108,2173 (2007)$
137CS2 H CUT=1-Oct-2006$
137CS  Q 1175.63  188278.2  197405.6  4 -3084   5      2012WA38
137CS cQ $Note: Current evaluation has used the following Q record
137CS2cQ 1175.63  17 {I8278}.2 {I19} 7409   7 -3084   5      2003Au03
137CS c Theory: 2000Yo08, 1998Su03, 1993Ch31
137CS c Isotope Shifts: 2000Ga58, high-resolution resonant laser spectroscopy
137CS c |g-ray source properties: 2000He14
137CS c References where {+137}Cs is used as the standard source, such as, for
137CS2c various calibrations, etc., and not in study of {+137}Cs structure,
137CS3c have not been included.
137CS cG $|g ray data are from either 1977We02 or 1999Br17,
137CS2cG unless noted otherwise.
137CS cL E$From least-squares fit to E|g
137CS cL J$From correspondence with calculated spectrum based on
137CS2cL shell model (1999Br17), unless given otherwise.
137CS cL J(B)      From analysis of isobaric analog resonances in (p,p)
137CS cL BAND(A)$ |pg7/2{+5} multiplet
137CS cL BAND(C)$ |pg7/2{+4}d5/2 multiplet
137CS cL BAND(E)$ |pg7/2{+4}h11/2 multiplet
137CS cL BAND(D)$ |pg7/2{+3}d5/2h11/2 multiplet
137CS cL BAND(F)$ |pg7/2{+3}d5/2{+2} multiplet
137CS cL BAND(G)$ |pg7/2{+5}|nf7/2h11/2 multiplet
```

¹³⁷Cs ENSDF file header

Online access

- A more human readable format is available online (pdf)
- An easy way to access data is to use the Nudat tool
 - Provided on NNDC website

<https://www.nndc.bnl.gov/nudat3/>



$^{137}_{55}\text{Cs}_{82}^{-1}$ From ENSDF - Evaluated October 2006 $^{137}_{55}\text{Cs}_{82}^{-1}$

Adopted Levels, Gammas

Type	Author	History Citation	Literature Cutoff Date
Full Evaluation	E. Browne, J. K. Tuli	NDS 108,2173 (2007)	1-Oct-2006

$Q(\beta^-)=1175.63\text{ 18}$; $S(n)=8278.2\text{ 19}$; $S(p)=7405.6\text{ 4}$; $Q(\alpha)=-3084\text{ 5}$ [2012Wa38](#)
Note: Current evaluation has used the following Q record 1175.63 17 8278.2 19 7409 7 -3084 5 [2003Au03](#).
Theory: [2000Yo08](#), [1998Su03](#), [1993Ch31](#).
Isotope Shifts: [2000Ga58](#), high-resolution resonant laser spectroscopy.
 γ -ray source properties: [2000He14](#).
References where ^{137}Cs is used as the standard source, such as, for various calibrations, etc., and not in study of ^{137}Cs structure, have not been included.

^{137}Cs Levels

Cross Reference (XREF) Flags

A	$^{137}\text{Xe}\beta^-$ decay	E	$^{138}\text{Ba}(d,^3\text{He})$
B	$^{136}\text{Xe}(p,p),(p,p')$ IAR	F	$^{232}\text{Th}(^{136}\text{Xe},X)$
C	$^{136}\text{Xe}(^3\text{He},d)$	G	$^{136}\text{Xe}(^{232}\text{Th},^{231}\text{Ac}\gamma)$
D	$^{138}\text{Ba}(\mu^-,n\gamma)$	H	^{252}Cf SF decay

E(level) [†]	J ^π [‡]	T _{1/2}	XREF	Comments
0.0 [@]	7/2 ⁺	30.08 y 9	A CDEFGH	$\% \beta^- = 100$ $\mu = +2.8413\text{ 1}$ (1989Ra17); $Q = +0.051\text{ 1}$ (1989Ra17) $T_{1/2}$: Deduced by evaluators using the Limitation of Relative Statistical Weights (LRSW) method for analyzing the following set of discrepant ($\chi^2/\nu = 18.6$) experimental values: 10970 d 20 (2004Sc04); 11018 d 10 (2002Un02); 10941 d 7 (1992Go24); 10968 d 5 (1990Ma15); 11009 d 11 (1980Ho17); 10906 d 33 (1978Gr08); 11034 d 29 (1973Co39); 11021 d 5 (1973Di01); 11023 d 37 (1972Em01); 10921 d 17 (1970Wa19); 11191 d 157 (1970Ha32); 11286 d 256, 10921 d 183 (1965Fi01); 11220 d 47 (1965Le25); 10665 d 110 (1963Ri02); 10840 d 18 (1963Go03); 10994 d 256 (1962Fi09); 11103 d 146 (1961Fa03); 10957 d 146 (1955Br06); and 9715 d 146 (1955Wi21). [1 y = 365.2422 d]. Other evaluated results: 30.09 y 11 (2004Wo02); 30.08 y 3 (1996ChZY, 1994Ka08); 30.11 y 3 (1992Ra08); and 30.18 y 15 (1991BaZS). J^π : from LASER spectroscopy (1978Sc27, see also 1976Fu06); L=4 in ($^3\text{He},d$) and ($d,^3\text{He}$). μ : 1989Ra17 value based on +2.8413 4 (1957St11). Others: +2.838 7 (1978Sc27), +2.84 1 (1981Th06). Q : 1989Ra17 value from 1975Ac01. Others: +0.053 4 (1972Ry03), +0.06 2 (1978Sc27), +0.03 4 (1981Th06).

^{137}Cs ENSDF file header display from nudat3

Nuclear Reaction databases

- Several libraries exist for nuclear reactions

■ ENDF/B	Evaluated Nuclear Data File	(USA)	From 1968
■ JEFF	Joint Evaluated Fission and Fusion	(EU / OECD)	From 1985
■ BROND	Russian evaluated neutron data library	(Russia)	From 1986
■ CENDL	Chinese Evaluated Nuclear Data Library	(China)	From 1985
■ JENDL	Japanese Evaluated Nuclear Data Library	(Japan)	From 1985

- Provide a very large variety of information

- Neutron-induced reaction cross sections
- Fission data
- Neutron scattering data
- Charged-particle reaction data
- Photonuclear data
- ...

How is it evaluated?

- Each library has its own process and guidelines
- They overall rely on both experiment and theoretical modelling
- An international effort to unify Nuclear Data evaluation is ongoing at the AIEA

Working Party on International Nuclear Data Evaluation Co-operation (WPEC)

JEFF NSC Nuclear data

Ongoing

The NEA's nuclear data evaluation co-operation activities involve the following evaluation projects: ENDF (United States), JENDL (Japan), ROSFOND/BROND (Russia), JEFF (other Data Bank member countries) and CENDL (China) in close co-operation with the Nuclear Data Section of the International Atomic Energy Agency (IAEA).

WPEC was established to promote the exchange of information on nuclear data evaluations, measurements, nuclear model calculations, validation, and related topics, and to provide a framework for co-operative activities between the participating projects. WPEC works to improve the quality and completeness of evaluated nuclear data, which represents our best understanding of the basic nuclear physics required to model nuclear systems, for use in science and technology and to promote the efficient use of resources through international collaboration.

[WPEC member's area](#) (password protected).

Active groups

WPEC operates primarily through focused, fixed-term subgroups that identify a specific topic and work toward a clear set of deliverables. When an area is in need of long-term, co-ordinated effort, an Expert Group may be mandated. Today, these include two Expert Groups that oversee the [High Priority Request List \(HPRL\)](#) for Nuclear Data and the [Generalised Nuclear Data Structure \(GNDS\)](#), a new international standard nuclear data format.

Over the 30+ years of operation, WPEC has raised 54 subgroups (SG) to address virtually all aspects of the nuclear data pipeline. The current, active subgroups include:

- **SG-51:** Evaluation, Processing and Validation in the Unresolved Resonance Region (URR).
- **SG-52:** Development and application of advanced methodologies to produce application specific nuclear data libraries (ND Adjustment).
- **SG-53:** Stable Zirconium Evaluations and Validation (Zr updates).
- **SG-54:** Continuation of Subgroup 50 on developing an automatically readable, comprehensive, and curated experimental reaction database.

ENDF Format

- These database are mainly distributed in a 80 column text file
 - Mostly using the ENDF-6 data format
 - Format defined in the ENDF format manual



CSEWG Document ENDF-102
Report BNL-224854-2023-INRE
Git Revision SHA1: 3576914

ENDF-6 Formats Manual

Data Formats and Procedures for the Evaluated Nuclear Data Files
ENDF/B-VI, ENDF/B-VII and ENDF/B-VIII

Written by the Members of the Cross Sections Evaluation Working Group

Edited by
D. A. Brown

September 28, 2023

```
55-Cs-137 INL+RI      EVAL-JUN06 R.G.HELMER,V.P.CHECHEV      1809 1451   5
                        DIST-FEB25                        20250209 1809 1451   6
-----JEFF-40      MATERIAL 1809                        1809 1451   7
-----RADIOACTIVE DECAY DATA                        1809 1451   8
-----ENDF-6 FORMAT                        1809 1451   9
*****1809 1451  10
**          JEFF-4.0 Radioactive Decay Data File      **1809 1451  11
**          Compiled for the NEA Data Bank - Feb 2025  **1809 1451  12
**          Original data taken from: DDEP            **1809 1451  13
*****1809 1451  14
*****1809 1451  15
* Converted from the ENSDF format by using the SDF2NDF code (1) *1809 1451  16
* (the CEA-Bruyeres version of the RADLST program).      *1809 1451  17
* (1) 0. Bersillon and J. Blachot, to be published.      *1809 1451  18
*****1809 1451  19
137CS DECAY 30.05 Y 8      I(min) = 0.0E+00 %      1809 1451  20
      Ex = 0.0      keV      1 decay mode(s)      1809 1451  21
137CS B- DECAY      Q = 1175.6300 keV      0.1700      1809 1451  23
      Branching      100.0000 %      0.0000      1809 1451  24
      Br*Q = 1175.6300 keV      0.1700      1809 1451  25
      1 isomeric state(s)      1809 1451  26
      Ex = 0.0000 keV      5.6406 %      1809 1451  27
      Ex = 661.6590 keV      94.3594 %      1809 1451  28
      1809 1451  29
Individual beta- transitions      1809 1451  30
Final level      end point      shape      av.energy      intensity      1809 1451  31
661.659      513.966      0.170 1      173.590      0.060      94.360 0.280 1809 1451  32
283.500      892.122      0.197 2      332.280      0.080      0.001 0.000 1809 1451  33
0.000      1175.619      0.170 1      284.900      0.050      5.640 0.280 1809 1451  34
      1809 1451  35
      100.001      1809 1451  36
      1809 1451  37
Mean alpha      energy      0.0000 keV      0.0000      1809 1451  38
Mean beta      energy      179.8699 keV      0.9359      1809 1451  39
Mean conv. e-      energy      0.0001 keV      0.0000      1809 1451  40
Mean Auger e-      energy      0.0000 keV      0.0000      1809 1451  41
Mean gamma      energy      0.0016 keV      1809 1451  42
Mean X      energy      0.0000 keV      0.0000      1809 1451  43
Mean recoil      energy      0.0051 keV      0.0000      1809 1451  44
Mean neutrino      energy      371.4190 keV      2.6705      1809 1451  45
Mean neutron      energy      0.0000 keV      0.0000      1809 1451  46
Total      energy      551.2957 keV      2.8297      1809 1451  47
Q effective      551.2924 keV      0.1700      1809 1451  48
diff. mode      0.0034 keV      0.0006 %      1809 1451  49
```

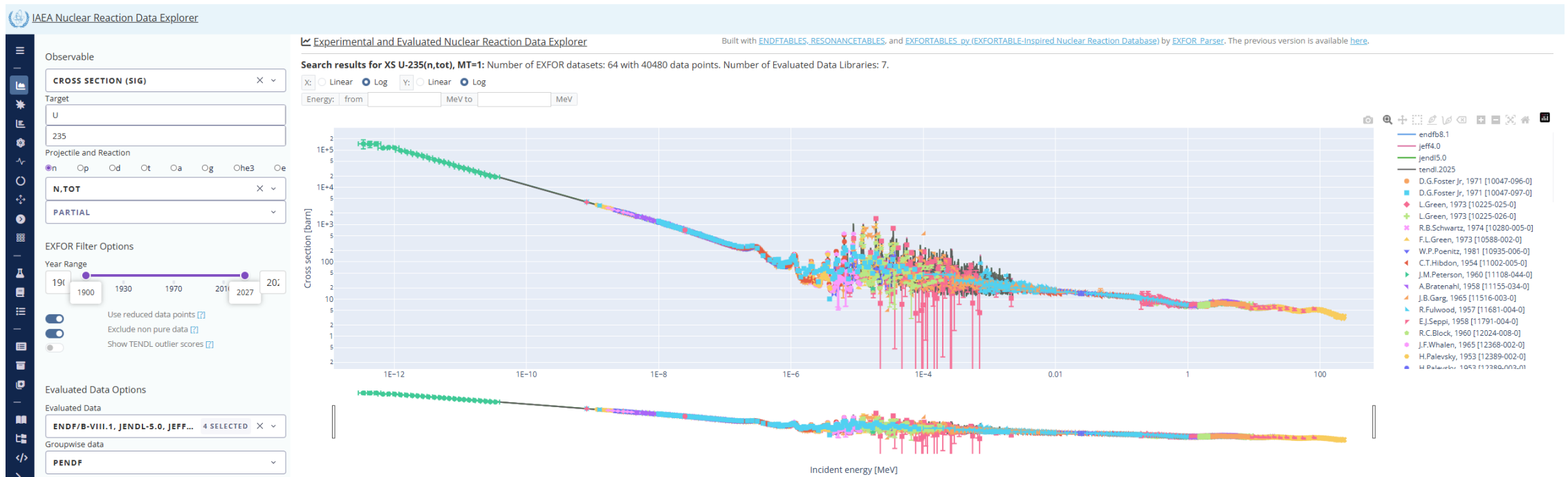
¹³⁷Cs JEFF 4.0 header file

Access, display & comparison

- Data can be downloaded from the various collaboration webpages

- Various tools can be used to display and compare the database

e.g. <https://nds.iaea.org/dataexplorer>



About Nuclear Data

1. What are nuclear data?
2. Presentation of the main databases
- 3. The Decay Data Evaluation Project**
4. Example of the ^{137}Cs half-life evaluation



About nuclear decay

■ A sequential process

1. Initial decay

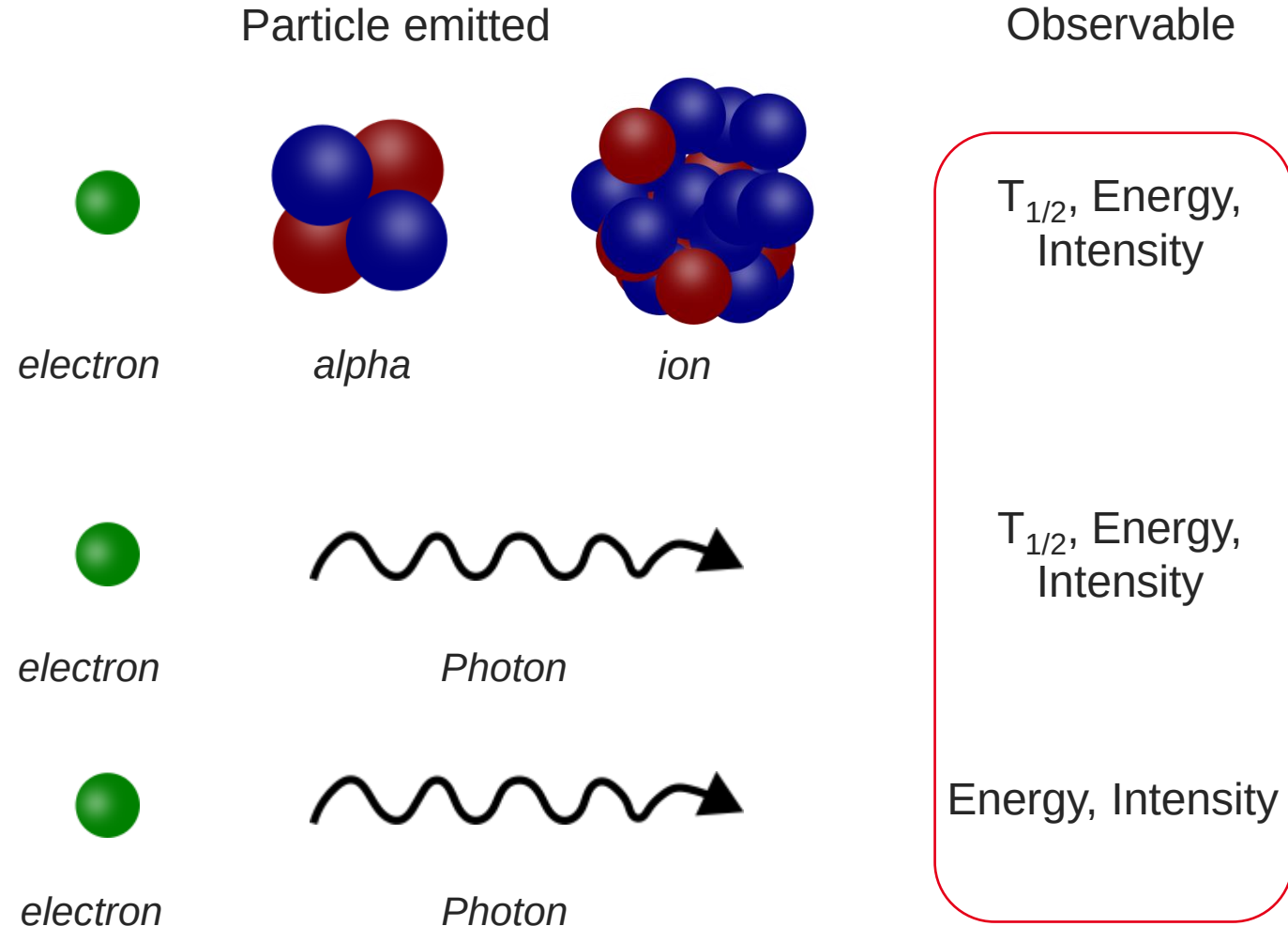
- β^-
- β^+ / electron capture
- Alpha
- Fission

2. Nucleus de-excitation

- γ transition
- Internal conversion

3. Atomic de-excitation

- X-rays
- Auger electrons



At the origin of DDEP

- Within the metrology community, in the early 1990s, there was a specific need identified for evaluated decay scheme data for use in absolute activity measurements, including important atomic data, e.g. conversion electrons, X-rays, Auger-electrons.
- During international inter-comparison exercises, differences in recommended activity values were seen to be dependent upon the decay scheme data used.
- A group dedicated to decay scheme evaluation was formed in 1993 between LNHb (France) & PTB (Germany), quickly followed by USA and others in 1994.
- Hence, the international DDEP group was established in 1995, in which a common evaluation methodology was defined and adopted, including a comprehensive review process.
- The Bureau International des Poids et Mesures (BIPM), which, through the Consultative Committee on Ionising Radiation, oversees the international metrology community inter-comparison exercises recommended that the DDEP evaluated decay scheme data should be used by all metrology institutes.



DDEP missions

- Provide recommended decay data to non-specialists

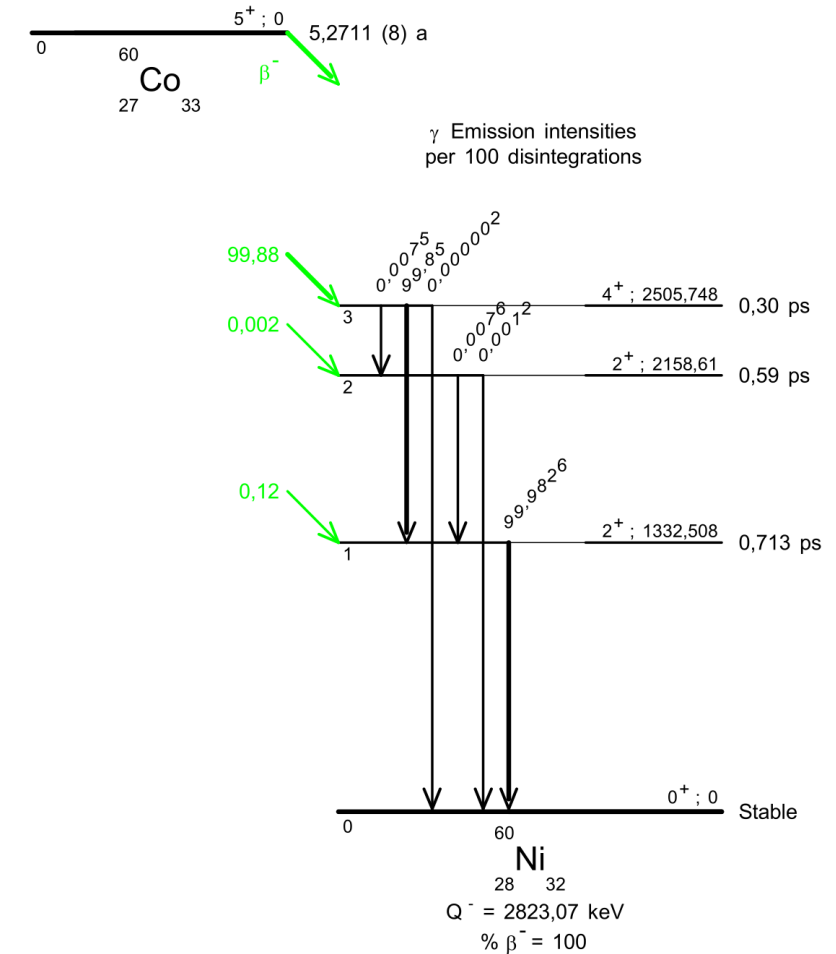
- Metrology
- Nuclear Physics (detector calibration)
- Nuclear Medicine
- Nuclear Power

- Main information of interest:

- Half-life, Q-value
- Decay scheme
- Intensity and energies of
 - Alpha / beta / electron capture
 - Gamma and internal conversion
 - X-rays & Auger electrons

Decay properties

Emitted particles



DDEP members

- DDEP Coordination: Xavier Mougeot
- LNHB Local team (evaluation, review, edition, publication)



- Sylvain Leblond
- Xavier Mougeot

- Mark A. Kellett (Special advisor)
- Christophe Dulieu (IT support)

- Decay data evaluators

- Alan L. Nichols
(Surrey University, UK)
- Aurelian Luca
(IFIN, Romania)

- Brian E. Zimmerman
(NIST, USA)
- Rob Shearman
(NPL, UK)

- Xialong Huang
(CIAE, China)
- Nikolai Kuzmenko
(KRI, Russia)

- Additional support

- Tibor Kibédi (BrIcc and BrIccMixing codes)



DDEP evaluation pipeline

1. Initiation of a evaluation

- Need from a project / collaboration
- Following a user request
- Evaluator initiative

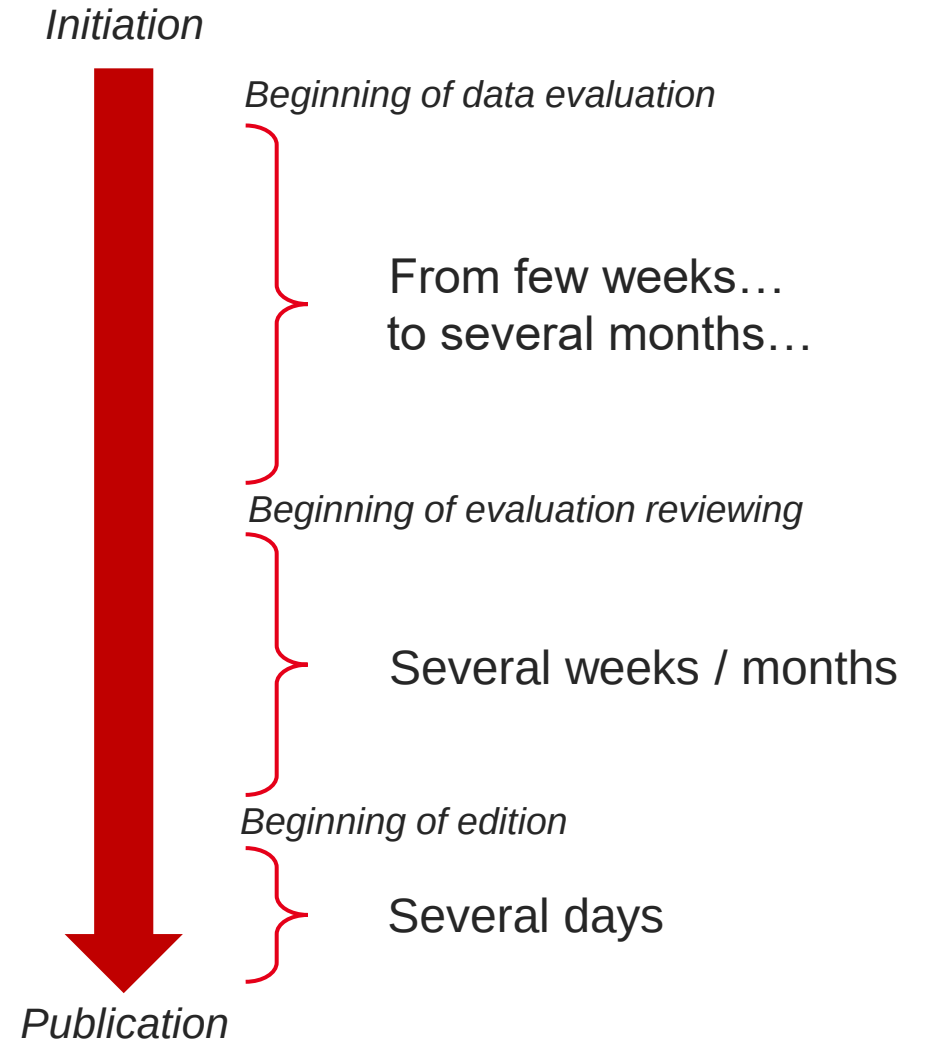
2. Data evaluation

- Performed independently by 1 or 2 evaluators
- Using DDEP guidelines and tools

3. Reviewing process

- One DDEP reviewer is assigned
- Complete verification of the evaluation
- Discussion with evaluator until agreement

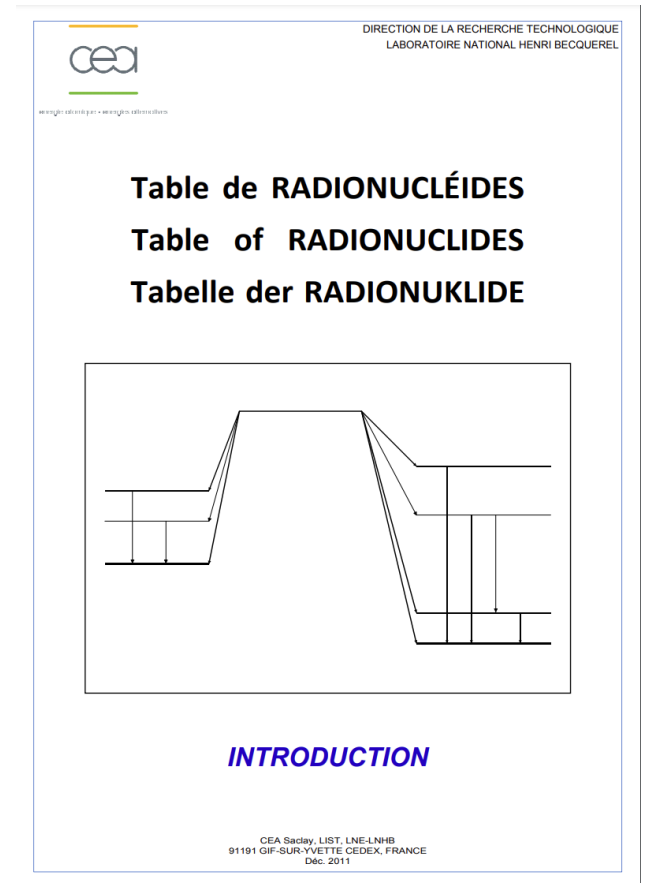
4. Edition and publication



How to make a DDEP recommendation?

1. Gather the dataset on a given quantity (half-life, energy, intensity...)
 - From previous evaluations
 - From online data base (NSR, OSTI, INIS...)
 - From journal and articles
2. Refine the dataset
 - Peer-reviewed publication only
 - With uncertainty estimation
 - One value per laboratory / author
 - Consistency: Chauvenet criterion
3. Calculate recommended value
 - Using a given averaging method (Lweight)
 - Using various codes (BrIcc, BetaShape, AlphaRad, Emission...)

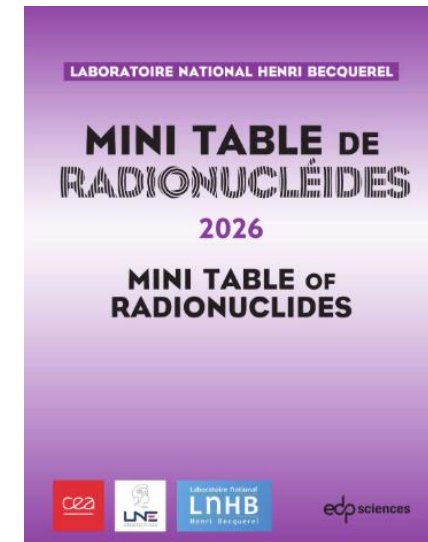
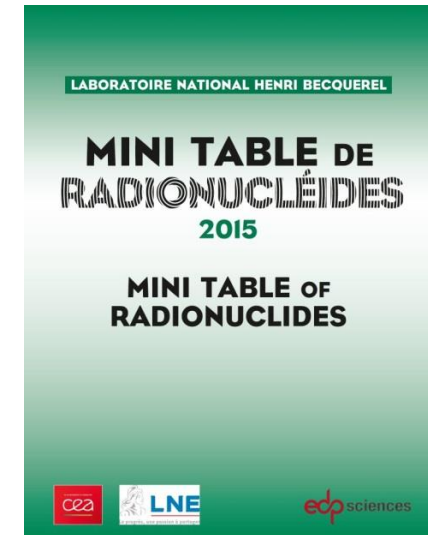
} DDEP guidelines



Publications

- Tables of Radionuclides
 - published by BIPM
 - 8 volumes from 2004 to 2016
 - Around 40 isotopes per volume
- Mini Table of Radionuclides
 - Published by EDP Sciences
 - Price: 25 €
 - 1884 units sold (paper + digital)
 - Around 300 isotopes
 - Small and compact

New edition to be
released in September!



On LNHB website!

- Download available
 - BIPM Monographies
 - Nucleus Evaluation
 - Comments file
 - ENSDF file
 - PenNuc input file
 - BetaShape file

- Access in 2022
 - ~ 130 access per day
 - ~ 20 downloads per day
 - ~ 20 countries
 - ~ 7 times more views in 5 years



This [introduction](#) presents a brief description of the radioactivity physical processes, the enumeration of the evaluation rules leading to the recommended values, and a summary of the symbols and terms used in all the publications.

Explanation on recommended data and their evaluation (in various languages):



Please cite our evaluations using the following references:

Vol.	Publication	Year	ISBN	NSR	BibTeX	Vol.	Publication	Year	ISBN	NSR	BibTeX
0	CEA Report - Table de Radionuclides	1999	2-7272-0200-3	1999a20	TabRad_v0.abb	5	Monographie BIPM-5 - Table of Radionuclides, vol. 5	2010	978-92-822-2234-8	2010a20	TabRad_v5.abb
1	Monographie BIPM-5 - Table of Radionuclides, vol. 1	2004	92-822-2206-9	2004a20	TabRad_v1.abb	6	Monographie BIPM-5 - Table of Radionuclides, vol. 6	2011	978-92-822-2242-9	2011a20	TabRad_v6.abb
2	Monographie BIPM-5 - Table of Radionuclides, vol. 2	2004	92-822-2207-4	2004a20	TabRad_v2.abb	7	Monographie BIPM-5 - Table of Radionuclides, vol. 7	2013	978-92-822-2248-5	2013a20	TabRad_v7.abb
3	Monographie BIPM-5 - Table of Radionuclides, vol. 3	2006	92-822-2218-7	2006a20	TabRad_v3.abb	8	Monographie BIPM-5 - Table of Radionuclides, vol. 8	2016	978-92-822-2264-5	2016a20	TabRad_v8.abb
4	Monographie BIPM-5 - Table of Radionuclides, vol. 4	2008	92-822-2231-4	2008a20	TabRad_v4.abb	9	Monographie BIPM-5 - Table of Radionuclides, vol. 9	2020	to be published	-	-

Filter data:

Enter value

☒ by Element

☐ by Atomic number (Z)

☐ by Mass number (A)



Sort by:

Atomic number

Nuclide	Z	Vol. (?)	UpDate	Type (?)	Table (?)	Comments (?)	ASCII files (?)				
H-3	³ H	1	3	04/09/2006	1	T	C	E	P	L	B
Be-7	⁷ Be	4	1	18/02/2004	1	T	C	E	P	L	B
C-11	¹¹ C	6	1	03/11/2011	2	T	C	E	P	L	B
C-14	¹⁴ C	6	7	22/11/2012	1	T	C	E	P	L	B
N-13	¹³ N	7	1	08/04/2004	1	T	C	E	P	L	B
O-15	¹⁵ O	8	1	01/06/2004	1	T	C	E	P	L	B
F-18	¹⁸ F	9	1	01/09/2014	2	T	C	E	P	L	B
Na-22	²² Na	11	5	06/08/2009	3	T	C	E	P	L	B
Na-24	²⁴ Na	11	1	16/06/2014	2	T	C	E	P	L	B
Al-26	²⁶ Al	13	99	24/07/2003	1	T	C	E	P	L	B
P-32	³² P	15	1	08/04/2004	1	T	C	E	P	L	B
P-33	³³ P	15	1	08/04/2004	1	T	C	E	P	L	B

<http://www.lnhb.fr/nuclear-data/nuclear-data-table/>

Laraweb online tool

- Laraweb online interface
 - Easy access to decay data
 - Decay scheme
 - Direct access to Tables & recommendations
 - Various tools (activity calculation, mass...)
 - Energy / intensity queries
- Statistics
 - ~ 2000 users per day
 - ~ 3000 requests per day
 - ~ 60 countries
 - Common queries: ^{241}Am , ^{137}Cs , ^{152}Eu ...

<http://www.lnhb.fr/Laraweb>

Fig.2: Advanced use (search)

Nucléide - Lara
Library for gamma and alpha emissions

Nuclide list:
208Tl
209Tl
209Po
209Bi
210Tl
210Po
210Pb

Nuclide, element or mass number search:
or 60Co
(e.g.: 57Co, Co-57, Co, 57)

Energy threshold (keV): 10
Intensity threshold (%): 2
Coincidence threshold (%): 10
Show γ - γ coincidences ☒
Sort by decreasing intensity ☐
Display:
☐ Data ☒ Tools ☐ Emissions ☐ Scheme
Emissions: ☒ X ☒ Gamma ☒ Alpha
Language: EN EO FR
[Show all data](#) [Show scheme only](#)

Nuclide search criteria

Decay mode: ☒ β^+ , α ☒ β^- ☒ IT ☒ α
(☐ And ☒ Or ☐ XOr)
Emissions: ☒ X ☒ Gamma ☒ Alpha

Energy 1 (or range):
511 $\pm$ / - 1 keV
Energy 2 (or range):
850 $\pm$ / - 50 keV
Energy 3 (or range):
 $\pm$ / - keV
Intensity range:
10 - %
Mass range:
- u
Atomic number range:
-
Half-life range:
1 d - s

[Find nuclides](#) 1

[Reset all forms](#) [Load last settings](#)

Last update: 2017-03-03 (data) & 2020-06-04 (code)

• [Quick user's guide](#)
• Printed version (2015) available by [EDP Sciences](#)
• [Contact us](#) (suggestions, comments, remarks, ...)
• [Back to LNH home page](#)
• [Subscribe to LNH RSS feed](#)

Selection results

3 nuclides disintegrating by β^+ , ϵ or β^- or I.T. or α giving 6 emissions where
Energy 1: $E = 511 \pm 1$ keV and
Energy 2: $E = 850 \pm 50$ keV
Intensity: $I \geq 10\%$
Half-life: $T_{1/2} \geq 1$ d

Energy / Intensity (nuclide):
(sorted by increasing energy)
511 3.92E+1 (56Co)
511 2.99E+1 (58Co)
511 5.14E+1 (84Rb)
810.7602 9.94E+1 (58Co)
846.7638 9.99E+1 (56Co)
881.61 6.90E+1 (84Rb)

[Show emissions](#)

Energy / Intensity (nuclide):
(sorted by decreasing intensity)
511 5.14E+1 (84Rb)
511 3.92E+1 (56Co)
511 2.99E+1 (58Co)
846.7638 9.99E+1 (56Co)
810.7602 9.94E+1 (58Co)
881.61 6.90E+1 (84Rb)

[Show emissions](#)

Nuclide (half-life):
56Co (77.236 d)
58Co (70.85 d) 2
84Rb (32.82 d)

Energy threshold (keV): 10
Intensity threshold (%):

[Show emissions](#) 3 [Show scheme only](#)

^{58}Co - Emissions and decay scheme

[Data](#) [Tools](#) [Emissions](#) [Scheme](#)

Data
Element: Cobalt (Z=27)
Daughter(s): Fe-58 (β^+ , α , 100%)
 Q^+ : 2307.9 keV
Possible parent(s): Co-58m (I.T., 100%)
Half-life ($T_{1/2}$): 70.85 (3) d ≈ 6.1214 (26) 10^6 s
Decay constant (λ): 113.233 (48) 10^{-9} s $^{-1}$
Specific activity (A_m): 1.17570 (50) 10^{15} Bq.g $^{-1}$
Reference: CEA/LNE-LNH - 2013
Associated data files: [Table](#) - [Comments](#) - [ENSDF](#) - [PenNuc](#)
Data and emissions file (ASCII text format): [Co-58.txt](#)

Emissions
Energy threshold: 10 keV
Emissions (4 lines out of 8) sorted by increasing energy
[Emissions meeting search criteria](#) [Other significantly intense emissions](#)

Energy (keV)	Intensity (%)	Type	Origin*	Levels Start*	End*
511 (-)	29.88 (32)	γ	Fe-58	-1	-1
810.7602 (20)	99.44 (2)	γ	Fe-58	1	0
863.958 (6)	0.700 (22)	γ	Fe-58	2	1
1 674.705 (6)	0.528 (13)	γ	Fe-58	2	0

^{84}Rb - Emissions and decay scheme

[Data](#) [Tools](#) [Emissions](#) [Scheme](#)

Data
Element: Rubidium (Z=37)
Daughter(s): Kr-84 (β^+ , α , 96.2%), Sr-84 (β^- , 3.8%)
 Q^+ : 2680.4 keV, Q^- : 890.6 keV
Half-life ($T_{1/2}$): 32.82 (7) d ≈ 2.836 (6) 10^6 s
Decay constant (λ): 244.4 (5) 10^{-9} s $^{-1}$
Specific activity (A_m): 1.7524 (37) 10^{15} Bq.g $^{-1}$
Reference: CEA/LNE-LNH - 2013
Data and emissions file (ASCII text format): [Rb-84.txt](#)

Emissions
Energy threshold: 10 keV
Emissions (8 lines out of 9) sorted by increasing energy
[Emissions meeting search criteria](#) [Other significantly intense emissions](#)

Energy (keV)	Intensity (%)	Type	Origin*	Levels Start*	End*
12.599 (-)	11.4 (3)	$X_{K\alpha 2}$	Kr-84		
12.65 (-)	22.1 (5)	$X_{K\alpha 1}$	Kr-84		
14.152 (-)	5.26 (13)	$X_{K\beta 1}$	Kr-84		
14.3215 (-)	0.53 (2)	$X_{K\beta 2}$	Kr-84		
511 (-)	51.4 (20)	γ	Kr-84	-1	-1
881.610 (3)	69.0 (22)	γ	Kr-84	-1	0
1 016.162 (13)	0.349 (13)	γ	Kr-84	-1	1
1 897.761 (14)	0.74 (3)	γ	Kr-84	-1	2

About Nuclear Data

1. What are nuclear data?
2. Presentation of the main databases
3. The Decay Data Evaluation Project
4. **Example of the ^{137}Cs half-life evaluation**

Discovery of an iconic radionuclide

- In **1941** at **Berkeley**
 - Margaret Melhase and Glenn Seaborg
 - First chemical extraction of radioactive Caesium
 - Produced by thermal neutron induced fission on ^{235}U
- Since then...
 - More than 80 000 publications in a wide range of applications



Margaret Melhase (1941)
Wikimedia Commons



Glenn Seaborg (1950)
Wikimedia Commons



Dukovany Nuclear Power Plant cooling towers, 2013
— Jiří Sedláček / Wikimedia Commons (CC BY-SA 4.0)



Irradiator inspection, 2023
— U.S. Nuclear Regulatory Commission



Caesium-137 radioactive source, 2008
— Wusel007 / Wikimedia Commons (CC BY-SA 3.0)

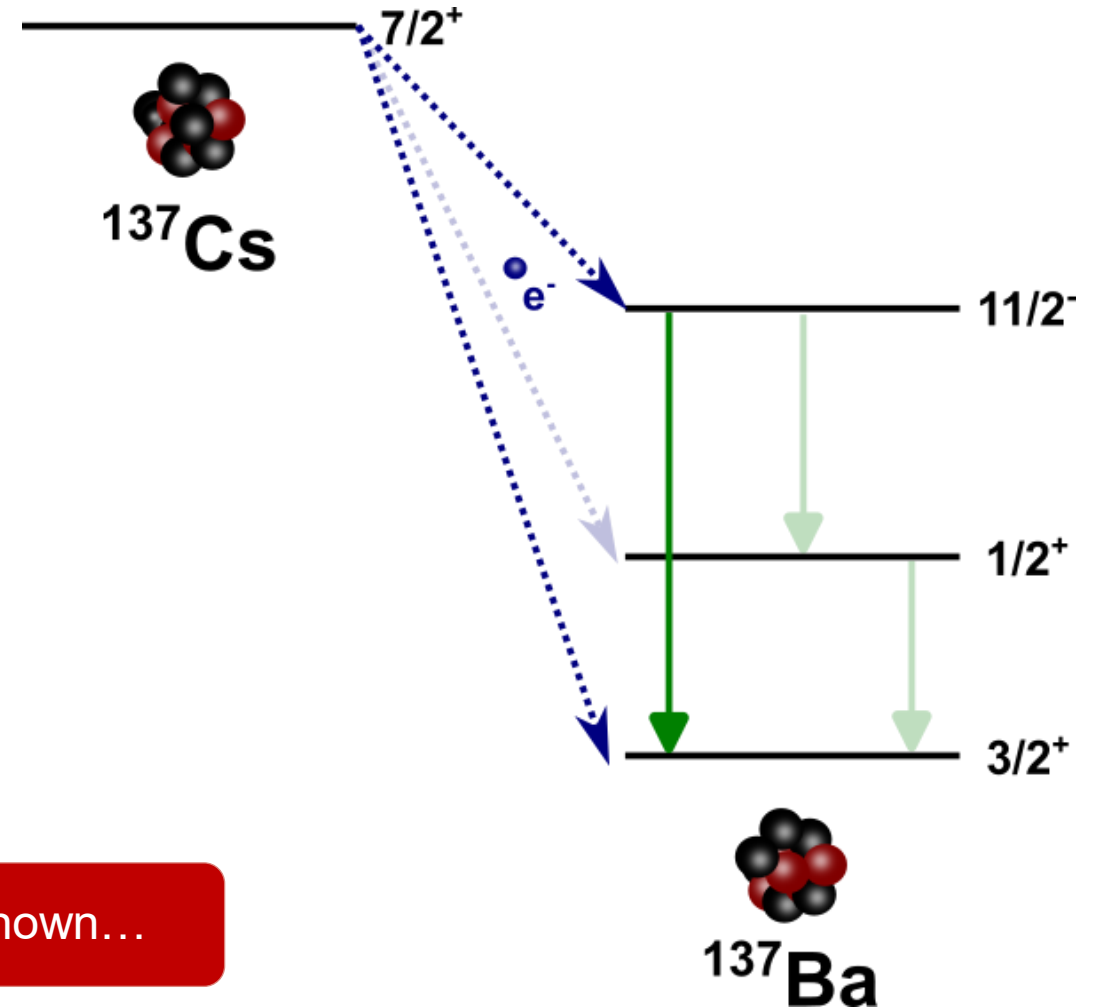


Industrial radiography camera, 2014
— U.S. Government Accountability Office

Decay overview of ^{137}Cs

- A β^- decay to ^{137}Ba
 - Populates ground & excited states
 - Half-life around 30 years
 - Total Q-value close to 1176 keV
- Emissions
 - Two main β^- branches
 - Ground state ($E_{\text{max}} \sim 1176 \text{ keV}$)
 - Second excited state ($E_{\text{max}} \sim 514 \text{ keV}$)
 - Iconic 662 keV gamma

Surely decay data are well known...



Decay data status in 2020

■ Latest ^{137}Cs decay data evaluations

■ DDEP

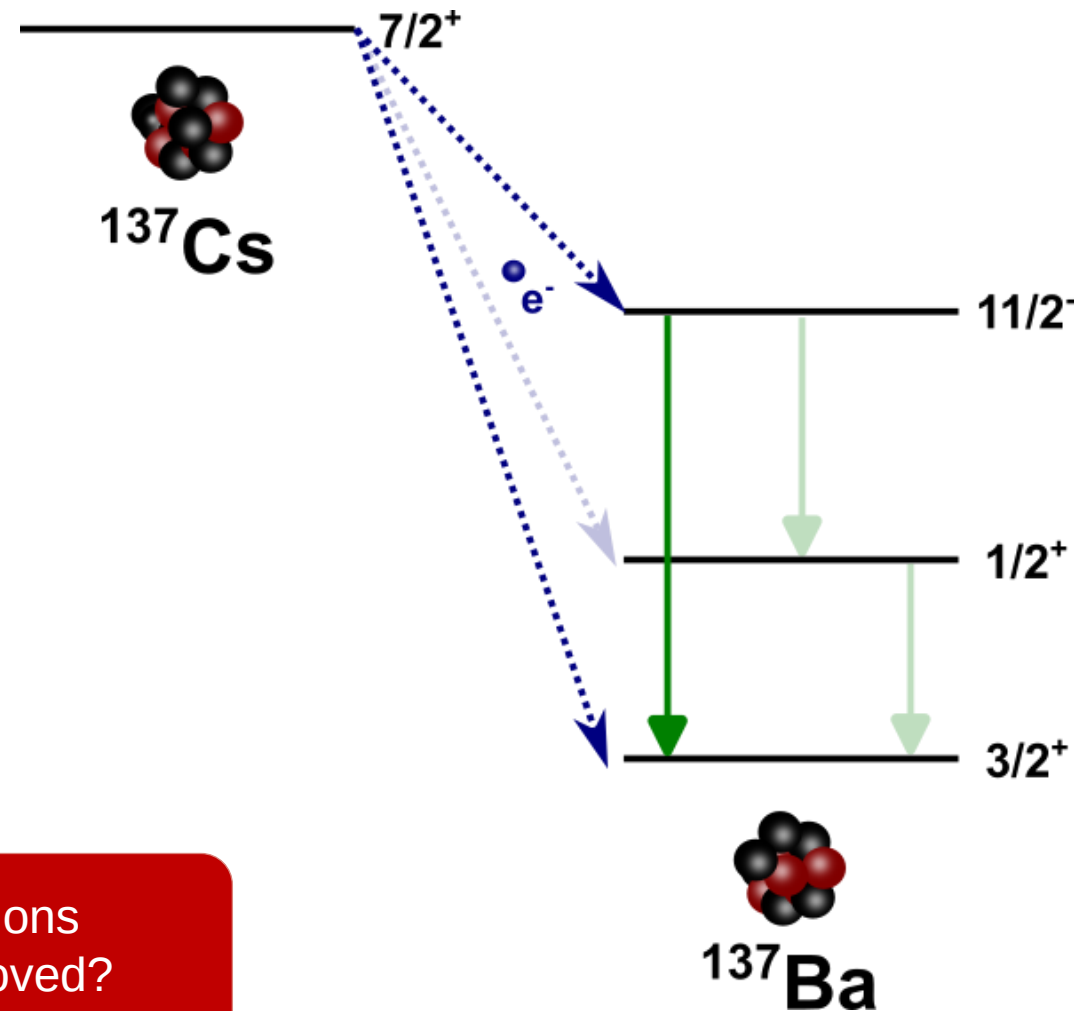
- R.G. Helmer and V.P. Chechev (2006)

■ ENSDF

- E. Browne and J.K. Tuli (2007)

	DDEP	ENSDF
$T_{1/2}$ (a)	30.05 (8)	30.08 (9)
$I_{\beta}(11/2^-)$ (%)	94.36 (28)	94.7 (2)
$I_{\beta}(3/2^+)$ (%)	5.64 (28)	5.3 (2)
I_{γ} (%)	84.99 (20)	85.1 (2)

New publications
Can it be improved?



Reminder on half-life

- Radioactive decay is a stochastic process

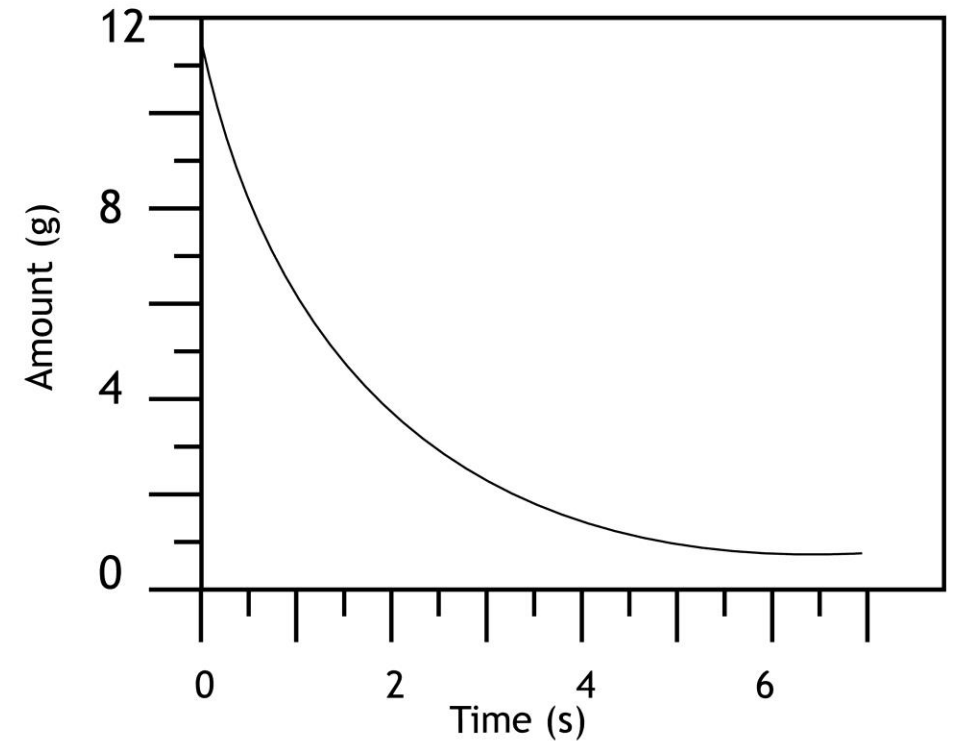
$$N(t) = N_{t=0}e^{-\lambda t}$$

Where λ is the radioactive constant

- The half-life ($T_{1/2}$) is defined as

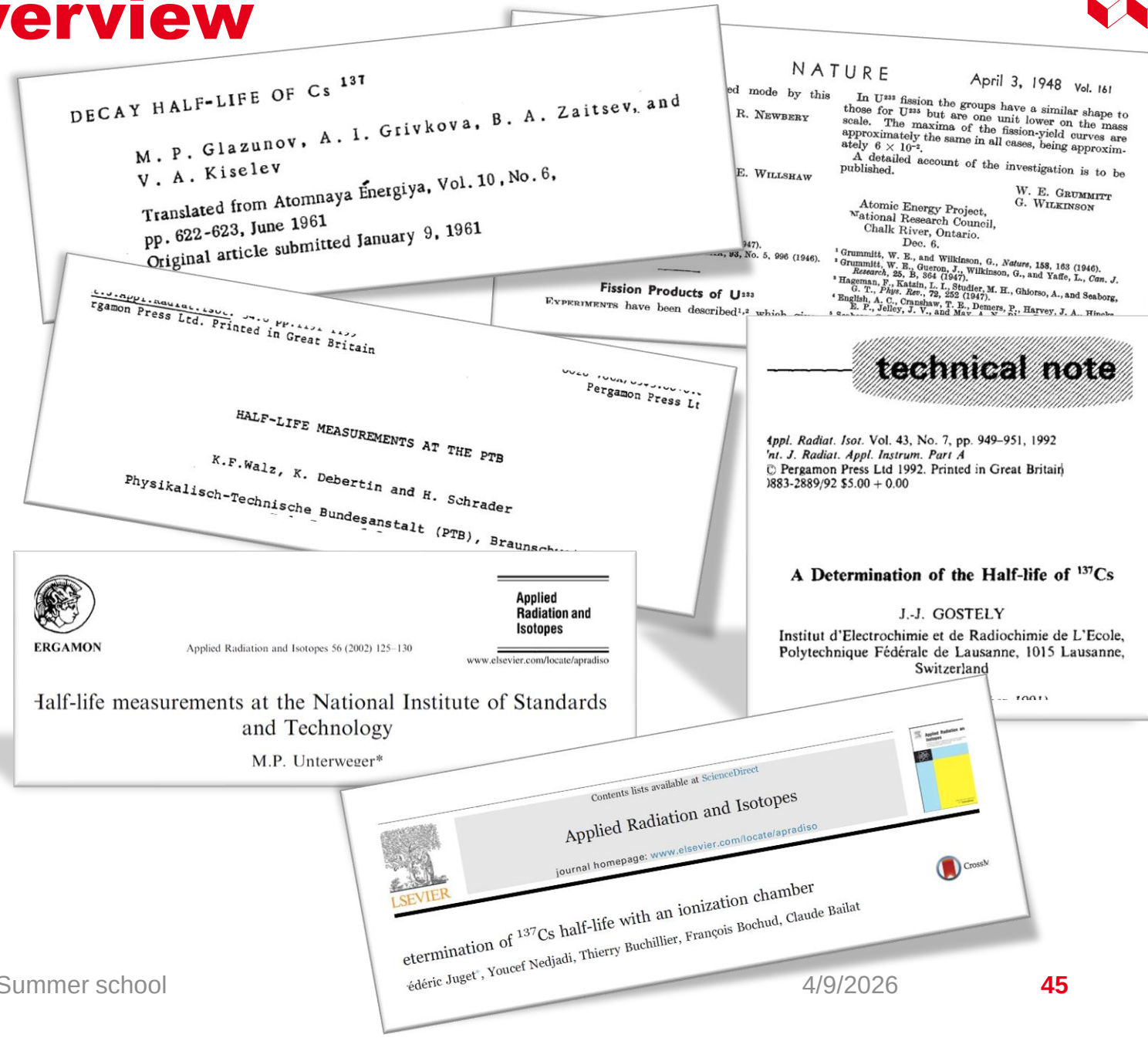
The time after which half the initial matter has decayed

$$N(t) = N_{t=0}e^{-\frac{\ln(2)t}{T_{1/2}}} \quad T_{1/2} = \frac{\ln(2)}{\lambda}$$



Half-life of ^{137}Cs : overview

- Abundant bibliography
 - More than 75 publications
 - From 1948 to 2016
 - Different experimental methods
 - Many languages
- How to select a meaningful dataset?
 - DDEP guidelines
 - Discard measurements without uncertainty estimation
 - One measurement per author / laboratory



Half-life of ^{137}Cs : a first dataset to work with

- Highly discrepant

- 23 references considered
- $T_{1/2}$ varying from 26 to 33 years
- Uncertainties from 0.011 to 3 years
- Statistical test of the distribution:

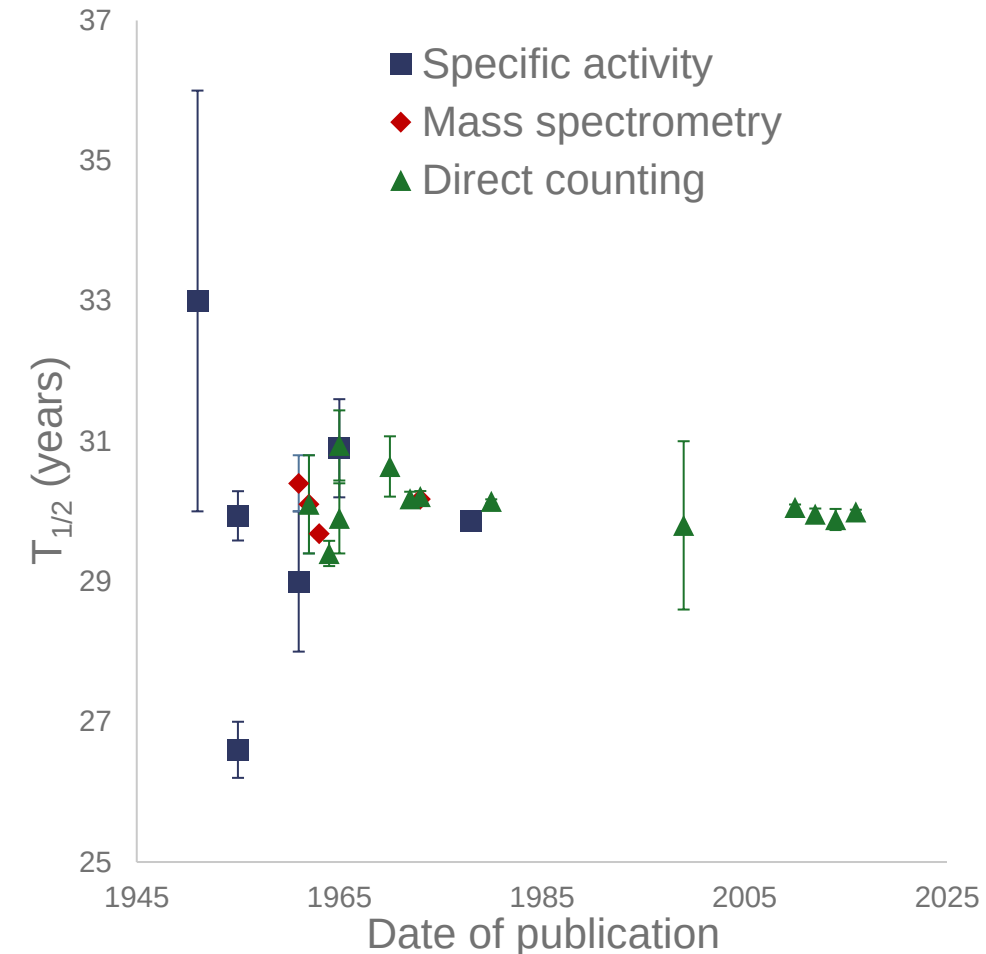
$$\chi^2 \sim 11 \gg \chi_{crit}^2 \sim 1.9$$

$$\chi^2 = (n - 1) \frac{\sigma_{ext}^2}{\sigma_{int}^2}$$

- Unweighted average $T_{1/2} = 30.09 (8) \text{ a}$

Reminder:		DDEP	ENSDF
	$T_{1/2} \text{ (a)}$	30.05 (8)	30.08 (9)

How to proceed further?



Cs-137 Half-life: final refinement

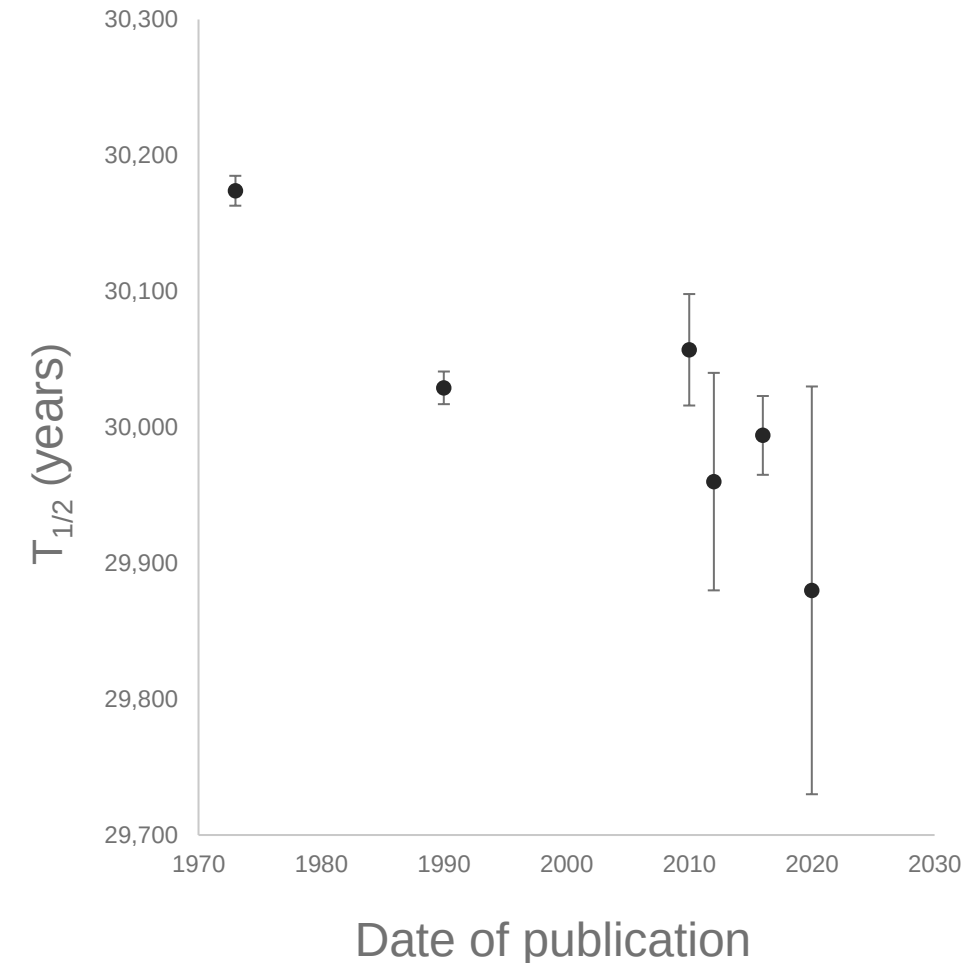
- Critical analysis of each publication
 - Evaluate possible experimental bias
 - Evaluate uncertainty budget assessment

- Support from previous works

M.J. Woods, *The Half-life of ^{137}Cs – A Critical Review*, NIM A286 (1990)

- Selected publications

■ Dietz et al. (1973)	GEC	$T_{1/2} = 30.174 (11) \text{ a}$
■ Martin et al. (1990)	CRNL	$T_{1/2} = 30.029 (12) \text{ a}$
■ Schrader et al. (2010)	PTB	$T_{1/2} = 30.06 (4) \text{ a}$
■ Bellotti et al. (2012)	INFN	$T_{1/2} = 29.96 (8) \text{ a}$
■ Juget et al. (2016)	IRP	$T_{1/2} = 29.994 (29) \text{ a}$
■ Unterweger et al. (2020)	NIST	$T_{1/2} = 29.88 (15) \text{ a}$



Cs-137 Half-life: final refinement

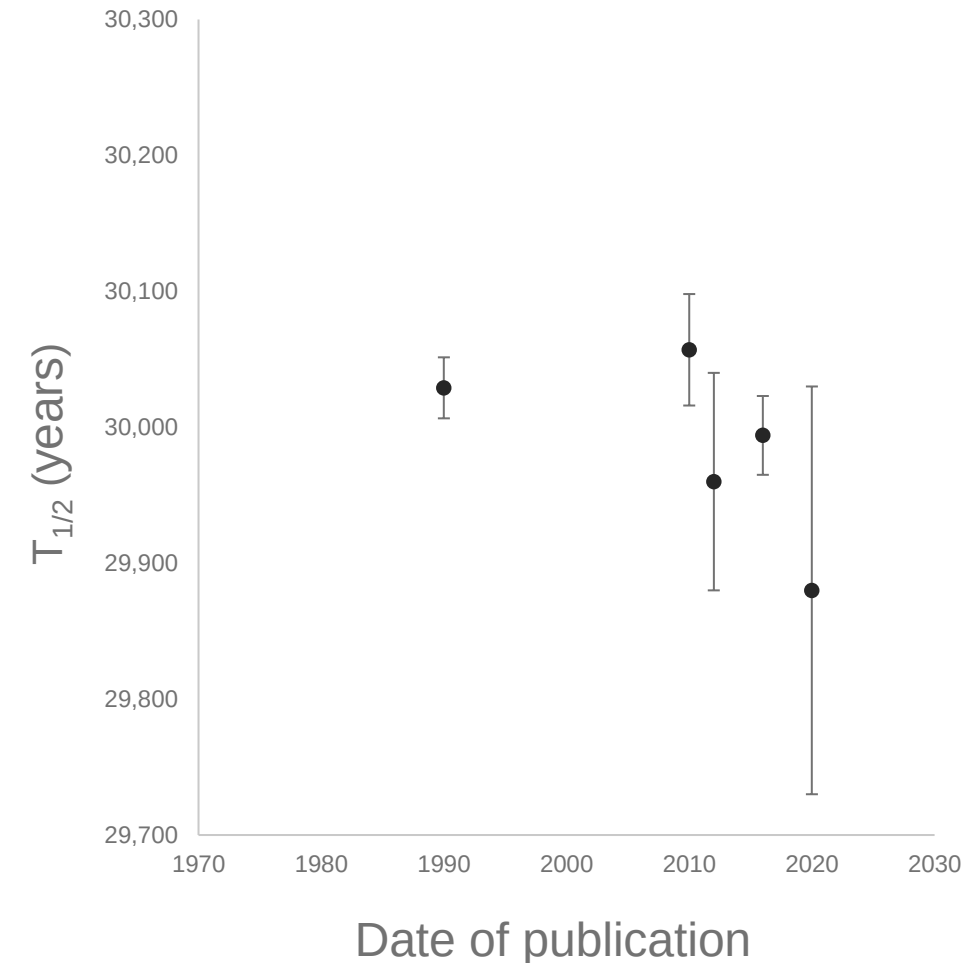
- Critical analysis of each publication
 - Evaluate possible experimental bias
 - Evaluate uncertainty budget assessment

- Support from previous works

M.J. Woods, *The Half-life of ^{137}Cs – A Critical Review*, NIM A286 (1990)

- Selected publications

~~■ Dietz et al. (1973)~~	~~GEC~~	~~$T_{1/2} = 30.174 (11) \text{ a}$~~
■ Martin et al. (1990)	CRNL	$T_{1/2} = 30.029 (24) \text{ a}$ x2
■ Schrader et al. (2010)	PTB	$T_{1/2} = 30.06 (4) \text{ a}$
■ Bellotti et al. (2012)	INFN	$T_{1/2} = 29.96 (8) \text{ a}$
■ Juget et al. (2016)	IRP	$T_{1/2} = 29.994 (29) \text{ a}$
■ Unterweger et al. (2020)	NIST	$T_{1/2} = 29.88 (15) \text{ a}$



Cs-137 Half-life: new DDEP recommendation

- A final dataset of 5 measurements
 - Consistent: $\chi^2 \sim 0,8 < \chi_{crit}^2 \sim 3.3$
 - Unweighted mean $T_{1/2} = 29.984 (30) \text{ a}$
 - Weighted mean $T_{1/2} = 30.018 (16)_{\text{int}} (14)_{\text{ext}} \text{ a}$
 - Recommended uncertainty extended to match *Martin* et al. (1990)

$$T_{1/2} = \mathbf{30.018 (22) \text{ a}}$$

- Outlooks
 - Lower dependency to *Martin* et al.
 - 50% of the weight
 - Need for additional measurements
 - Unpublished results?
 - PTB (continuation of Schrader works)
 - NRC (IC from 1995 2009)

	DDEP	ENSDF	This work
$T_{1/2} \text{ (a)}$	30.05 (8)	30.08 (9)	30.018 (22)

Nuclear data: take away

- Evaluated Nuclear Data are critical for most applications
 - Consistency & reliability
 - Robust uncertainty evaluation
- A wide variety of nuclear databases is available
 - Produced to answer different needs and applications
 - Nuclear databases are often correlated
(using recommendations from other databases)
- Evaluation is a complex and tedious process
 - Relies on the quality of existing measurements / models
 - There is no unique procedure to evaluate: it is strongly based on the evaluator's experience
 - When the data are critical for any usage, reading the evaluator's comments is strongly recommended
 - The DDEP Tables & associate Comment files is probably the easiest way to start



2 ■ Radionuclide metrology

How is it useful?

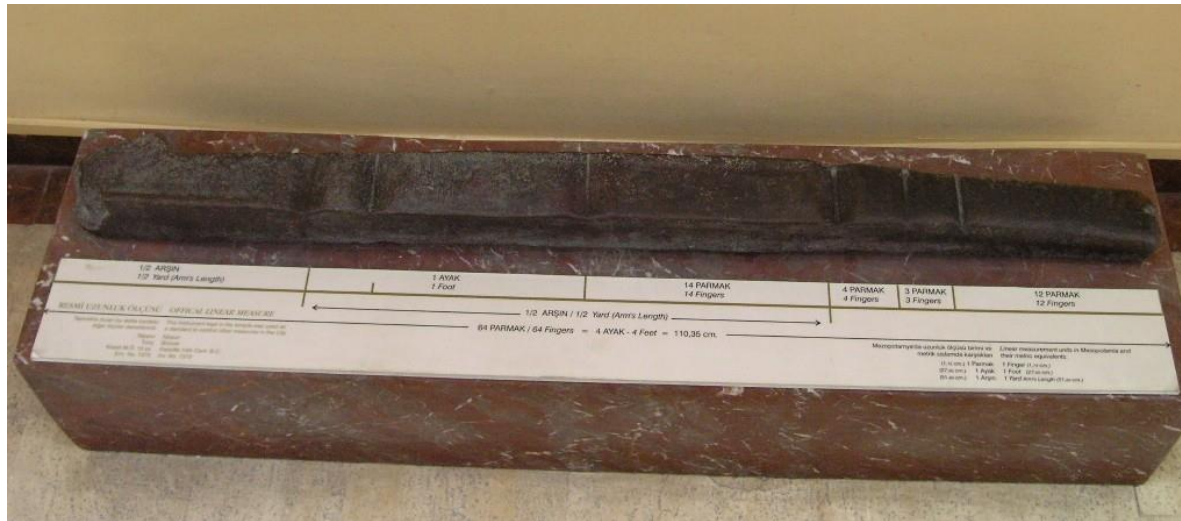
About Metrology & Nuclear Physics

- 1. What is radionuclide metrology?**
- 2. Reminders on radioactive decays & radiation detection**
- 3. A designated National metrology Institute: the LNHB**



The first reference standard

- For trade purposes civilisations have quickly understood the need to define standards for basic units (mass and length)
- The reference standards were used as reference to define a unit



Nippur cubit-rod (2650 BCE)
Ana al'ain / Wikimedia Commons (CC BY-SA 3.0)



First metre standard, Paris 1796
— Wikimedia Commons

Why the International System of Units?



- In France in 1775 about 700 different units were used
- Even the same unit would have different definition depending on the city

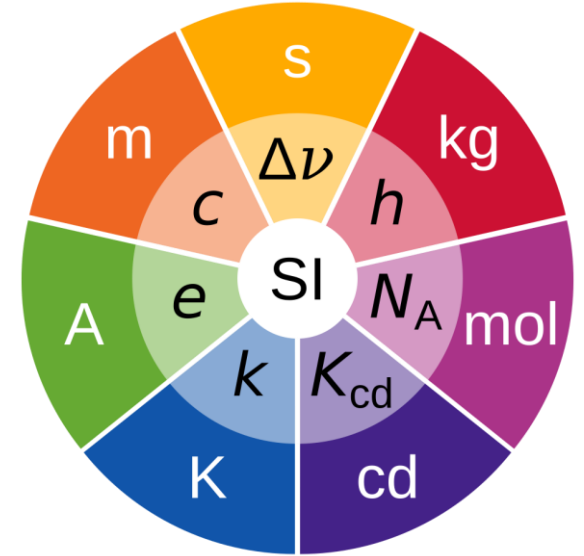
Weight	
Pounds poids de marc (Aix)	408.51 g
Pounds poids de marc (Calais)	509.53 g
Pounds of Charlemagne	367.128 g
Pounds of Paris	489.505 85 g

Length	
Pied-de-roi (Rouen)	270.7 mm
Pied-de-roi (Calais)	341.8 mm
Pied de Paris	324.839 416 7 mm
Canne de Provence	2 005.2 mm
Canne de Troyes	792 mm

Large constraint on
domestic and international trade

Advent of an international convention

- In 1875, 17 nations sign an international treaty: **the Metre Convention**
- The convention aims at developing an International System of Units
 - Initially only metre and kilogram were considered
 - Today the SI is based on
 - 7 base units
 - And 22 derived units *(among which: Bq, Gy and Sv)*
- A permanent organizational structure is overseeing the process
 - International Bureau of Weights and Measures (BIPM)
 - Located in France in Pavillon de Breteuil, Saint-Cloud, France



<https://www.bipm.org/en/>

Bureau
International des
Poids et
Mesures

<https://www.bipm.org/en/>

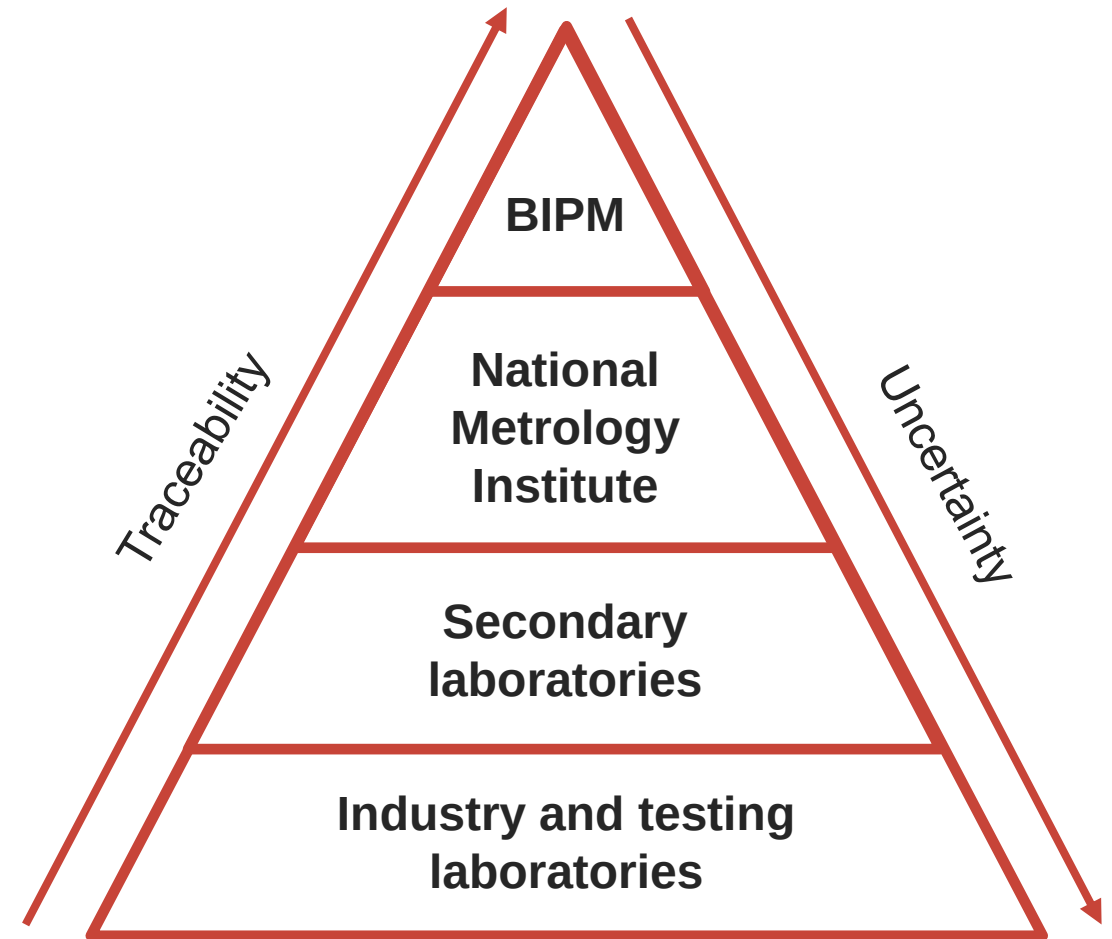
Traceability & transfer

- Metrological chain
 - Each measurement can be linked to a reference
 - A continuous and documented chain
 - Ensure tracing to the primary standard
- Transfer are performed following a strict regulation

ISO/IEC 17025

Testing and calibration laboratories

ISO/IEC 17025 enables laboratories to demonstrate that they operate competently and generate valid results, thereby promoting confidence in their work both nationally and around the world.



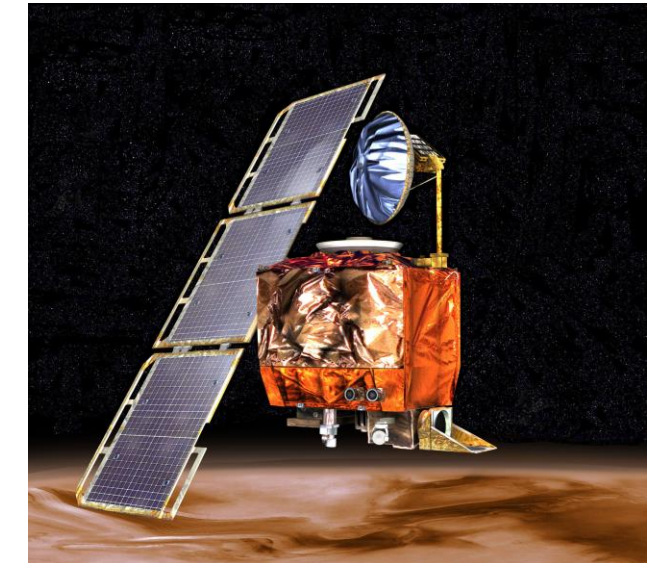
Why is all this still relevant today?

- Gimli Glider (1983)
 - Air Canada Flight 143 from Montreal to Edmonton
 - Inaccurate conversion from mass to volume of fuel
 - Airplane ran out of fuel at 12500 m altitude
 - Emergency gliding and landing at Gimli (Motorsport Park)
- Mars Climate Orbiter (1998)
 - NASA Spacecraft designed to study mars atmosphere and surface
 - Lost during orbital insertion (crashed onto Mars)
 - Inconsistency between two teams
 - NASA
 - Lockheed Martin (spacecraft builder)
 - Estimated cost: 125 M\$

metric system
US customary



Air Canada Flight 143 after emergency landing — Wikimedia Commons



Mars Climate Orbiter, 1998 — NASA / Wikimedia Commons

National Metrology Institute



- Insuring the metrological chain at a national level
 - By participating to international intercomparison
 - By transferring it to secondary laboratories



- By realizing the units of the SI
 - By maintaining the existing standards
 - By developing new standards

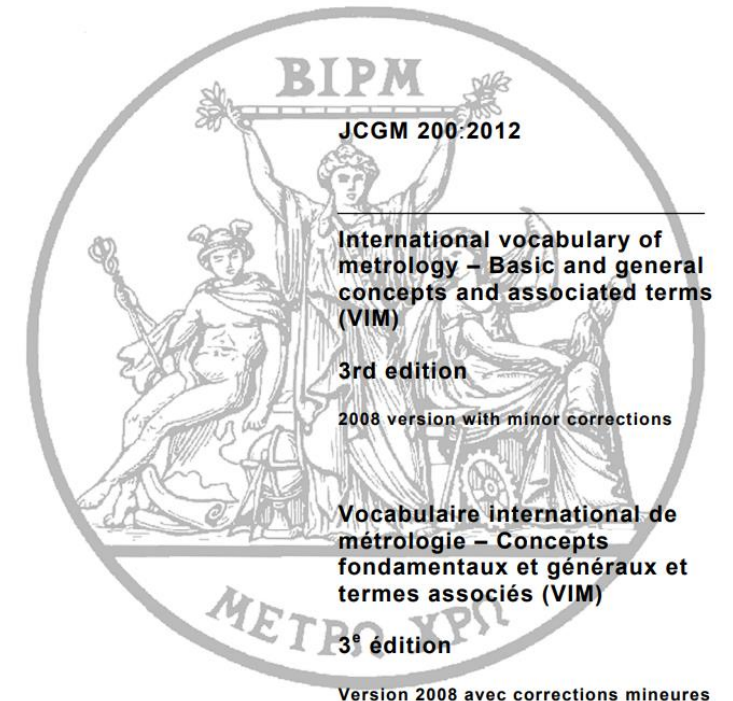


- By performing user requests on specific measurements



What is a measurement?

- According to the VIM
 - Measurement: process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity
- In metrology two types of measurements can be distinguished
 - Primary measurement method
 - Does not rely on a calibrated standard of the same quantity
 - Secondary measurement method
 - Rely on a calibrated standard of the same quantity



<https://www.bipm.org/en/>

What is an uncertainty?

- To provide a meaningful information, any measurement should be provided with an uncertainty
 - The uncertainty quantifies the confidence on the said measurement
 - According to the Guide to the Expression of Uncertainty in Measurement:

Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand



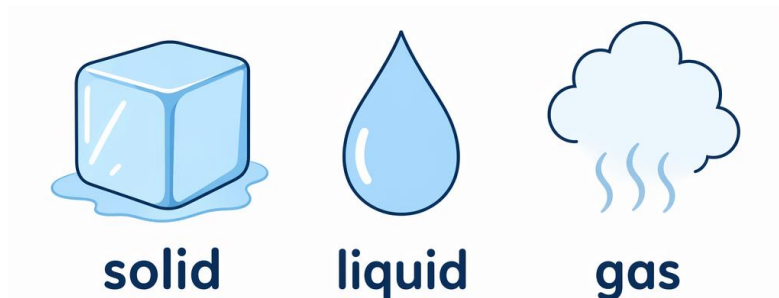
<https://www.bipm.org/en/>

Metrology and Nuclear Physics?

- There are officially three SI units linked with Nuclear Physics and ionizing radiations
 - Radioactivity (activity measurement)
 - Becquerel (Bq) - Since 1975
 - The average number of disintegrations per second (s^{-1})
 - Dose deposition
 - Absorbed dose: Gray (Gy) - Since 1975
 - Quantify the energy deposited in matter (J kg^{-1})
 - Equivalent dose - Since 1979
 - Quantify effect of the energy deposited in matter (J kg^{-1})

Specificity of radionuclide metrology

- A wide variety of
 - decay types: alpha, beta, electron capture...
 - radiations : Electron, gamma, neutron, ion...
- Physical state



Radionuclide	Half-life
^{11}C	20.4 minutes
^{18}F	1.83 hours
^{131}I	8.05 days
^{14}C	5 730 years
^{239}Pu	24 100 years
^{238}U	4.47 10^9 years

Different measurement methods are necessary
to be able to standardize each radionuclide

About Metrology & Nuclear Physics

1. What is radionuclide metrology?
- 2. Reminders on radioactive decays & radiation detection**
3. A designated National metrology Institute: the LNHB

Radioactive decay

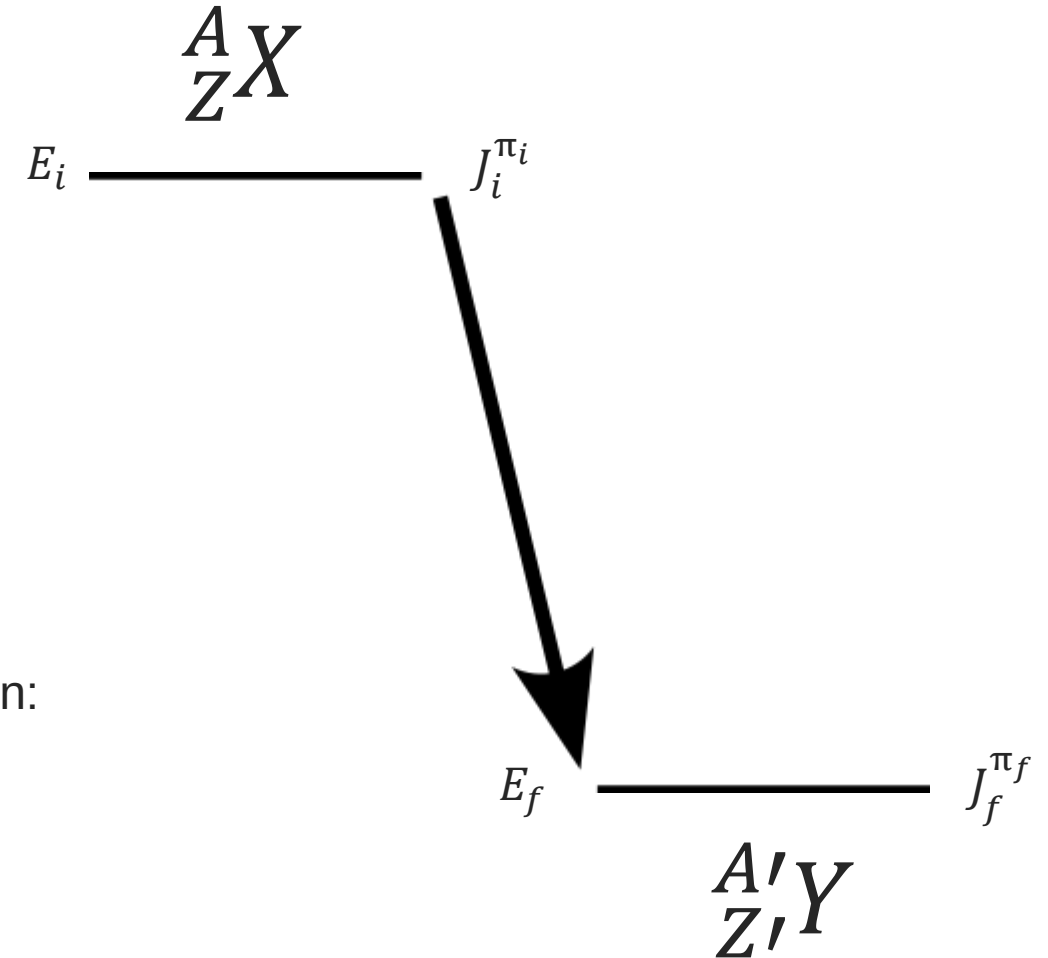
A spontaneous process during which the atomic nucleus undergoes transformation(s)

- Each radioactive decay is unambiguously characterized by several properties:
 - Half-life
 - Q-value
 - Emission of, at least, one particle with specific energy and probability distributions
- Two different types of physical processes
 - Involving the nucleus
 - Involving the atomic cloud

Notation about radioactive decay

A given decay transforms the nucleus

- From an initial state in the parent nucleus defined by
 - An excitation energy E_i
 - A spin-parity $J_i^{\pi_i}$
- To a final state in the daughter nucleus defined by
 - An excitation energy E_f
 - A spin-parity $J_f^{\pi_f}$
- The energy available for the decay (or Q-value) depends on:
 - The relative mass of the parent and daughter nuclei
 - The mass of the particles emitted during the decay
 - The excited energy of the parent and daughter nuclei



General concepts on radioactive decay

A given nucleus can decay

- Through different decay processes
- To different states in the daughter nucleus

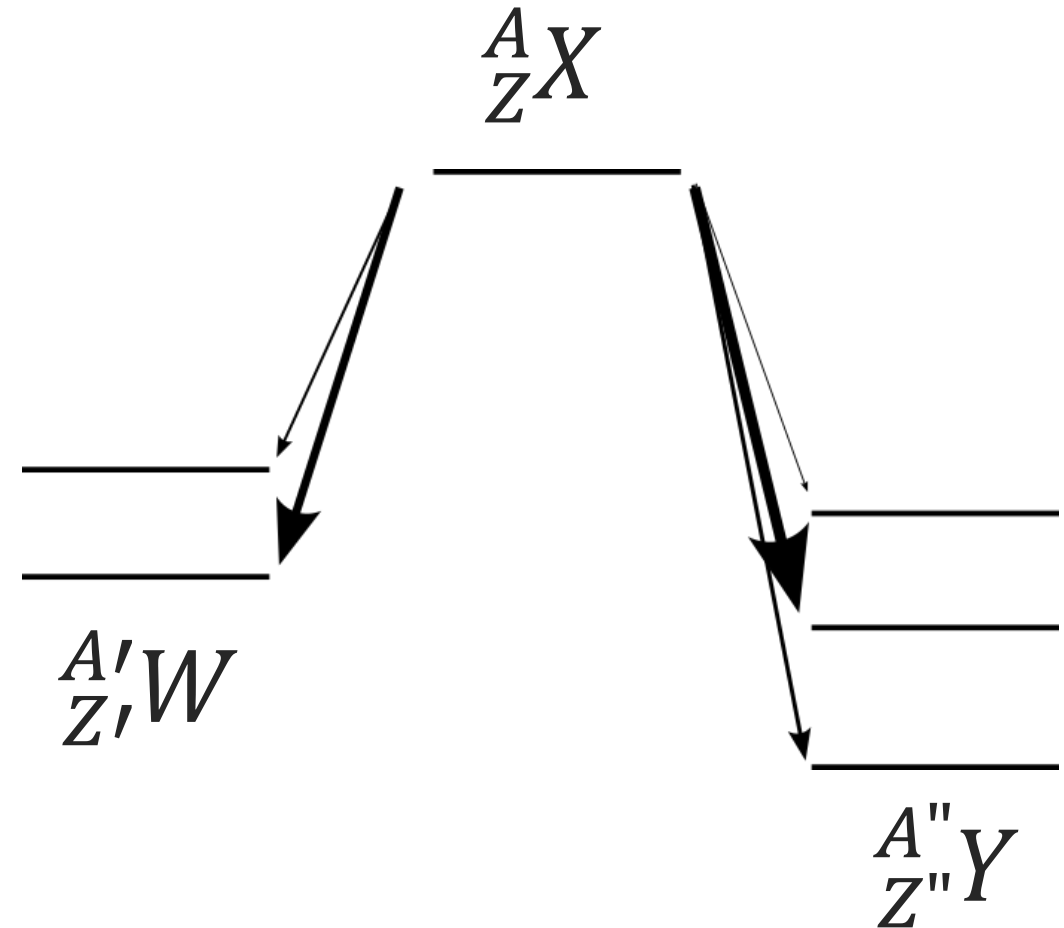
The relative probability of each transition strongly depends on the initial properties of the initial and final state

The sum of probabilities of all available transitions is equal to unity

$$\sum_j P_j = 1$$

The overall decay process occurs according to the radioactive law

$$N = N_0 e^{-\lambda t} \quad \text{with } \lambda = \frac{\log 2}{T_{1/2}}$$



Overview of all decay processes

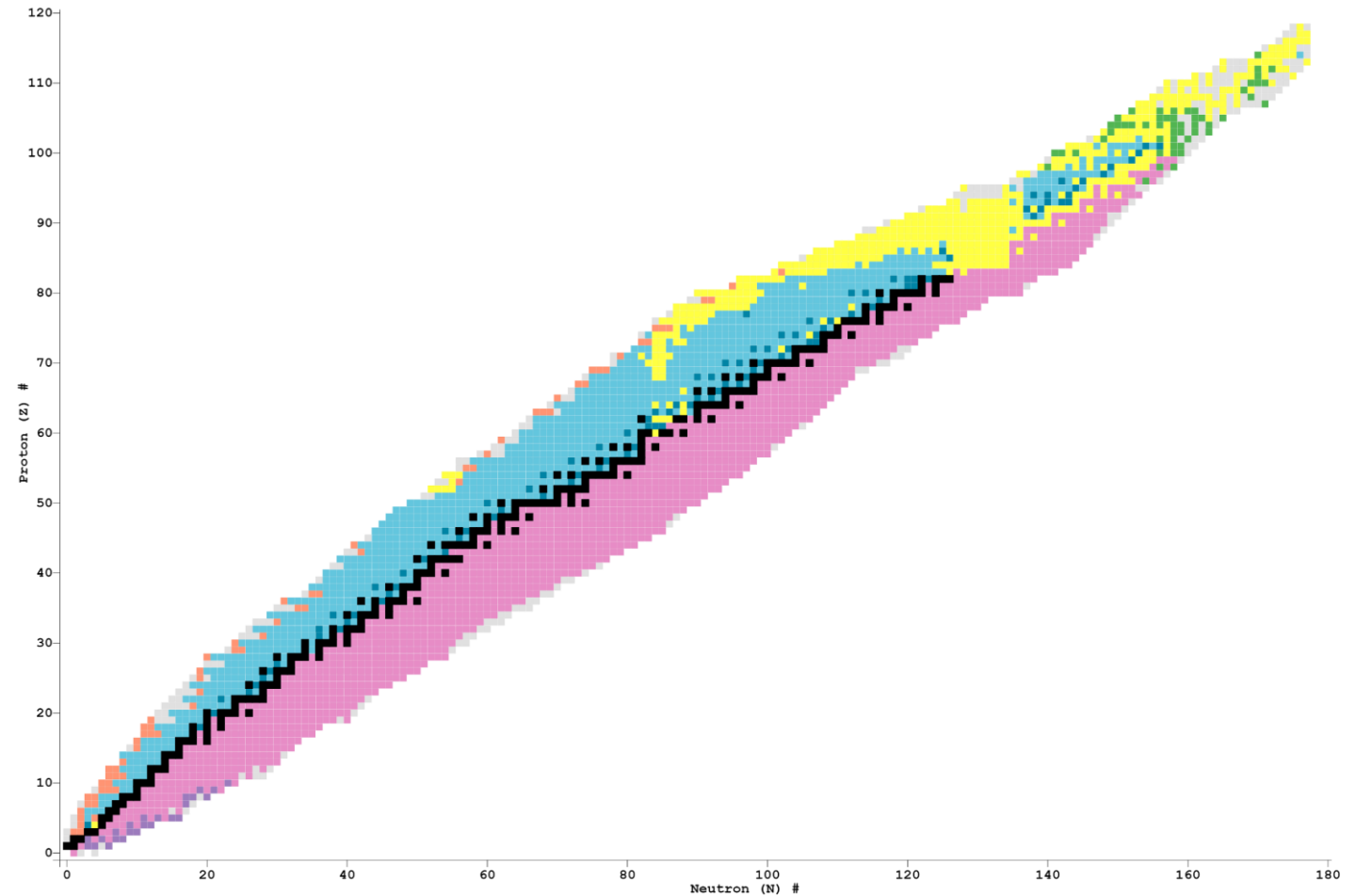
Main decay processes:

- β^- decay
- β^+ decay / Electron capture
- α decay
- Spontaneous fission

But also

- Neutron-decay
- Proton-decay
- β^- delayed neutron

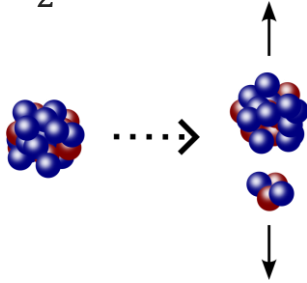
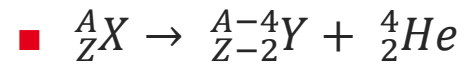
Out of
today's
scope



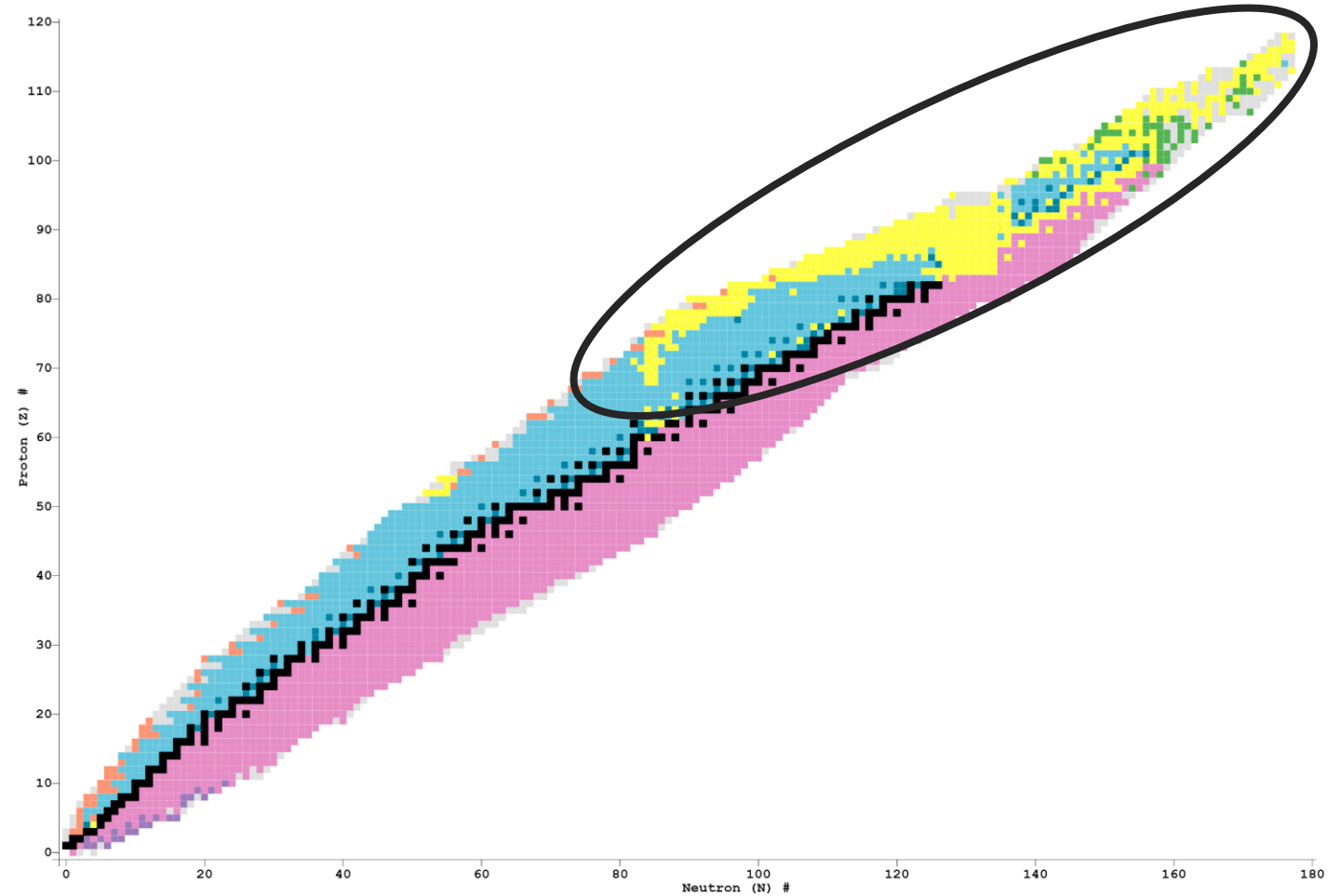
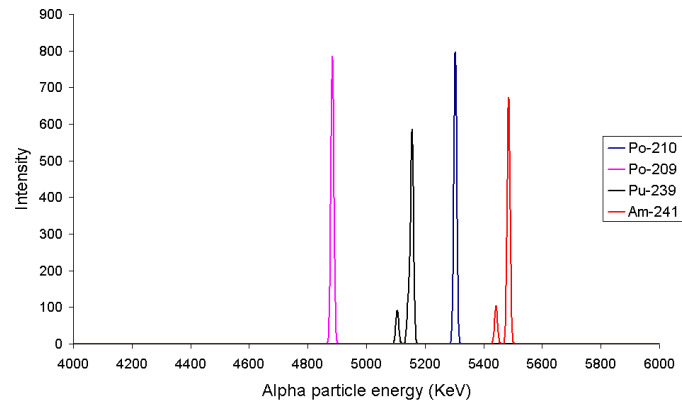
Alpha decay: decay process

A two-body decay

- A process occurring mainly at $Z > 82$



- Energy of emitted particle is discrete



Alpha decay: energy considerations

- Q value of the decay is expressed as

$$Q_{\alpha} = (m({}_Z^AX^*) - m({}_{Z-2}^{A-4}Y^*) - m({}_2^4He))c^2$$

- The energy is spread between the two emitted particles

$$E_{{}_2^4He} = \frac{Q_{\alpha}}{(1 + \frac{m({}_2^4He)}{m({}_{Z-2}^{A-4}Y^*)})} \quad E_{{}_{Z-2}^{A-4}Y^*} = \frac{m({}_2^4He)}{m({}_{Z-2}^{A-4}Y^*)} E_{{}_2^4He}$$

- Emitted alpha energy is typically between 4 and 10 MeV
- The shorter is the half-life, the larger is the alpha energy

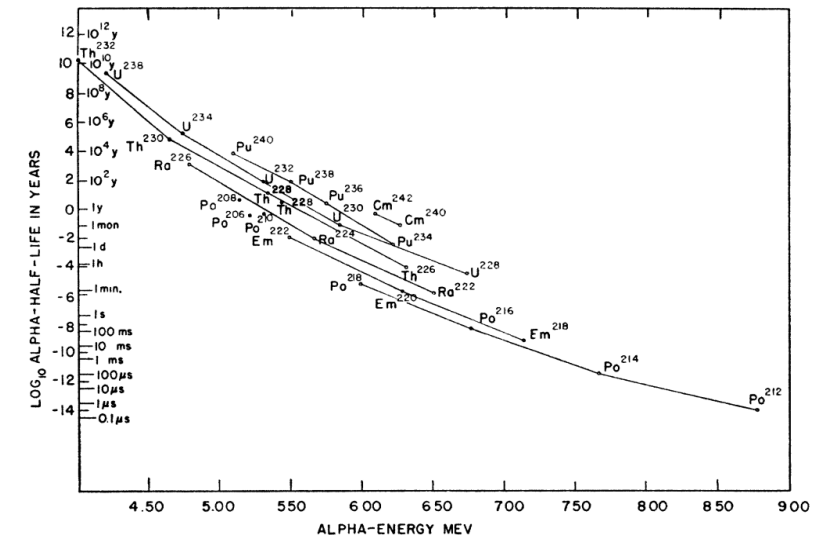


2.1 α Transitions

	Energy keV	Probability $\times 100$
$\alpha_{0,36}$	4838,00 (13)	0,00004 (3)

4 α Emissions

	Energy keV	Probability $\times 100$
$\alpha_{0,36}$	4757,58 (13)	0,00004 (3)

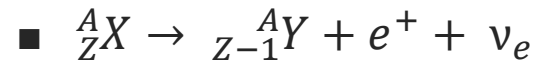


I. Perlman et al. Physical Review 75, 1096 (1949)

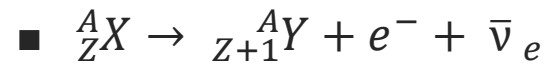
Beta decay: decay process

A three-body decay

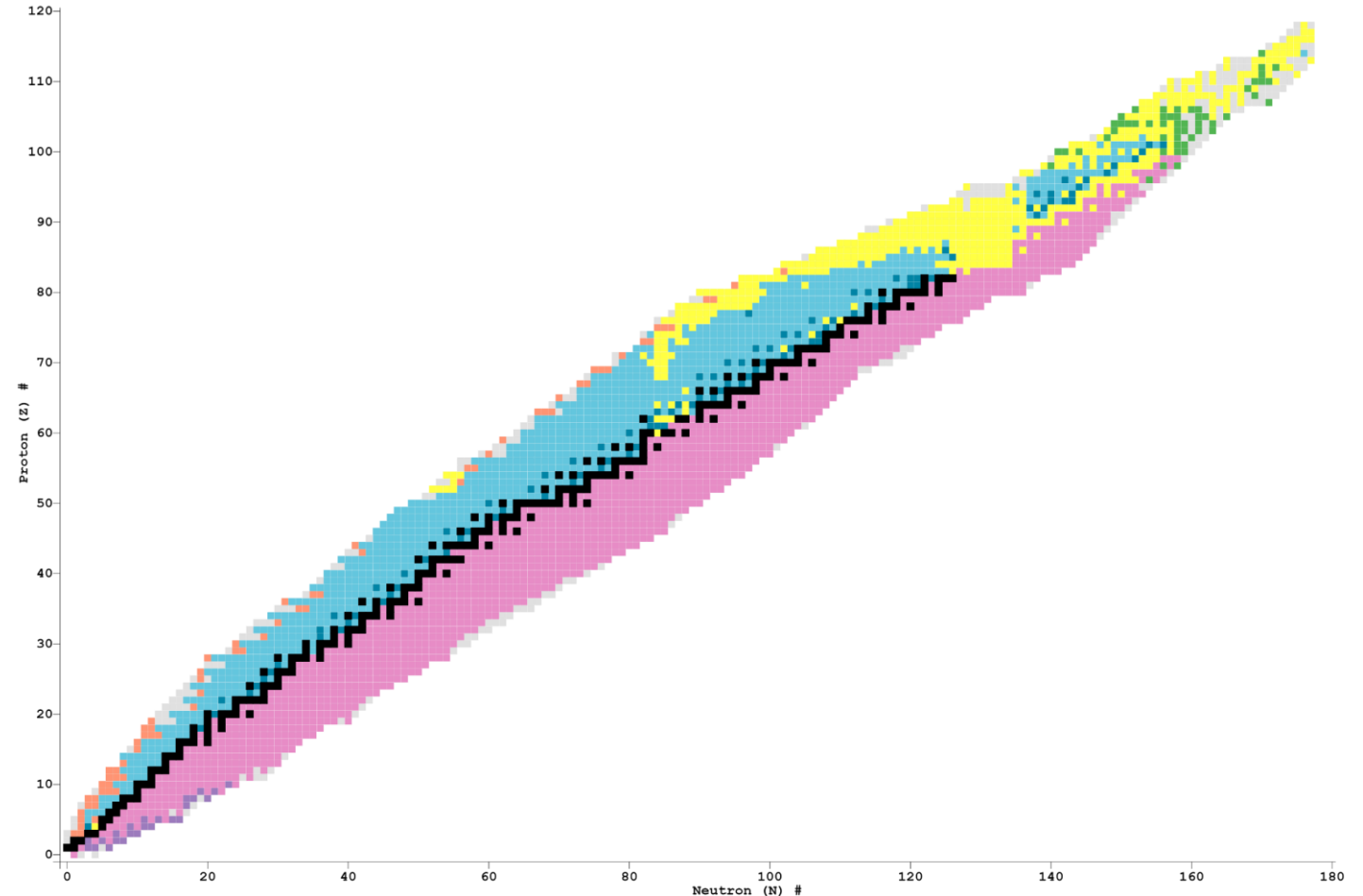
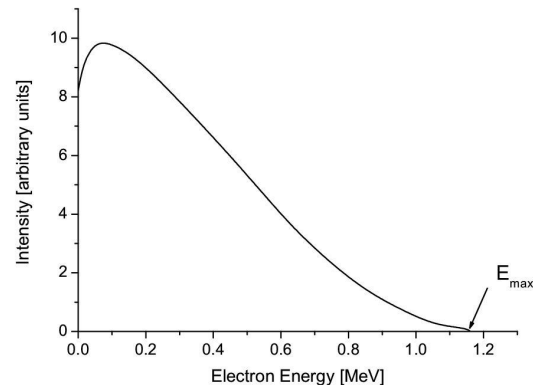
- For neutron deficient nuclei: β^+



- For neutron rich nuclei: β^-



- Energy of emitted particle is continuous



Beta decay: energy considerations

- Q value of the decay is expressed as

- $Q_{\beta^-} = \left(m\left({}_Z^AX^*\right) - m\left({}_{Z+1}^AY^*\right) \right) c^2$

- $Q_{\beta^+} = \left(m\left({}_Z^AX^*\right) - m\left({}_{Z-1}^AY^*\right) - 2m_e \right) c^2$
 $\left(m\left({}_Z^AX^*\right) - m\left({}_{Z-1}^AY^*\right) \geq 2m_e \right)$ required to decay by β^+

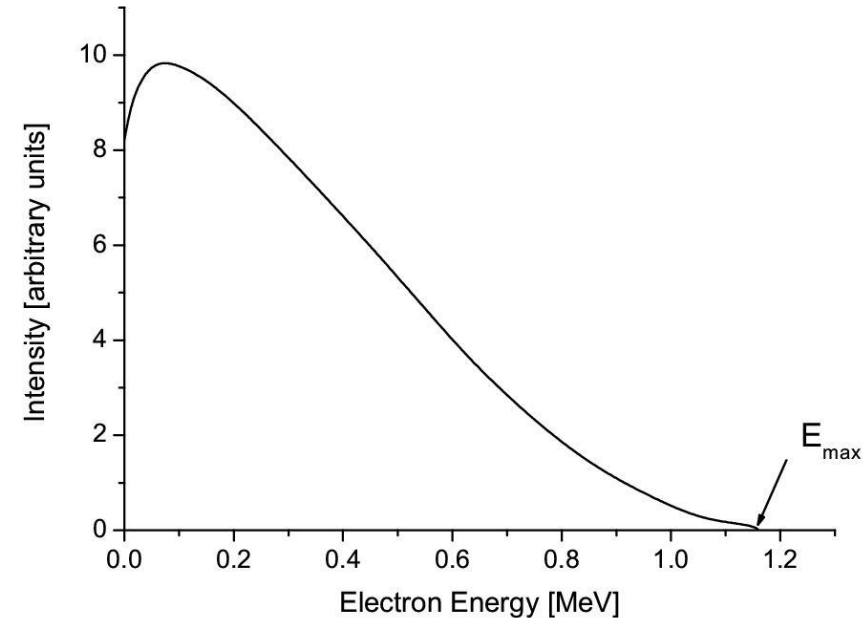
- Beta spectrum shape is described by

$$\frac{dN}{dW} \propto pWq^2 F(Z, W) C(W)$$

- The $\log ft$ value of a transition is calculated from

- f_i the integral of the beta spectrum of the given transition

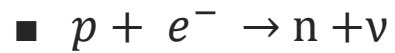
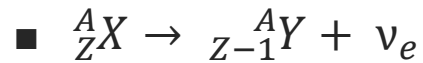
- The partial half-life $t_i = \frac{T_{1/2}}{P_{\beta_i}}$



Electron capture: decay process

A two-body decay

- For neutron deficient nuclei

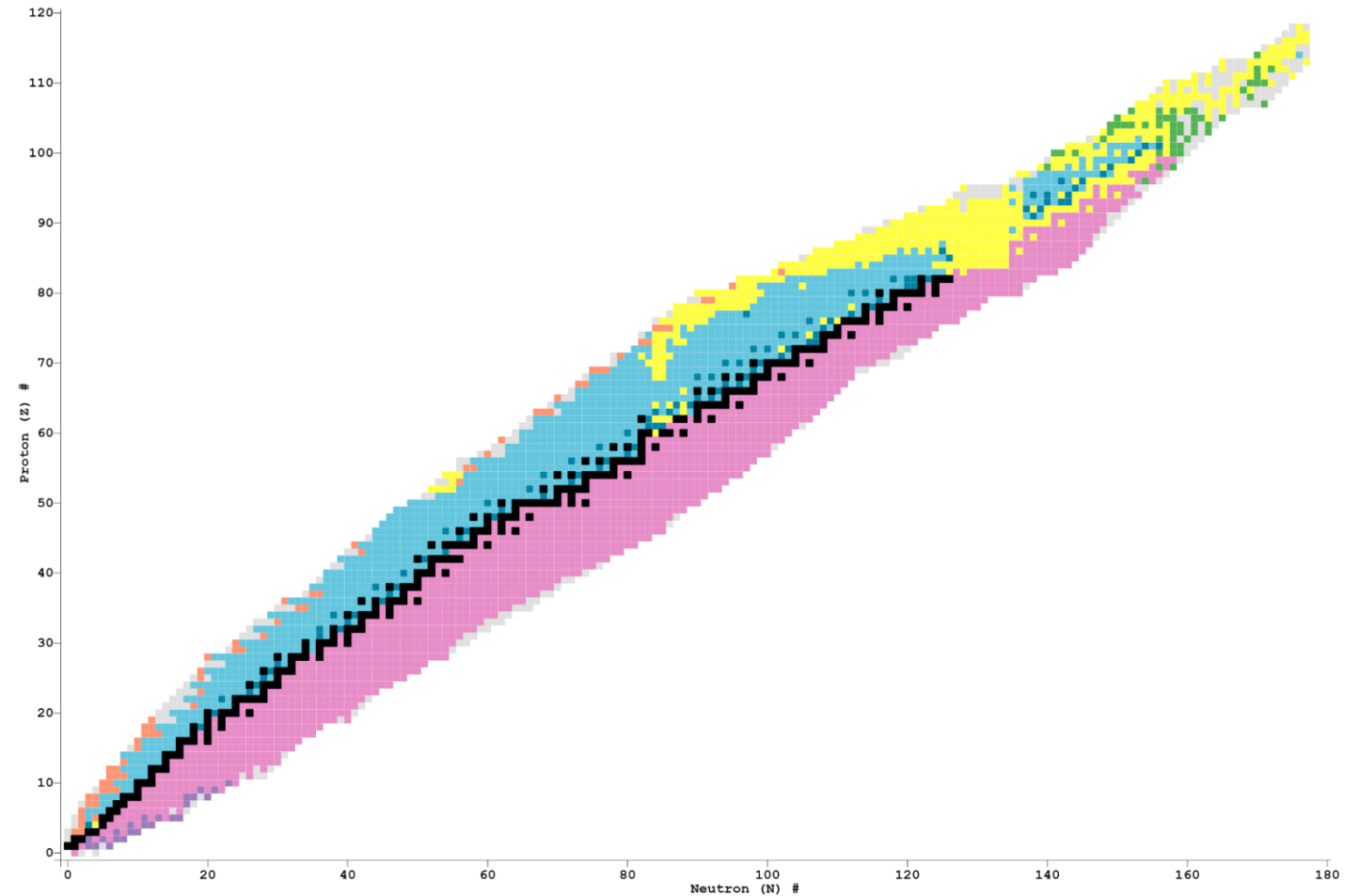


- This process competes with β^+ decay

- The process affects the atomic cloud

- Induces atomic rearrangement

⇒ Emission of atomic radiations



Electron capture: additional information

- Q value of the electron capture is expressed as

$$Q_{EC} = (m({}_Z^AX^*) - m({}_{Z-1}^AY^*))c^2 - B(e_i)$$

where $B(e_i)$ is the binding energy of the captured electron

(Electron capture transition can occur while β^+ decay is energetically impossible)

- The recoil energy of the nucleus can be neglected (except ${}^7\text{Be}$ where $E_r = 57$ eV)
- The capture process can occur with all available shells and subshells of the atomic nucleus
 - The probability to capture a specific shell depends on the transition type and properties
 - The relative capture probabilities are calculated such as

$$P_K + P_L + P_M + P_N + \dots = 1$$

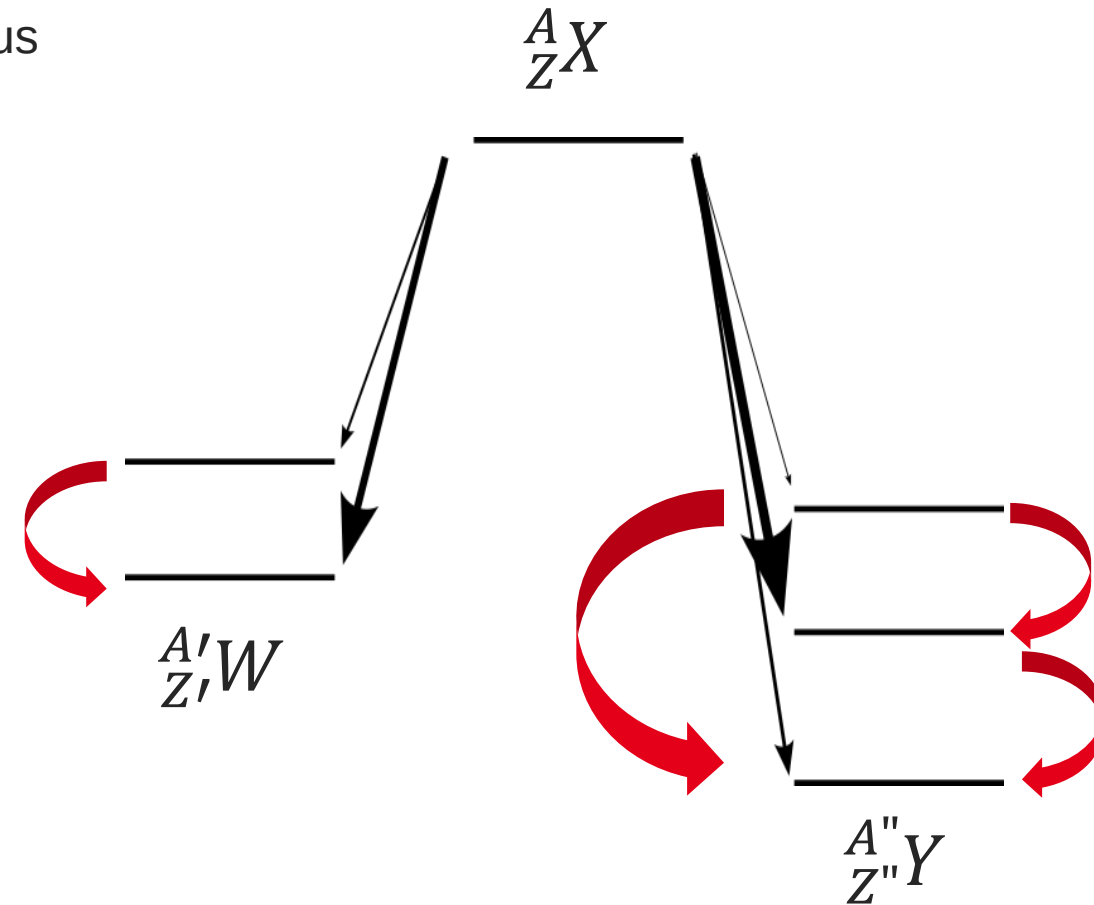
- Capture probabilities are often calculated as ratio : $\frac{P_L}{P_K}, \frac{P_M}{P_L} \dots$

Gamma transition: an overview

The previous decay processes can leave the daughter nucleus in an excited state

- The nucleus will deexcite through one of these processes
 - Photon (gamma) emission
 - Internal conversion
 - Pair creation
- The process can go directly to the ground state or to an intermediate excited state
- The overall gamma transition probability is expressed:

$$P_g = I_\gamma + I_{ce} + I_{e^\pm}$$



Gamma transition: internal conversion

During the internal conversion, the energy is transferred to a shell electron which is ejected

- The energy of the ejected electron is calculated as

$$E_{ce} = E_{\gamma} - B(e_i)$$

where $B(e_i)$ is the binding energy of the ejected electron

- The relative intensity between internal conversion and photon emission is defined by the conversion coefficient:

$$\alpha = \frac{I_{ce}}{I_{\gamma}}$$

- The total conversion coefficient can be expressed as a function of the various available shells

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \alpha_N + \dots$$

- Internal conversion is high for low energy gamma transition with high order of multipolarity
 - This process is usually negligible beyond few hundreds of keV

Gamma transition: pair creation

The electric field of a nucleus can create a pair $e^+ - e^-$ from a photon of high energy

- In this three-body process
 - The energy transfer to the particle is : $E_{e^+} + E_{e^-} = E_\gamma - 2 m(e^-)$
 - The gamma energy needs to verify $E_\gamma \geq 1.022 \text{ MeV}$

- The relative probability to the gamma emission is expressed as

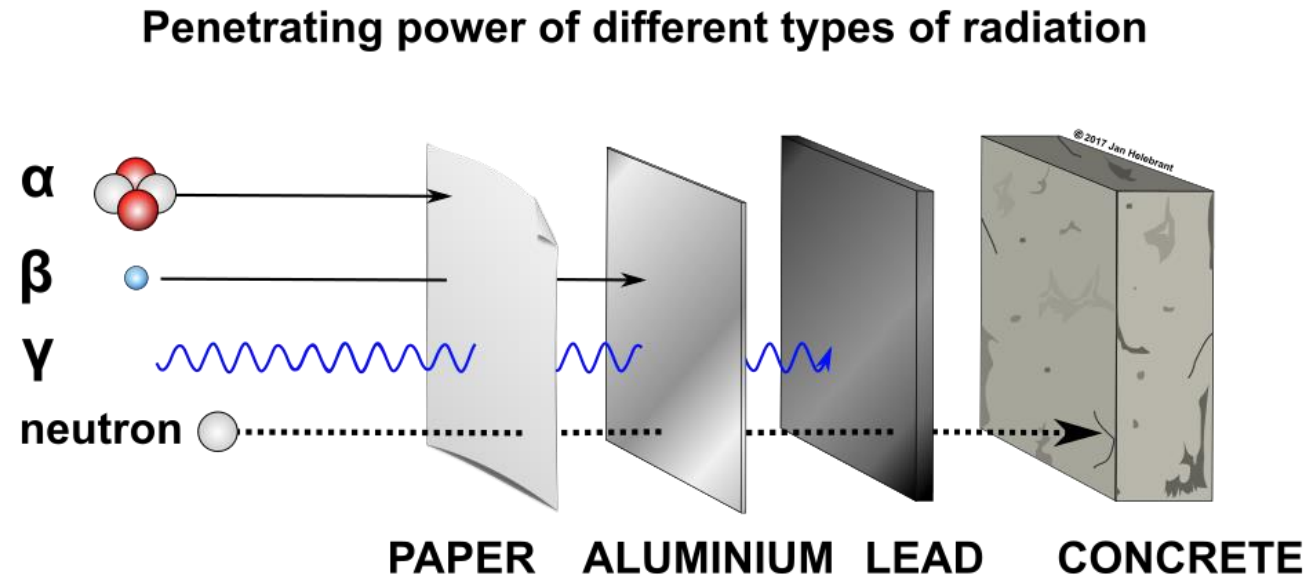
$$\alpha_\pi = \frac{I_{e^\pm}}{I_\gamma}$$

- α_π increases for large gamma energy and with Z of the nucleus

Radiation detection

The radioactivity is almost impossible to detect directly.

- In radionuclide metrology all of the measurements are based on the detection of the emitted radiation



Charged particle detection

- Continuous energy loss in matter
 - Electromagnetic interaction (ionization, excitation of atoms)
 - Nuclear scattering
 - Bremsstrahlung
- Finite travel path in a material
 - Range: characteristic distance that a given charged particle can travel in a material at a given energy
- Travel path can strongly deviate from a straight line, especially for light particle

Photon & neutron



Different interaction processes depending on the energy.

- Photons
 - Photoelectric effect
 - Compton scattering
 - Pair creation
- Neutron
 - Elastic scattering
 - Induced fission
- No characteristic “range” can be defined. The particle has a non zero probability to never interact

About Metrology & Nuclear Physics

1. What is radionuclide metrology?
2. Reminders on radioactive decays
3. **A designated National Metrology Institute: the LNHB**



Laboratoire National Henri Becquerel

Designated institute in France for the metrology of the Dose and the Activity

- One of the historical laboratory of CEA
- Located in the CEA Saclay center near Paris
- Member of the CEA applied research division
- Around 41 permanent staff members
 - 21 in radioactivity metrology
 - 15 in dose metrology
- Around 16 Ph.D. students and postdocs



Focus on activity measurements

- The LNHB is in charge of defining the **becquerel** in France
- The activity measurement for one detection system is usually deduced as

$$A = \frac{N}{\varepsilon}$$

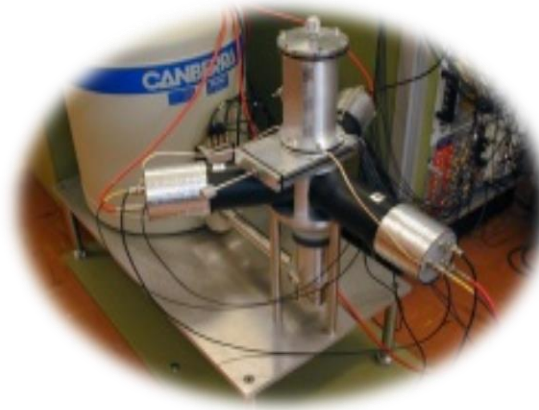
where A is the activity, N is the counting rate and ε the detection efficiency

- Determination of ε
 - For **primary measurements**, $\varepsilon \sim 1$ or is deduced without activity standards
 - For **secondary measurements**, ε is calculated from activity standards (calibration)

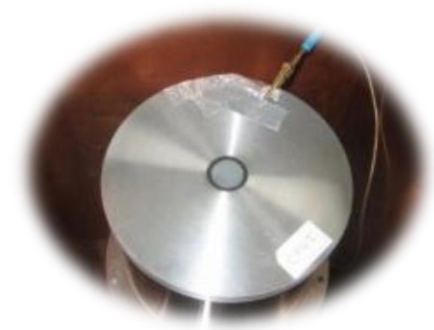
Primary methods



**TDCR liquid scintillation
(alpha, beta)**



**4 π coincidence counting
(alpha, beta - gamma)**



**Well type detector
(gamma)**



**Defined Solid Angle
(alpha)**

Typical uncertainty
 $\approx 0.1 \% - 0.5 \%$

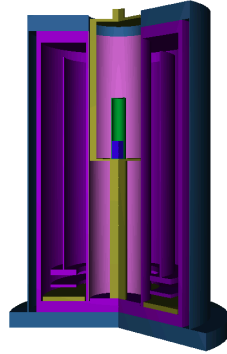


**Manganese bath
(neutron)**



**Triple counters
(gas)**

Secondary methods



**Ionization chambers
(gamma)**



**Liquid scintillation
counting
(alpha, beta, gamma)**

**Typical uncertainty
 $\approx 0.5 \% - 1.5 \%$**

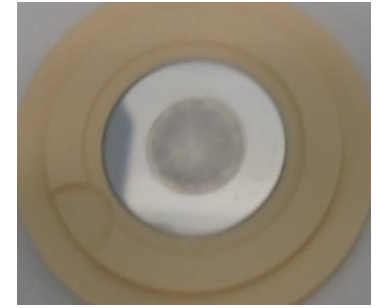


**Gamma spectrometry
(gamma)**

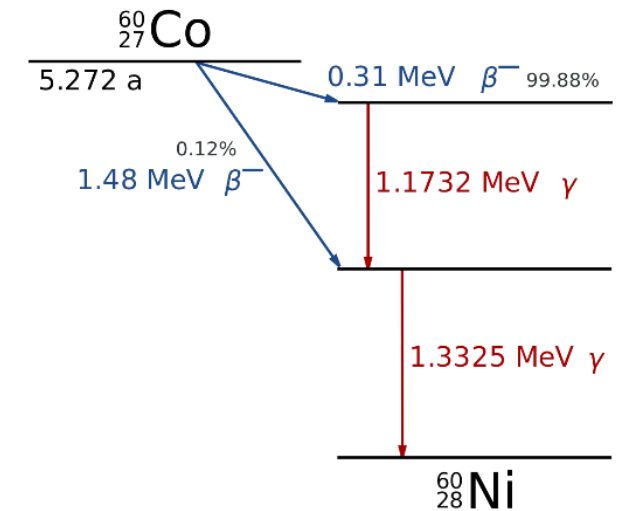
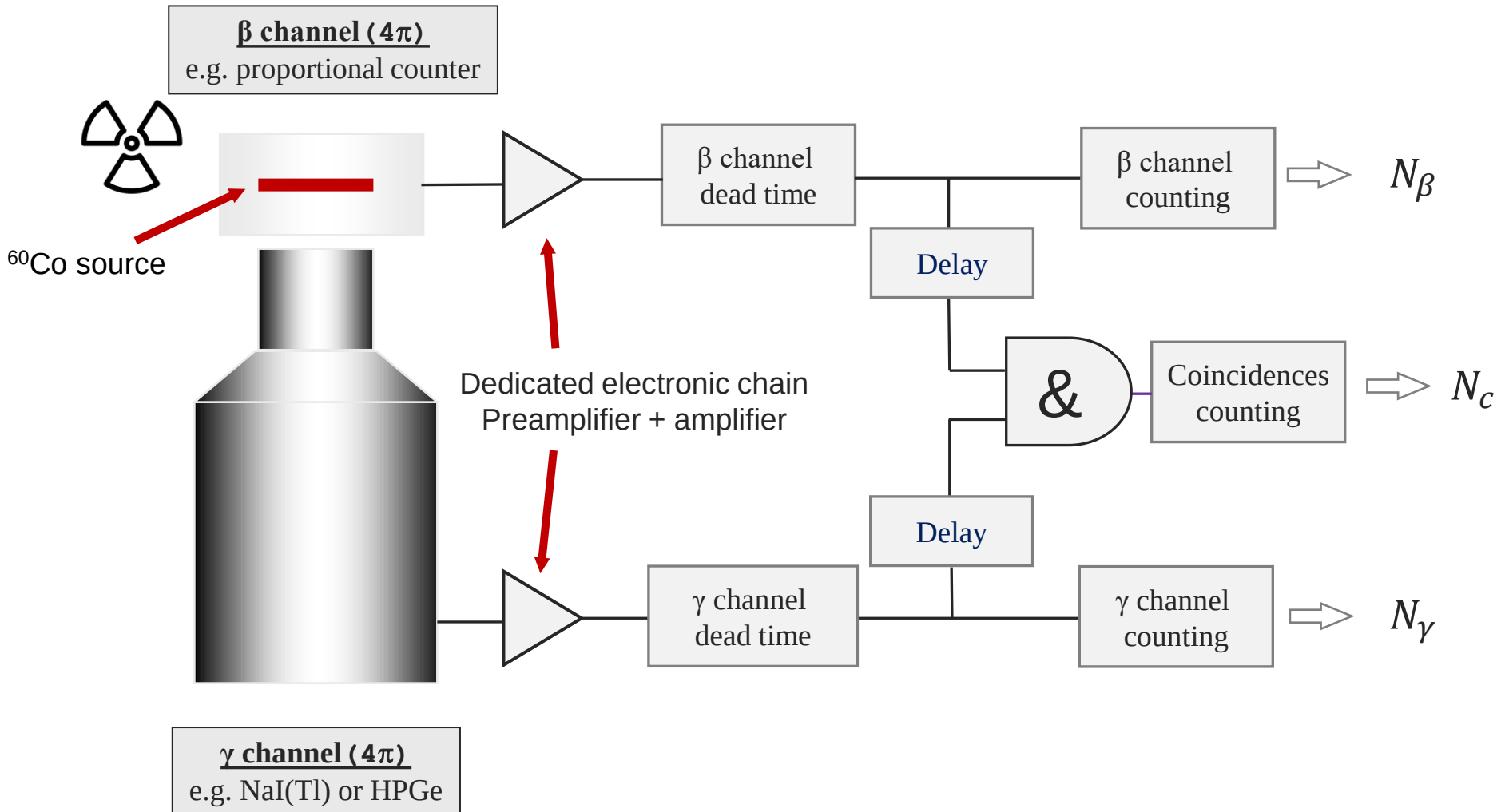
Source preparation

In order to perform an accurate standardization it is critical to know precisely the mass of the radioactive compound.

- Dedicated source preparation at the LNHB
 - Each method has a specific source type to match its requirement
 - High control of the mass of radioactive solution $\frac{u(m)}{m} \sim 10^{-4}$
 - Various states: solid, liquid, gas
- Strict protocol to insure
 - No evaporation, no autoabsorption...
 - Stability over time



Example $4\pi\beta\text{-}\gamma$ coincidence method



Recovering the sample activity with $4\pi\beta\text{-}\gamma$

As a primary method, it does not require any prior activity calibration

- In principle

- Beta channel

$$N_{\beta} = A \cdot \varepsilon_{\beta}$$

- Gamma channel

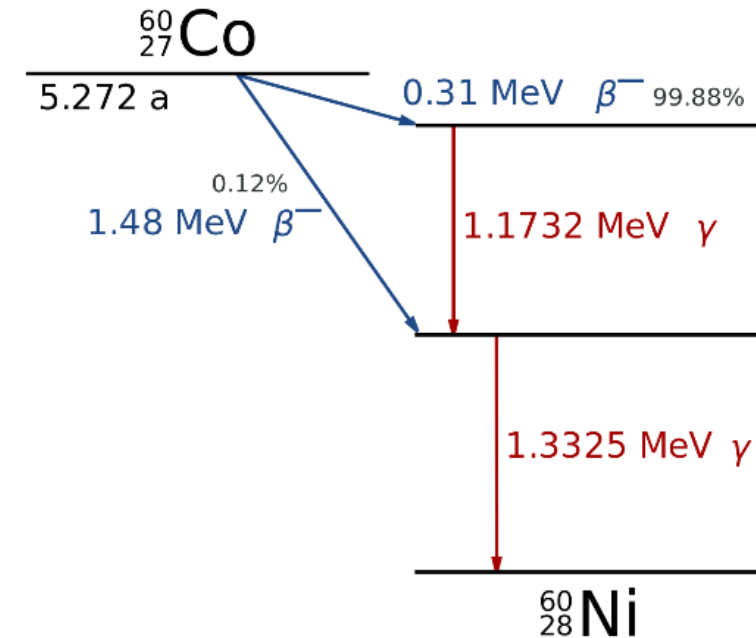
$$N_{\gamma} = A \cdot \varepsilon_{\gamma}$$

- Coincidence channel

$$N_c = A \cdot \varepsilon_{\beta} \cdot \varepsilon_{\gamma}$$

- Thus one can deduce

$$A = \frac{N_{\beta} \cdot N_{\gamma}}{N_c}$$



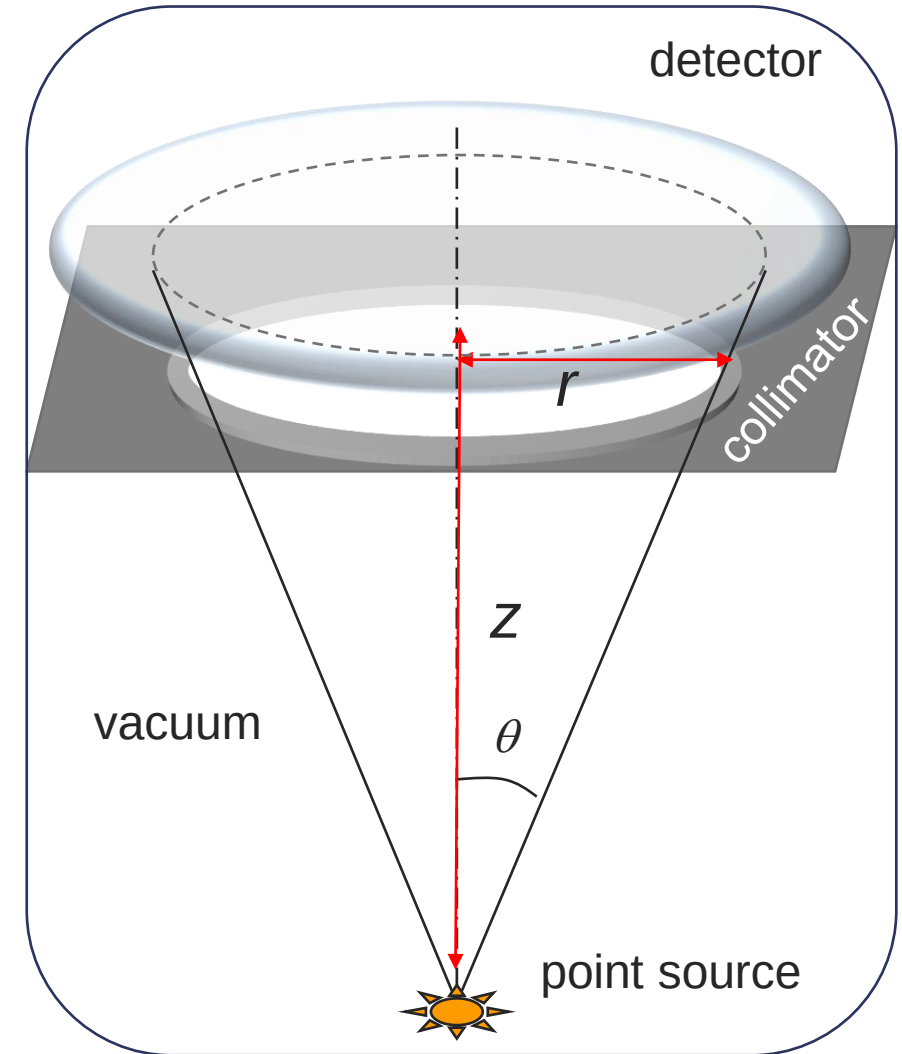
Defined solid angle method

A primary method, for alpha emitters

- The method requires
 - A detector 100% efficient to alpha
 - A good vacuum
 - An extremely well-known solid angle
 - A well controlled source – detector distance
 - Well define collimator

- Thus one can deduce the activity

$$A = \frac{N_{\alpha}}{\Omega_{eff}}$$





4 ■ Dismantling Applications

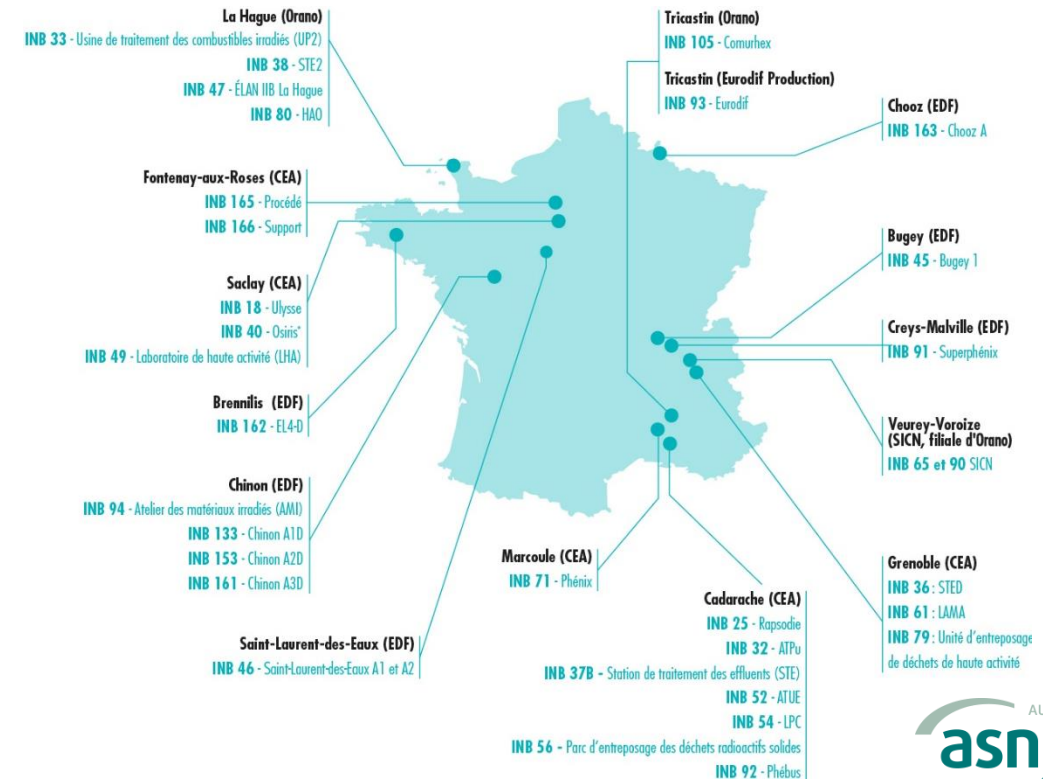
Illustrations of latest developements in ionizing radiation detection

Dismantlement & decommissioning context

- Industrial process during which the remaining radioactivity is removed from a facility after shutdown
- Main objective: Remediation of site
 - Protection of people
 - Protection of environment
- Key figures to keep in mind
 - Time scale: long and tedious process.
Typically about 10–20 years (or more)
 - Cost: many millions of euros
(EDF estimation: 20-60 billions € for 58 reactors)

Dismantlement in France

- Two approaches are usually taken
 - Safe storage
 - Immediate dismantlement
- France specificities
 - Immediate dismantlement
 - Waste Remediation: no clearance level
- Upcoming challenges
 - Current facilities are aging
 - Many facilities to dismantle in the next decades



Facilities under dismantlement in France
(source ASN - January 2018)

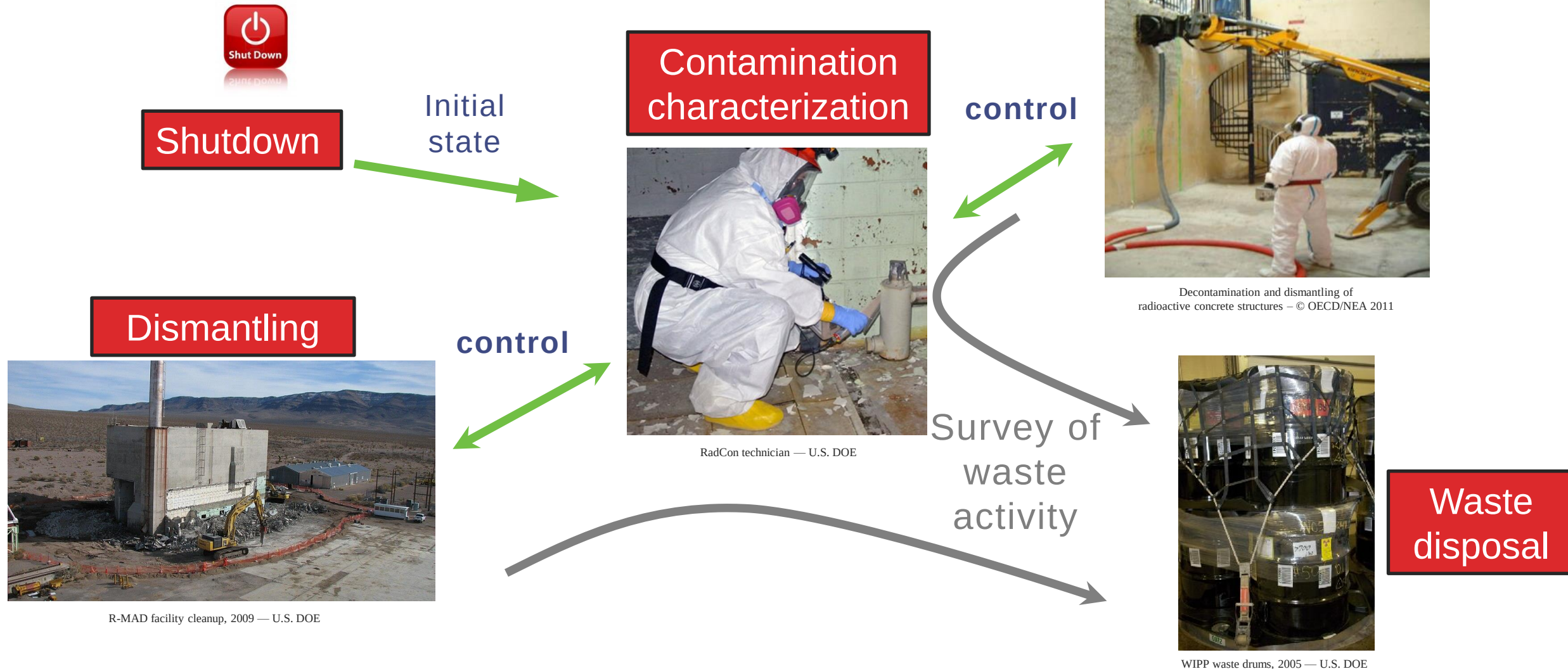
D&D tools

- Main steps
 - Removal of the source term (e.g. used fuel in power plant)
 - Dismantlement of used tools and apparatus
 - Decommissioning of buildings and soils
- Decommissioning tools
 - Surface shaving
 - Chemical attacks
 - Laser cutting
 - ...



Remote-controlled demolition robot — EWN GmbH

D&D process



Laboratory characterization

- Radiochemical analysis
 - Based on samples from the field ~1 g
 - Chemical process
- Pros
 - Sensitive to all emitters
 - Low detection limit
 - Various isotope discrimination
- Cons
 - Delayed analysis
 - Sampling representativeness?
 - Limited mapping capability



Dean Calma / IAEA, 2023
— Wikimedia Commons (CC BY 2.0)



Core drilling, Nevada Test Site, 1982 — U.S. DOE



Gamma spectrometer @ LNHB



Dean Calma / IAEA, 2023
— Wikimedia Commons (CC BY 2.0)

On site characterization

- Long range radiation: gamma camera
 - Real time & in situ
 - Good sensitivity
 - Accurate discrimination
 - Localization capability
- Short range radiations: contamination monitors
 - Real time & in situ
 - Limited sensitivity
 - Limited discrimination
 - Limited localization capability



Dean Calma / IAEA, 2018, CC BY 2.0



RadCon technician — U.S. DOE

Detection of short range radiations



Isotope	^3H (18 keV)	^{14}C (156 keV)	^{36}Cl (710 keV)	^{241}Am (5.4 MeV)
Range in air	6.5 mm	27 cm	2.6 m	43 mm
Range in water	7 μm	0.3 mm	2.8 mm	40 μm

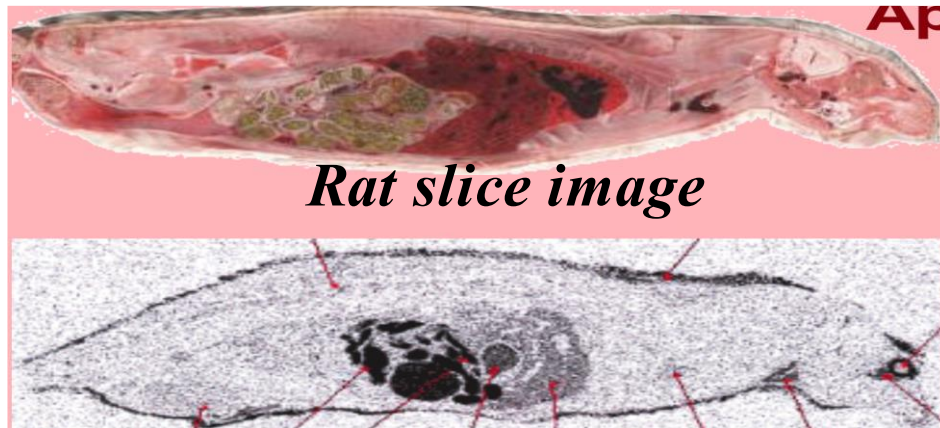
- How to detect?
 - Radiation must reach sensitive part of the detector
 - Need to minimize the thickness of any layer of material
- Dismantlement requirements
 - Portable device
 - Real time imaging
 - Dedicated to short range radiation

Context summary

- Dismantling process
 - Tedious and costly industrial process
 - Will strongly increase in France in the next decade
- Need for contamination characterization tool
 - Critical during each step of any dismantlement
 - Lack of solutions for short range emitters
 - In-situ & real time
 - Imaging & mapping
 - Sensitive
- Short range detection
 - Quickly stopped by any matter
 - Require dedicated detection system

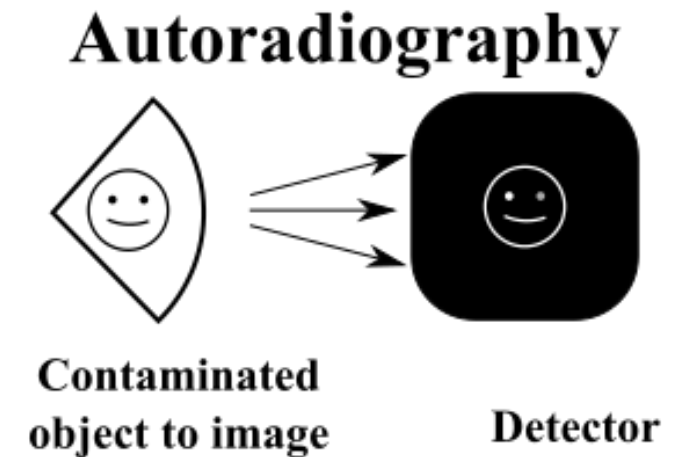
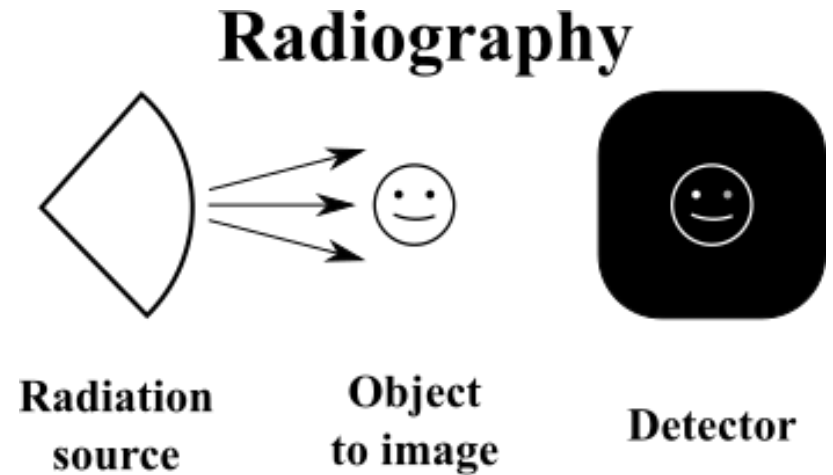
What is autoradiography?

- Imaging method based on radiation emission
 - Source of emission = object to image
 - Use in CEA for dismantlement since 2010
 - Mainly used in biology



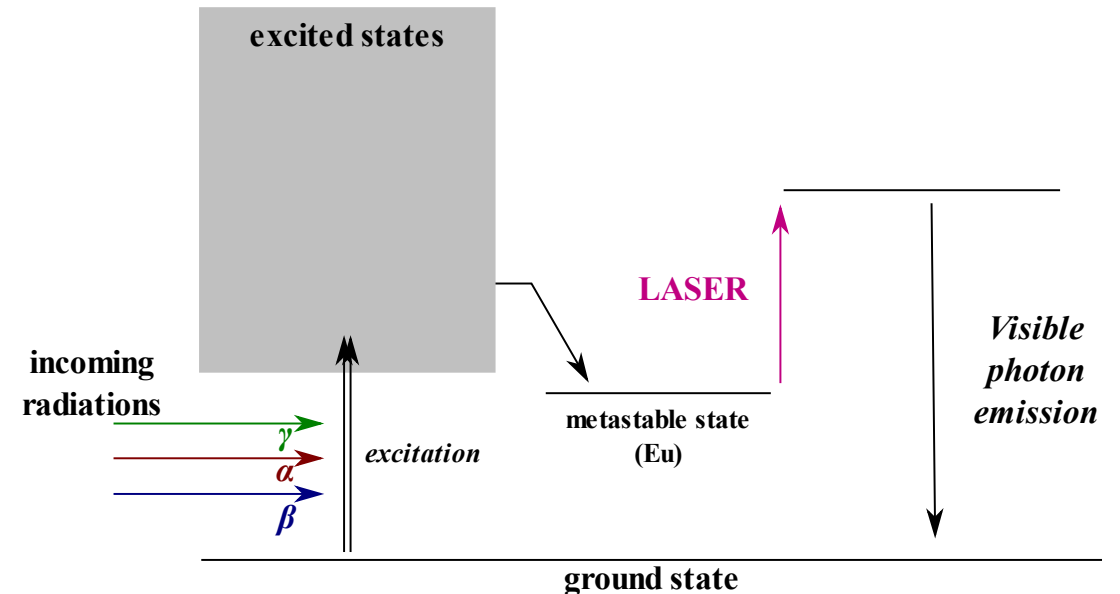
Rat slice image

Rat slice autoradiography

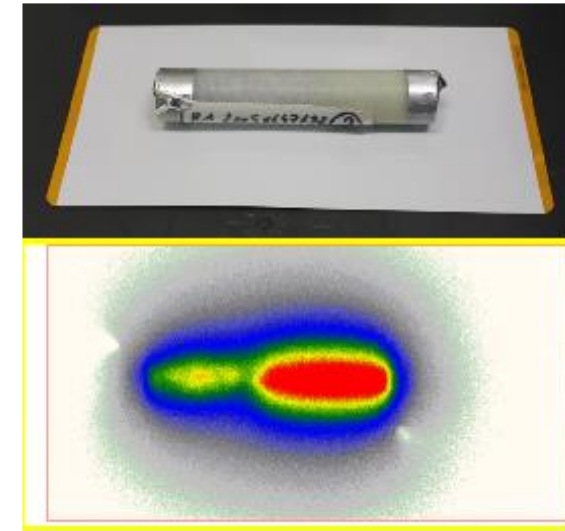
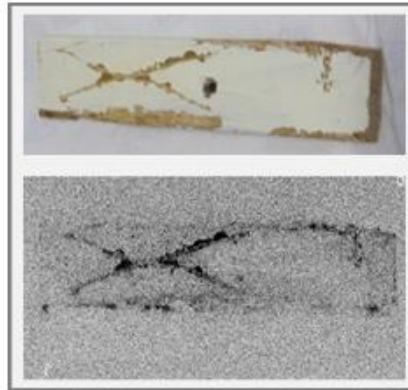
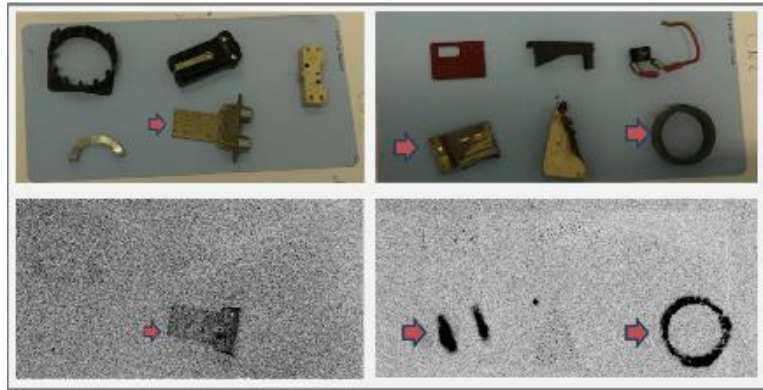


Phosphor screen

- Industrial technology
 - Historical method (Becquerel's Maltese cross)
 - Photo-stimulated fluorescence
 - Reusable screens
- Very convenient tool
 - Sensitive to all radiation types
 - Linear response to activity
 - Low detection limit ($\sim \text{Bq/cm}^2$)
 - High resolution ($\sim 50 \mu\text{m}$)
- But with huge limitations...
 - Handling requires dark environment
 - Exposure time is a priori unknown



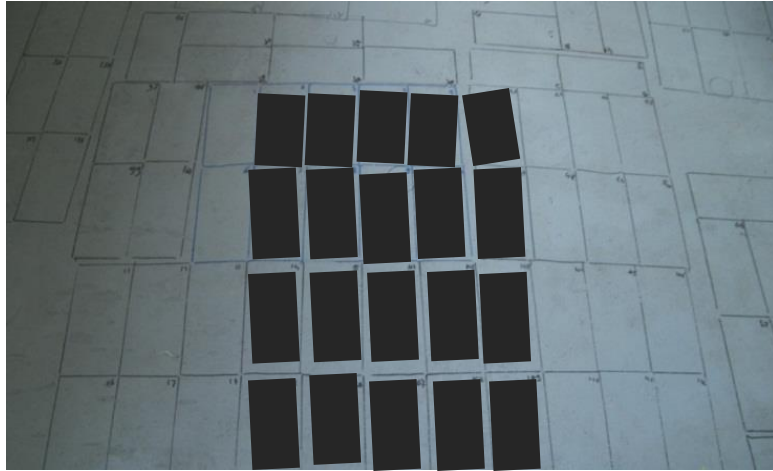
Example of use for dismantling applications



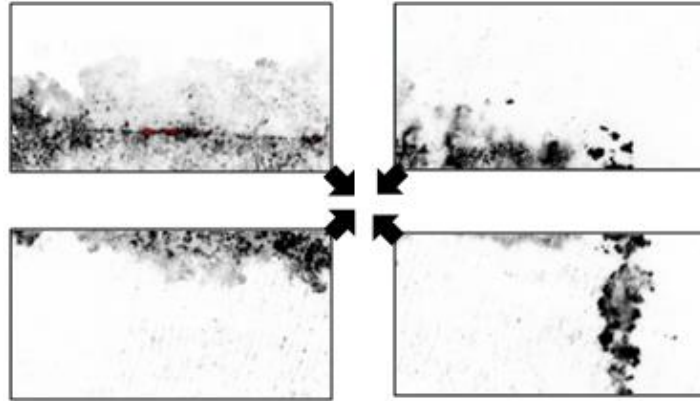
Facility contamination mapping



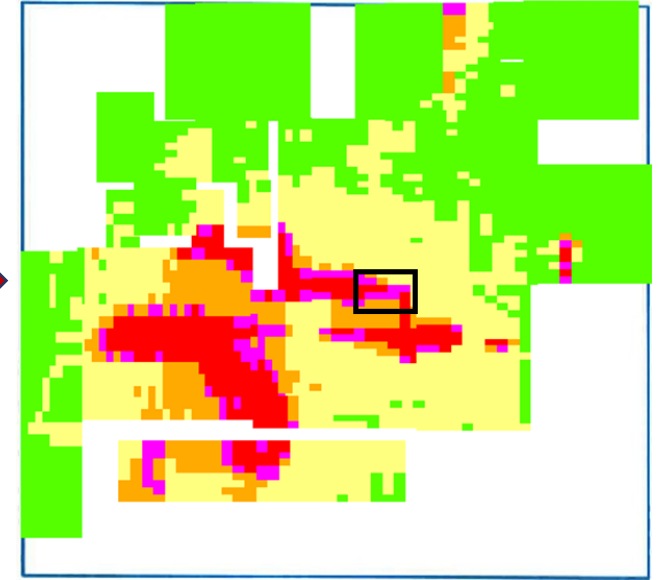
Facility contaminated with ^{14}C



Individual screen result



^{14}C contamination map



- Great results with support of geostatistical tool
 - e.g. Kartotrak ©Géovariances Company
- However...
 - About 24 hours measurement per batch
 - ~100 m² performed in two weeks of measurements

Autoradiography summary

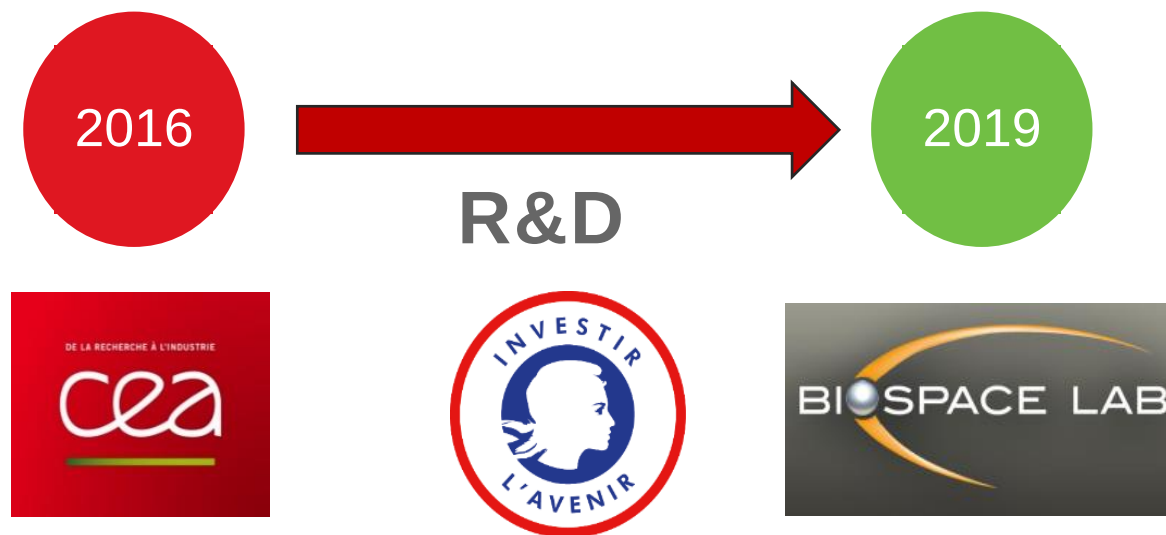
- Phosphor screen
 - Historical detection technique
 - Mainly used in biology
 - Recently applied at CEA for dismantlement
- Several advantages
 - Sensitive to all radiations
 - Low detection limit
 - Surface contamination imaging / Facility contamination mapping
 - Some radiation discrimination
- But cannot be industrialized
 - Requires to be handled in dark environment
 - Exposure time is unknown

Maud project

- Mesure par Autoradiographie Digitale
 - PIA ANDRA project (3 years)
 - Collaboration : ARL (SME), CEA, CNRS & University
- Goals
 - Industrial detector (TRL 7)
 - Measurement in-situ and in real time
 - α / β contamination imaging & mapping
- Specifications
 - Image resolution: $\sim cm^2$
 - Sensitivity:
 - $\alpha \sim 0.04 \text{ Bq/cm}^2$
 - $\beta \sim 0.4 \text{ Bq/cm}^2$
 - Tritium $\sim 100 \text{ Bq/cm}^2$

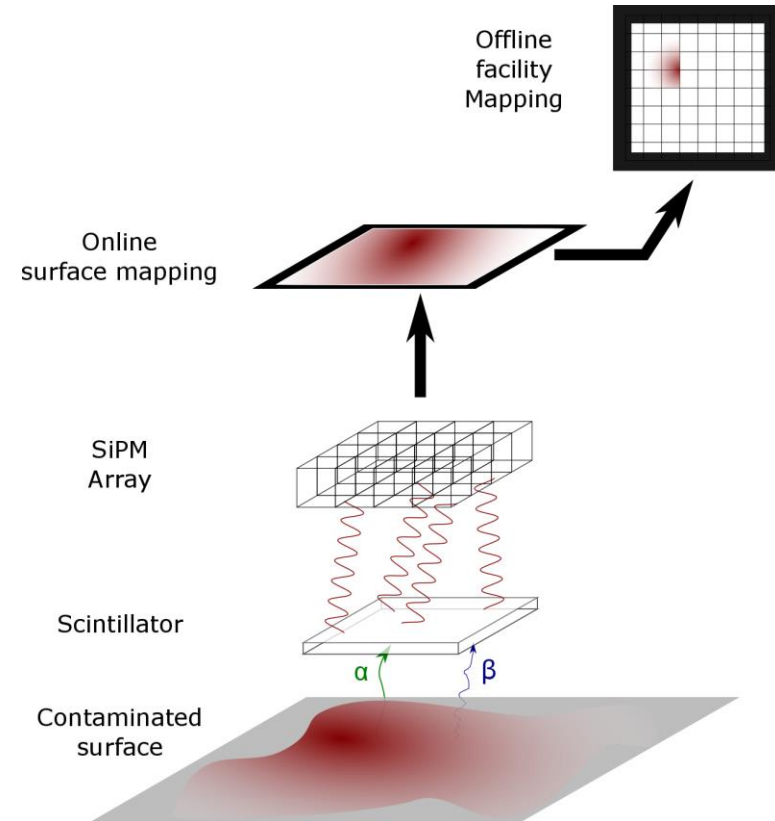


MAUD / AUTORADIOGRAPHY / ALPHA BETA CAMERA



Detection principle

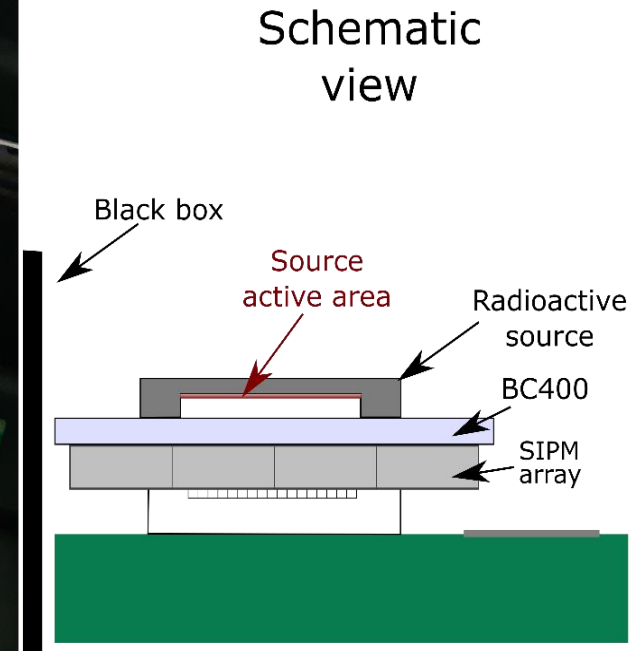
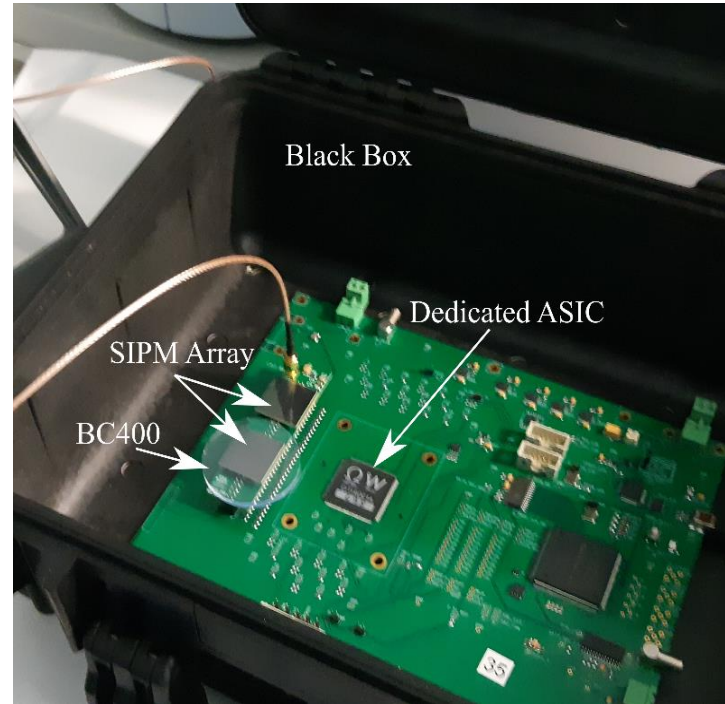
- Direct contact detection
 - Thin organic scintillator
 - SiPM arrays
- Detection principle
 - Radiation loses energy in BC400
 - BC400 converts excitation in photon emission
 - Light is collected by SiPM
 - Amplitude of SiPM signal is measured



- Suited for dismantlement
 - Online imaging / Offline mapping
 - Robust / Affordable
 - Autonomous solution
 - Contamination can be cleaned

Detection principle

- Setup
 - Black box
 - 2 SiPM arrays (4x4 pixels) Hamamatsu
 - BC400 from 1 to 3 mm
 - Regulated power supply
- Electronic readout
 - Dedicated ASIC
 - 14 bits ADC
- Measurement protocol
 - Search of light leakage
 - Stabilization of temperature
 - Background measurement
 - 5 minutes acquisition



Laboratory characterization

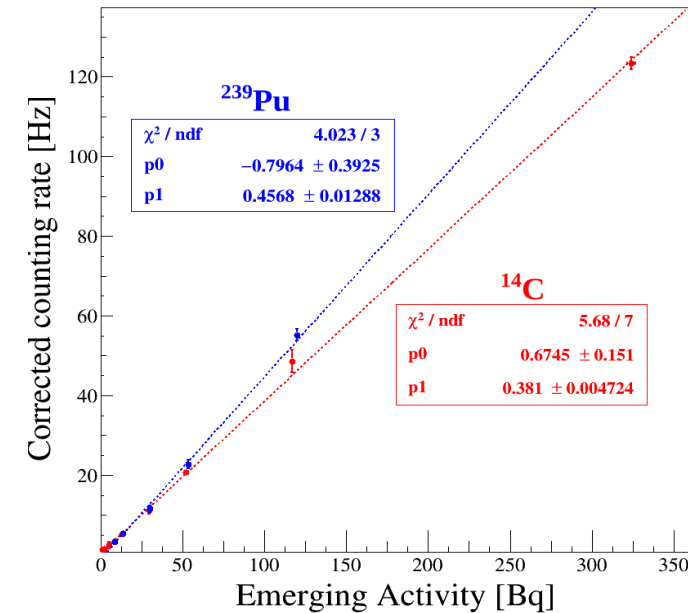
■ Sensitivity study (using calibrated sources)

- α : ^{233}U , ^{239}Pu , ^{241}Am
- β : ^3H , ^{14}C , ^{36}Cl , ^{90}Sr
- γ : ^{137}Cs
- Activity < 300 Bq (2π)
- Background $\sim 0.8 \pm 0.1$ cps

■ Linearity study

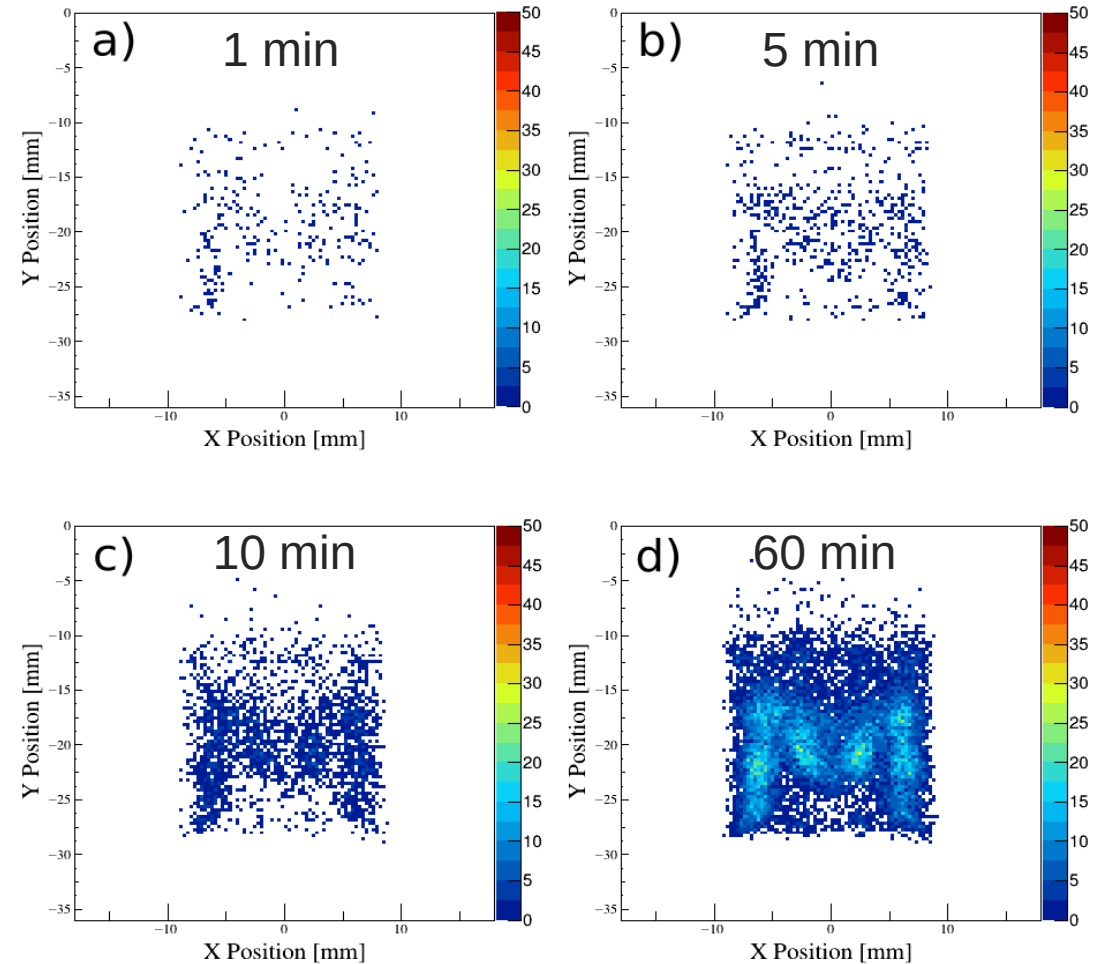
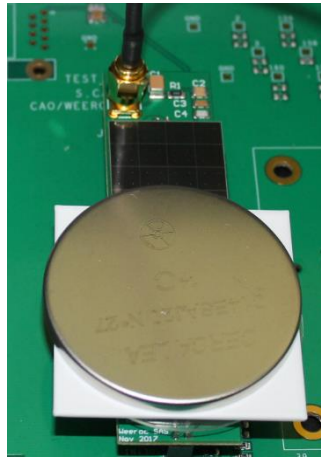
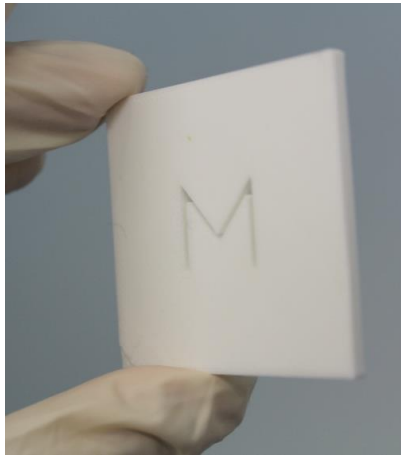
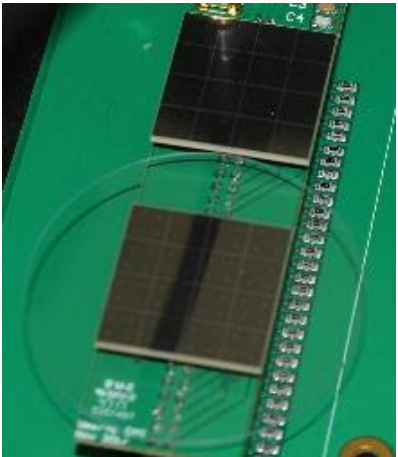
- Evaluated with ^{14}C and ^{239}Pu
- Using various collimators
- From 1 to 400 Bq

Isotope	Radiation	Detection efficiency (%)	Detection limit (Bq/cm ²)
^3H	β	0.15 ± 0.05	108
^{14}C	β	38.1 ± 0.5	0.43
^{239}Pu	α	45.7 ± 1.3	0.36
^{137}Cs	γ	6.0 ± 1.3	3



Laboratory imaging

- Shape reconstruction
 - Using M-shaped collimator
 - ^{14}C radiation source
 - Estimated flux ~ 40 Bq
 - Various algorithms tested



Industrial demonstrator

- Produced by the industrial partner
 - TRL 7 to TRL 9
 - Easy to handle
 - Touchscreen on the top
 - Equipped with a battery (portable)

