Nuclear reactions studies for improved nuclear data for science and technology

Stephan Pomp
Department of physics and astronomy, Uppsala University

- Where do the **needs** come from?
- How do we **provide** nuclear physics knowledge?
- What is currently going on and what are the **plans** for NFS?

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Nuclear data for SDG

IAEA
International Atomic Energy Agency

Safety and Security:
Nuclear security and counter terrorism, Remote controlled radiation measurements, radiation detection systems…

Environment:
Climate and earth science, Urban pollution, Ocean acidifications, Environmental radioactivity, …

Materials:
Materials characterization or modification, radiation damage, semiconductors, metallurgy, nanoscience application, …

Medical:
Particle therapy, Imaging, Radio-isotope production and for therapy, Theranostic approach, Radioprotection, …

Science:
Heritage science, Space radiations, Astrophysics, Geology, …

Energy:
LWR, Gen IV reactors, Accelerator Driven Systems, Fusion reactors, Nuclear power sources for space applications, …

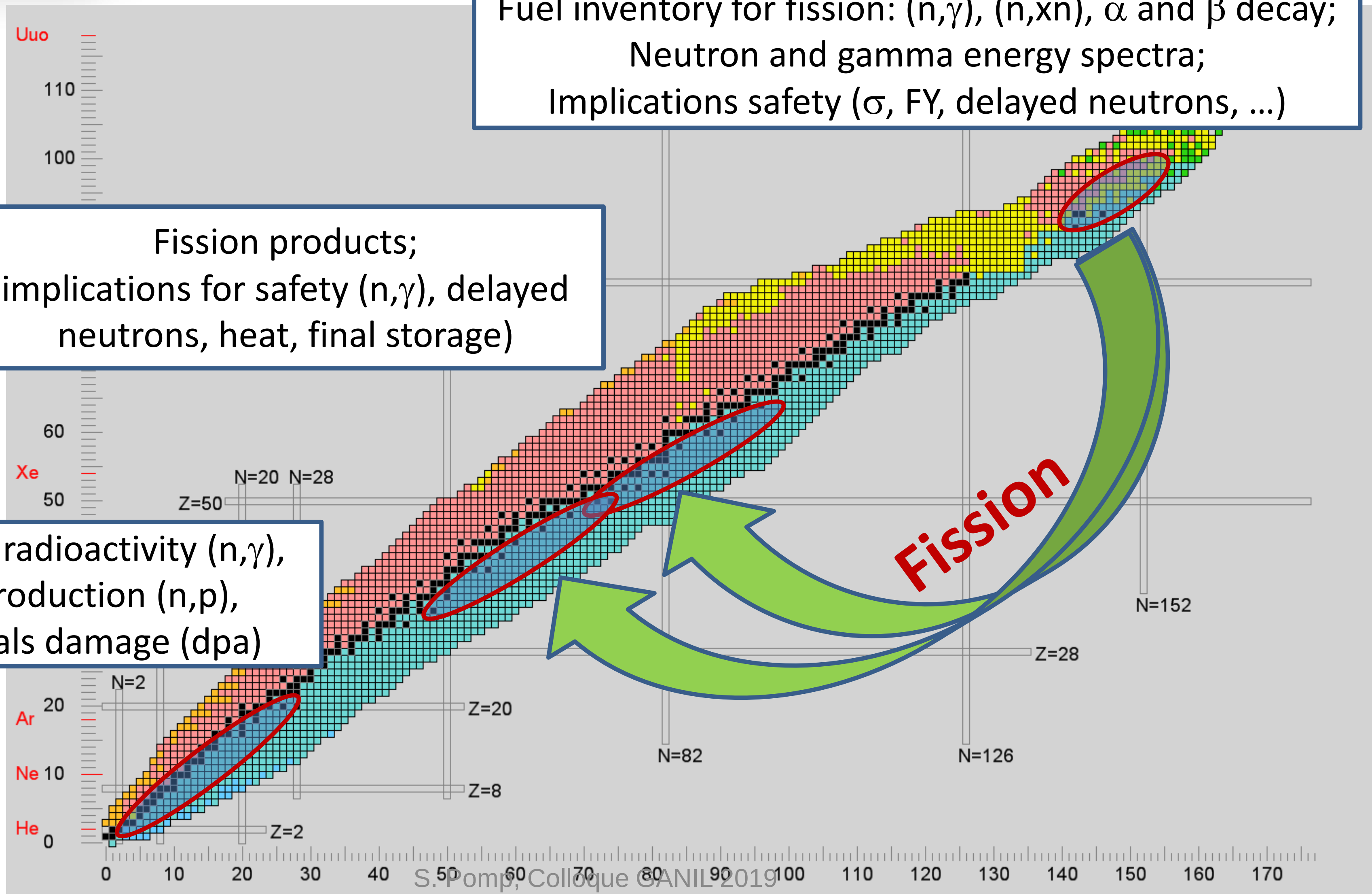
Slide adapted from Maëlle Kerveno

Example from nuclear energy

Fuel inventory for fission: (n,γ), (n,xn), α and β decay;
Neutron and gamma energy spectra;
Implications safety (σ, FY, delayed neutrons, …)

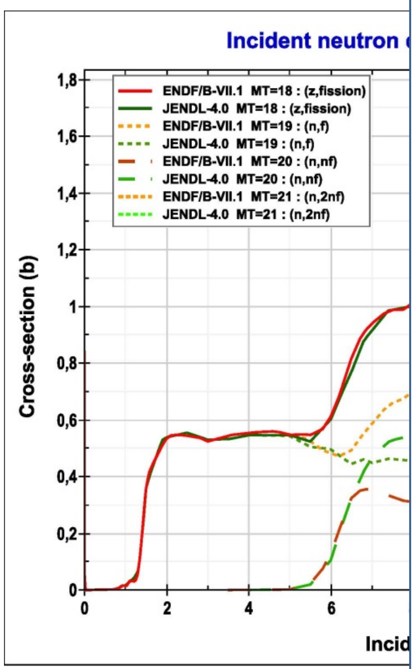
Fission products;
implications for safety (n,γ), delayed neutrons, heat, final storage)

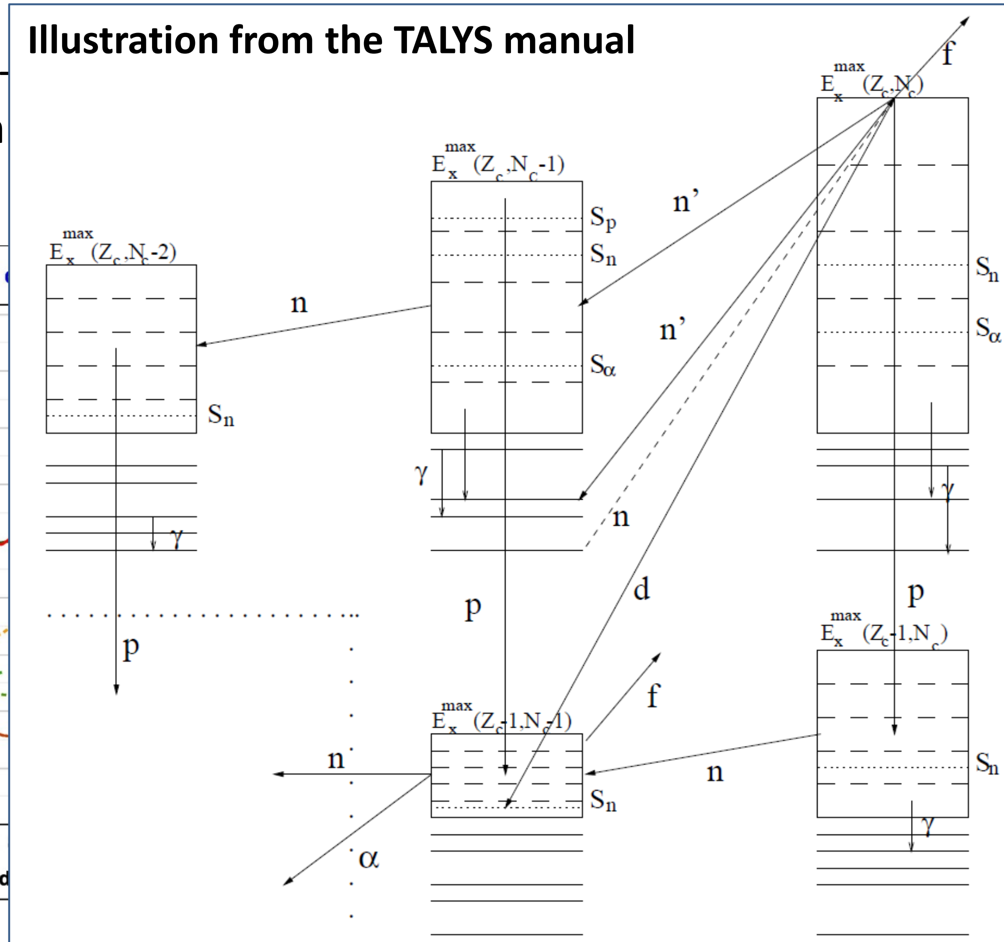
Induced radioactivity (n,γ),
gas production (n,p),
materials damage (dpa)

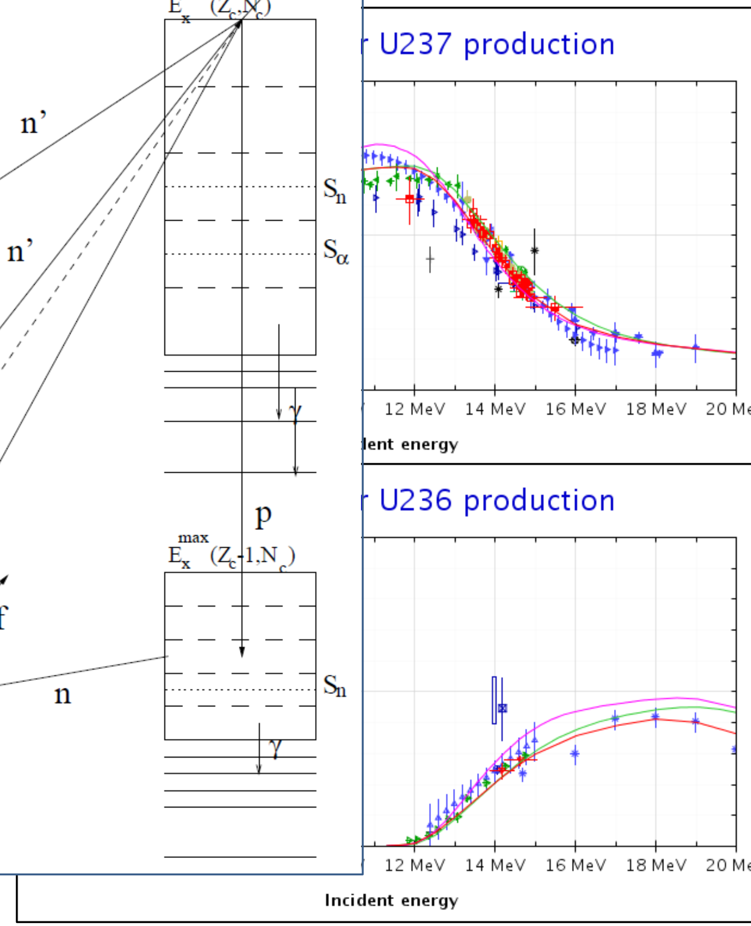


(n,xn) and fission

Disentangling multi-
from other reaction
Isotopes):

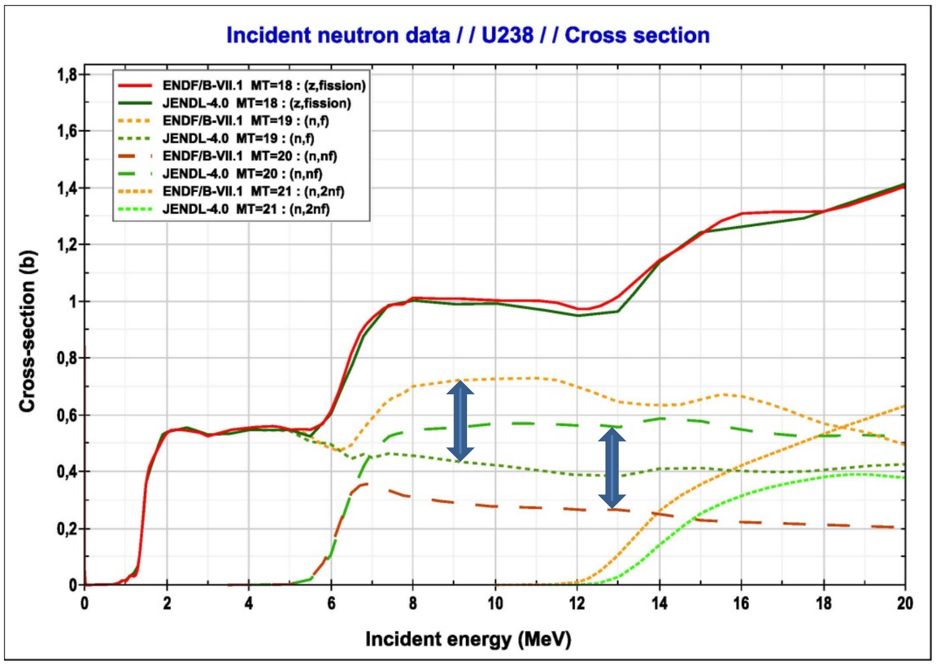


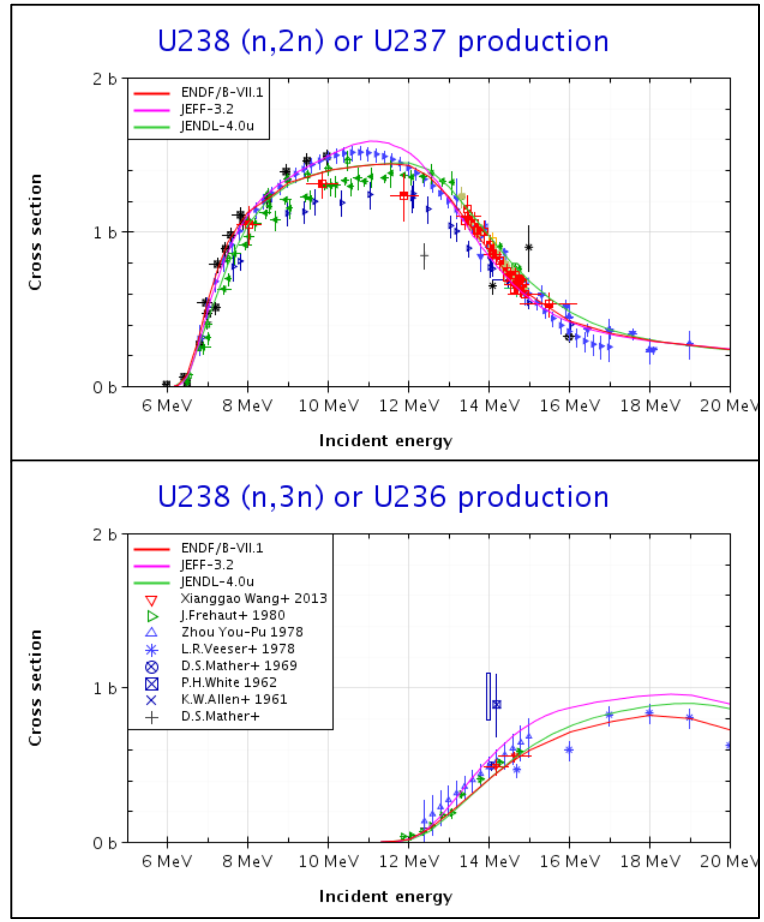




(n,xn) and fission

Disentangling multi-chance fission needs input from other reaction channels (and neighboring Isotopes):





See talk by Greg Henning today

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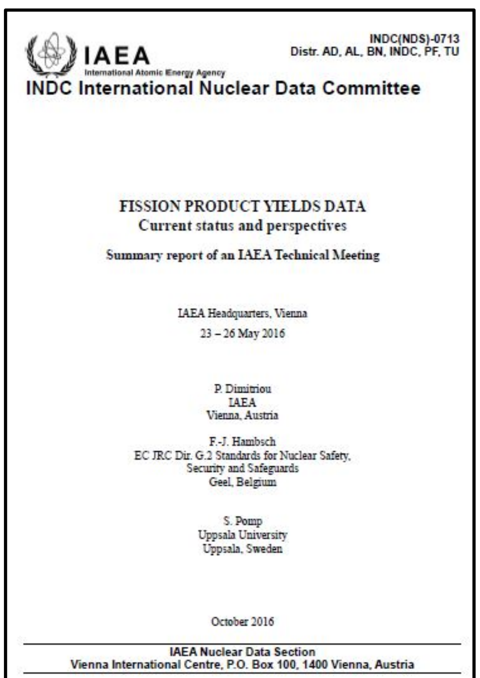
Fission yields

FY for many systems and excitation energies are needed for both *fuel cycle and nucleosynthesis scenarios*.

Such needs can be fulfilled by **direct measurements** combined with **theoretical developments** that need guidance from other experimental input (e.g. $\overline{\nu}$(A)).

INDC(NDS)-0713 (2016)



IAEA
International Atomic Energy Agency

INDC(NDS)-0713
Distr. AD, AL, BN, INDC, PF, TU

INDC International Nuclear Data Committee

FISSION PRODUCT YIELDS DATA
Current status and perspectives

Summary report of an IAEA Technical Meeting

IAEA Headquarters, Vienna
23 – 26 May 2016

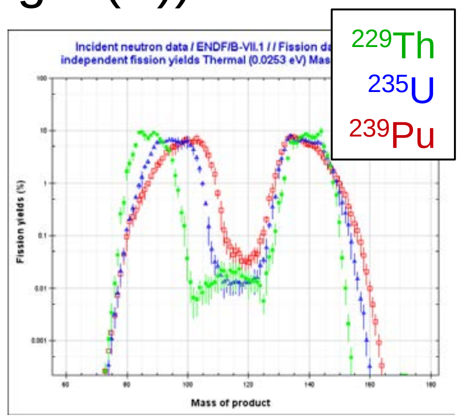
P. Dimitriou
IAEA
Vienna, Austria

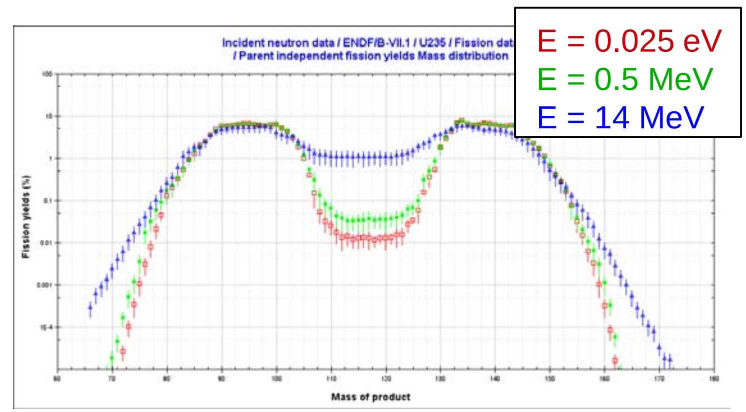
F.-J. Hambsch
EC JRC Dir. G.2 Standards for Nuclear Safety, Security and Safeguards
Geel, Belgium

S. Pomp
Uppsala University
Uppsala, Sweden

October 2016

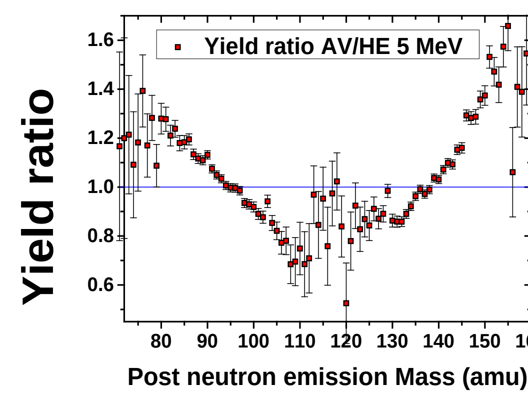
IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria





Impact of "sawtooth" $\overline{\nu}$(A,E) on FY:

A. Al-Adili, et al, PRC86 (2012) 054601



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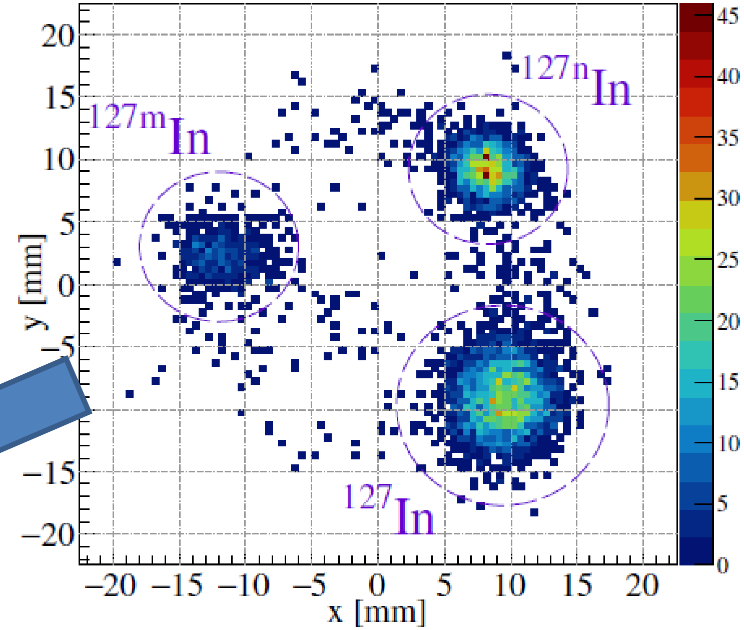
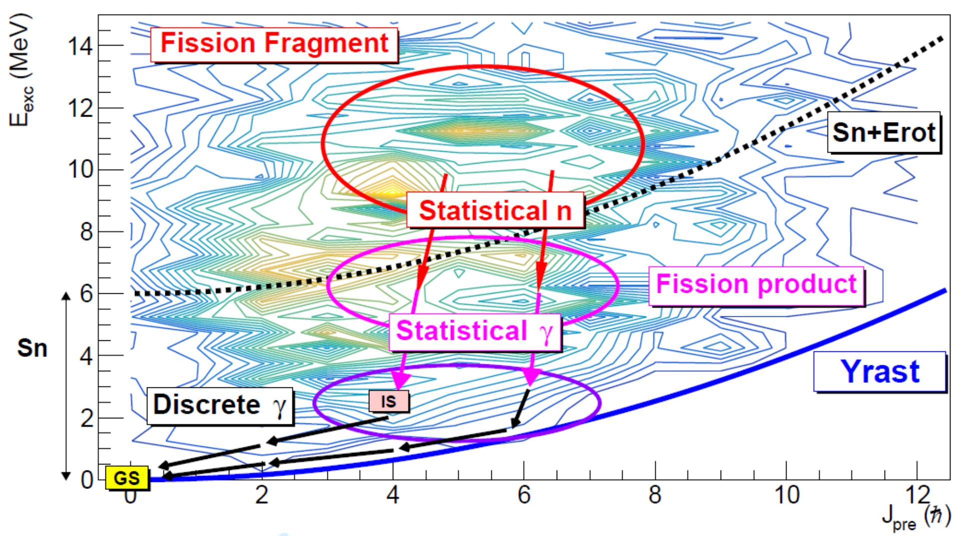
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Penning trap for fission studies

Use **Penning trap** to measure yields and isomeric yield ratios (IYR) using *direct ion counting* from (proton-induced) fission.





Use IYR to trace back and deduce *angular momentum of fragment*

(Huizenga and Vandenbosch 1960)

Improves modeling of angular momentum generation; impact on n/γ-emission competition.

Extracted J_{rms}^{av} for isotopes in the ^{132}Sn region

(p,f); (n,f) in progress

Cd: g.s. is low spin state; In: g.s. is high spin state

Nuclide	Ground state		Isomeric state			IYR	J_{rms}^{av}
	I^π	$T_{1/2}$	I^π	$T_{1/2}$	E_x (keV)		
^{81}Ge	$9/2^+$ #	8 (2) s	$(1/2^+)$	8 (2) s	679.14(4)	0.975(7)	
^{119}Cd	$1/2^+$	2.69 (2) m	$11/2^-$	2.20 (2) m	146.54(11)	0.871(15)	12.3(5)
^{121}Cd	$3/2^+$	13.5 (3) s	$11/2^-$	8.3 (8) s	214.86(15)	0.867(4)	14.7(1)
^{123}Cd	$3/2^+$	2.10 (2) s	$11/2^-$	1.82 (3) s	143(4)	0.876(7)	15.7(2)
^{125}Cd	$3/2^+$	680 (40) ms	$11/2^-$	480 (30) ms	186(4)	0.902(8)	
^{127}Cd	$3/2^+$	360 (40) ms	$11/2^-$	450 (120) ms	276(15)	0.872(38)	
^{119}In	$9/2^+$	2.4 (1) m	$1/2^-$	18.0 (3) m	311.37(3)	0.978(15)	26.2(4)
^{121}In	$9/2^+$	23.1 (6) s	$1/2^-$	3.88 (10) m	313.68(7)	0.971(11)	25.1(5)
^{123}In	$(9/2)^+$	6.17 (5) s	$(1/2)^-$	47.4 (4) s	327.21(4)	0.958(2)	21.2(2)
^{125}In	$9/2^+$	2.36 (4) s	$(1/2)^{(-)}$	12.2 (2) s	360.12(9)	0.950(3)	15.9(3)
^{127}In	$(9/2^+)$	1.09 (1) s	$1/2^-$ #	3.67 (4) s	408.9(3)	0.921 (2)	9.5 (2)
			$(21/2^-)$	1.04 (10) s	1870 (60)		
^{129}Sb	$7/2^+$	4.366 (26) h	$(19/2^-)$	17.7 (1) m	1851.31(6)	0.441(32)	

$T_{1/2}$ for ^{127}Cd: recent measurement by C. Lorenz et al. at JYFLTRAP (priv. comm.)

V. Rakopoulos et al., PRC **99**, 014617 (2019)

Identifying mesurement needs

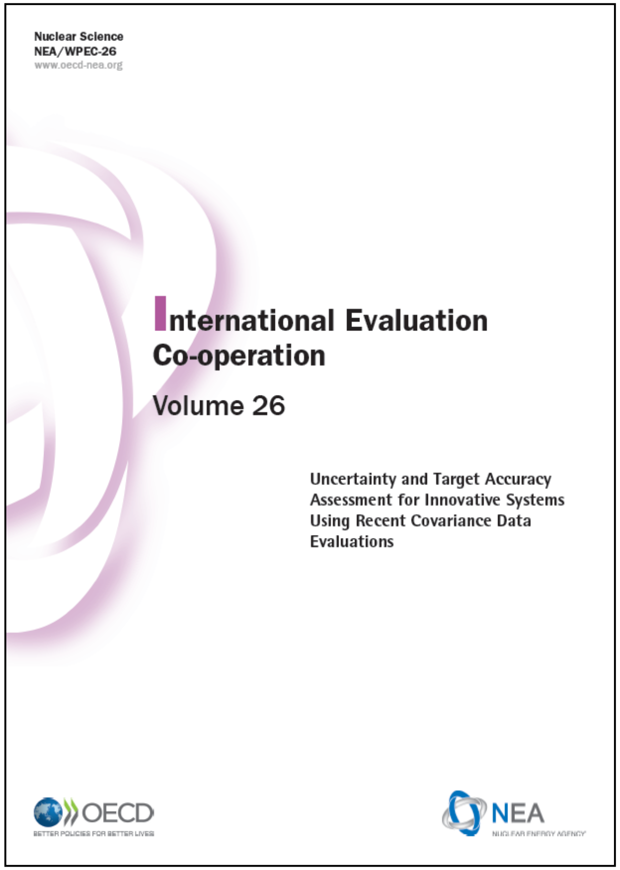
- Sensitivity studies (for a certain system)
- Target accuracy (requirements for safety/economy)
- HPRL for specific *measurements*

Results of your search in the request list

Requests are shown from the following list(s):
High Priority (H)

Explanations of each column can be found in the table heads. To view the details of a request, please click on the **link symbol** after the request ID.
To send a comment on a particular entry, please view the request, and click on the **'letter'** symbol there.

ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field	Date
2H		8-O-16	(n,a),(n,abs)	SIG	2 MeV-20 MeV		See details	Y	Fission	12-SEP-08
3H		94-PU-239	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y	Fission	12-MAY-06
4H		92-U-235	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y	Fission	12-MAY-06
8H		1-H-2	(n,el)							-APR-07
15H		95-AM-241	(n,g),(n,tot)							-SEP-08
18H		92-U-238	(n,inl)							-SEP-08
19H		94-PU-238	(n,f)							-SEP-08
21H		95-AM-241	(n,f)							-SEP-08
22H		95-AM-242M	(n,f)							-SEP-08
25H		96-CM-244	(n,f)							-SEP-08
27H		96-CM-245	(n,f)							-SEP-08
29H		11-NA-23	(n,inl)							-SEP-08
32H		94-PU-239	(n,g)							-SEP-08
33H		94-PU-241	(n,g)							-SEP-08
34H		26-FE-56	(n,inl)							-SEP-08
35H		94-PU-241	(n,f)							-SEP-08
37H		94-PU-240	(n,f)	SIG	0.5 keV-5 MeV		See details	Y	Fission	15-SEP-08
38H		94-PU-240	(n,f)	nubar	200 keV-2 MeV		See details	Y	Fission	15-SEP-08
39H		94-PU-242	(n,f)	SIG	200 keV-20 MeV		See details	Y	Fission	15-SEP-08
41H		82-PB-206	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y	Fission	15-SEP-08
42H		82-PB-207	(n,inl)	SIG	0.5 MeV-6 MeV		See details	Y	Fission	15-SEP-08
45H		19-K-39	(n,p),(n,np)	SIG	10 MeV-20 MeV		10	Y	Fusion	11-JUL-17
97H		24-CR-50	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission	05-FEB-18
98H		24-CR-53	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission	05-FEB-18
99H		94-PU-239	(n,f)	nubar	Thermal-5 eV		1	Y	Fission	12-APR-18
102H		64-GD-155	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y	Fission	09-MAY-18
103H		64-GD-157	(n,g),(n,tot)	SIG	Thermal-100 eV		4	Y	Fission	09-MAY-18
114H		83-BI-209	(n,g)Bi-210g,m	BR	500 eV-300 keV		10	Y	ADS,Fission	09-NOV-18
115H		94-PU-239	(n,tot)	SIG	Thermal-5 eV		1	Y	Fission	08-APR-19



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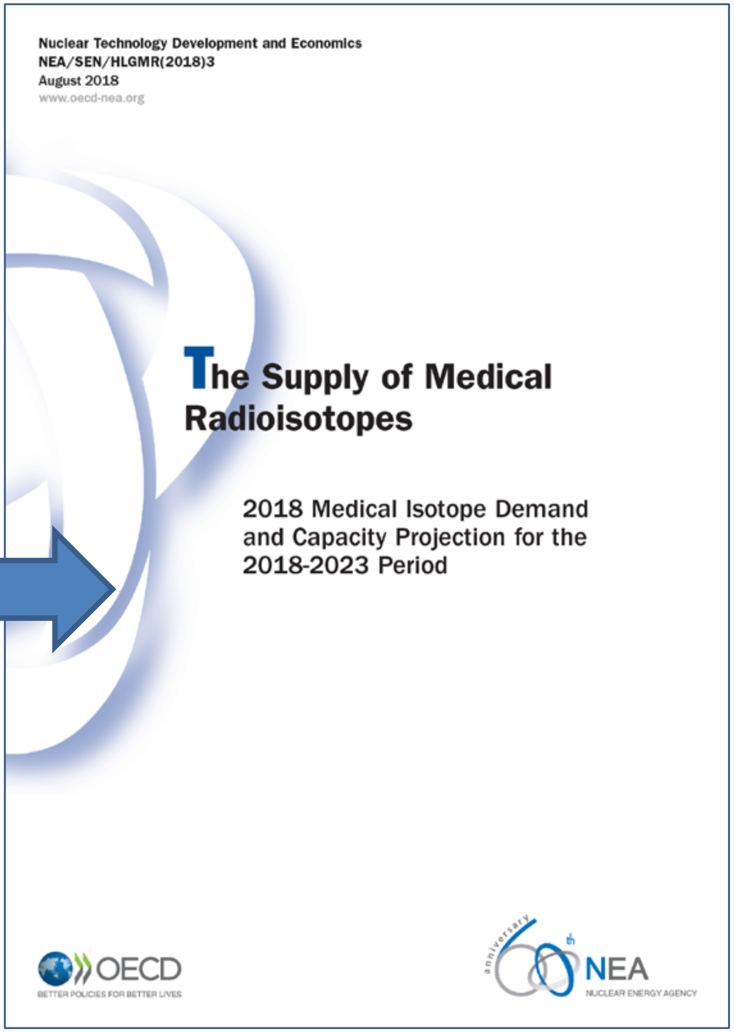
Example from nuclear medicine

- See talk by Ferid Haddad (Tuesday)
- Nuclear data needed for
  - optimizing (accelerator-based) production,
  - minimizing impurities (e.g. ^{211}At),
  - development of innovative radionuclei.

- Need for large scale production, reducing dependency on few (reactor) suppliers (like in the case of ^{99}Mo/^{99m}Tc).

- Other examples:
  - Dosimetry and
  - dose reconstruction.


Nuclear Technology Development and Economics
NEA/SEN/HLGMR(2018)3
August 2018
www.oecd-nea.org

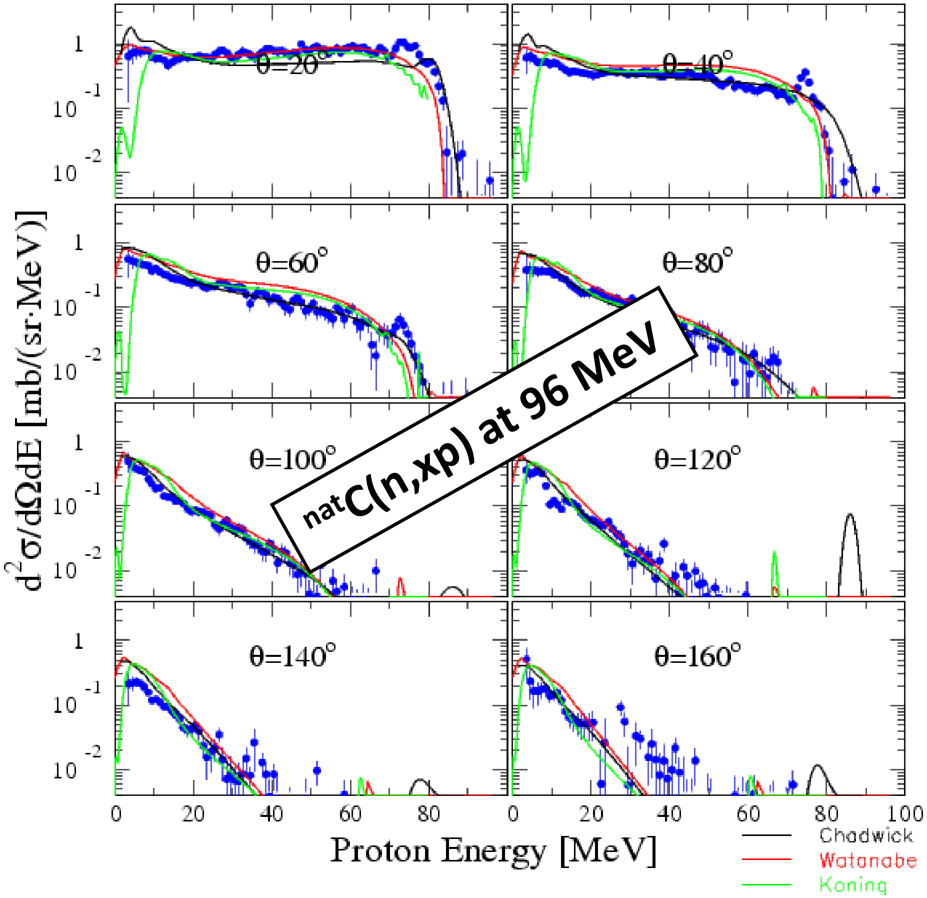
The Supply of Medical Radioisotopes

2018 Medical Isotope Demand and Capacity Projection for the 2018-2023 Period

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

DDX for better dose calculations



U. Tippawan et al., PRC 79, 064611 (2009)

$$K = \Phi \cdot k_\Phi$$

Φ : fluence of uncharged particles at the same point

k_Φ : kerma coefficient; unit: [J m² kg⁻¹] or [fGy m²]

$$k_\Phi(E_n) = N \sum_i \int E \int \left(\frac{d^2\sigma_i(E_n)}{d\Omega\, dE} \right) d\Omega\, dE$$

Kerma: Kinetic energy of the secondary charged particles released by the primary neutron per unit mass.

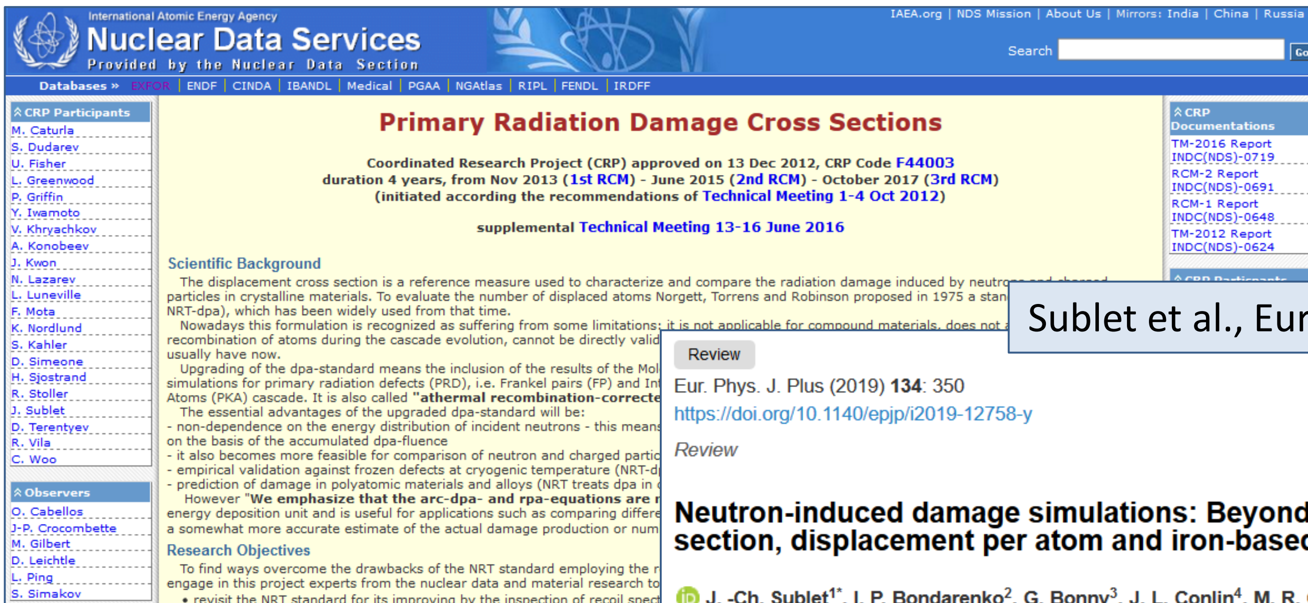
Dose: Absorbed energy per unit mass from the secondary charged particles.

- range of the secondary charged particles?
- their angular distribution?
- biological response?

And: reaction mechanisms?!

Example from material science

- Reactor materials:
  - dpa and gas production leading to embrittlement and swelling;
- Action by IAEA: https://www-nds.iaea.org/CRPdpa/



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CRP Participants: M. Caturla, S. Dudarev, U. Fisher, L. Greenwood, P. Griffin, Y. Iwamoto, V. Khryachkov, A. Konobeev, J. Kwon, N. Lazarev, L. Luneville, F. Mota, K. Nordlund, S. Kahler, D. Simeone, H. Sjostrand, R. Stoller, J. Sublet, D. Terentyev, R. Vila, C. Woo

Observers: O. Cabellos, J-P. Crocombette, M. Gilbert, D. Leichtle, L. Ping, S. Simakov

CRP Documentations: TM-2016 Report INDC(NDS)-0719; RCM-2 Report INDC(NDS)-0691; RCM-1 Report INDC(NDS)-0648; TM-2012 Report INDC(NDS)-0624

Primary Radiation Damage Cross Sections

Coordinated Research Project (CRP) approved on 13 Dec 2012, CRP Code F44003
duration 4 years, from Nov 2013 (1st RCM) - June 2015 (2nd RCM) - October 2017 (3rd RCM)
(initiated according the recommendations of Technical Meeting 1-4 Oct 2012)

supplemental Technical Meeting 13-16 June 2016

Scientific Background

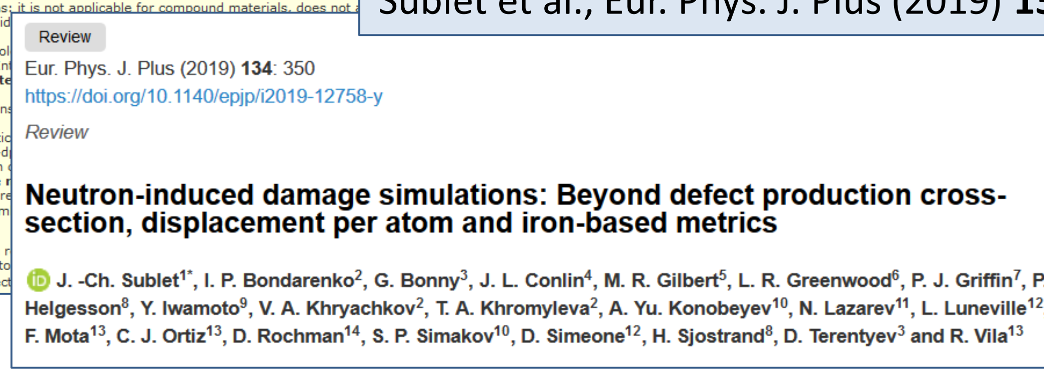
The displacement cross section is a reference measure used to characterize and compare the radiation damage induced by neutr…
particles in crystalline materials. To evaluate the number of displaced atoms Norgett, Torrens and Robinson proposed in 1975 a stan…
NRT-dpa), which has been widely used from that time.
Nowadays this formulation is recognized as suffering from some limitations: it is not applicable for compound materials, does not …
recombination of atoms during the cascade evolution, cannot be directly valid…
usually have now.
Upgrading of the dpa-standard means the inclusion of the results of the Mol…
simulations for primary radiation defects (PRD), i.e. Frankel pairs (FP) and Int…
Atoms (PKA) cascade. It is also called **"athermal recombination-correcte…**
The essential advantages of the upgraded dpa-standard will be:
- non-dependence on the energy distribution of incident neutrons - this means…
on the basis of the accumulated dpa-fluence
- it also becomes more feasible for comparison of neutron and charged partic…
- empirical validation against frozen defects at cryogenic temperature (NRT-d…
- prediction of damage in polyatomic materials and alloys (NRT treats dpa in …
However "**We emphasize that the arc-dpa- and rpa-equations are …**
energy deposition unit and is useful for applications such as comparing differe…
a somewhat more accurate estimate of the actual damage production or num…

Research Objectives

To find ways overcome the drawbacks of the NRT standard employing the r…
engage in this project experts from the nuclear data and material research to…
- revisit the NRT standard for its improving by the inspection of recoil spect…

Important given the ageing of current LWR.

Sublet et al., Eur. Phys. J. Plus (2019) **134**: 350



Review

Eur. Phys. J. Plus (2019) **134**: 350
https://doi.org/10.1140/epjp/i2019-12758-y

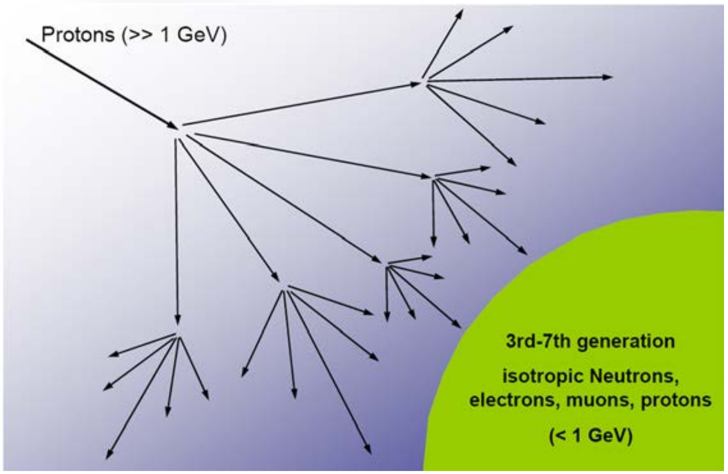
Review

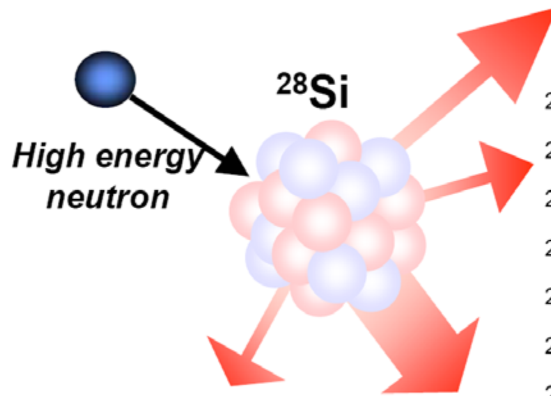
Neutron-induced damage simulations: Beyond defect production cross-section, displacement per atom and iron-based metrics

J. -Ch. Sublet[1*], I. P. Bondarenko[2], G. Bonny[3], J. L. Conlin[4], M. R. Gilbert[5], L. R. Greenwood[6], P. J. Griffin[7], P. Helgesson[8], Y. Iwamoto[9], V. A. Khryachkov[2], T. A. Khromyleva[2], A. Yu. Konobeyev[10], N. Lazarev[11], L. Luneville[12], F. Mota[13], C. J. Ortiz[13], D. Rochman[14], S. P. Simakov[10], D. Simeone[12], H. Sjostrand[8], D. Terentyev[3] and R. Vila[13]

- Somewhat "easier": Radiation effects in electronics

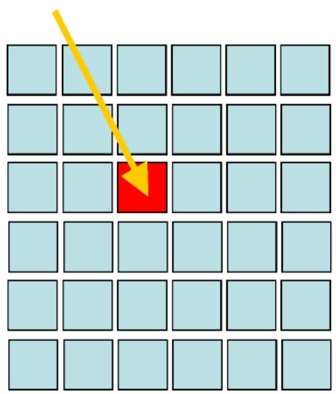
Radiation effects in electronics



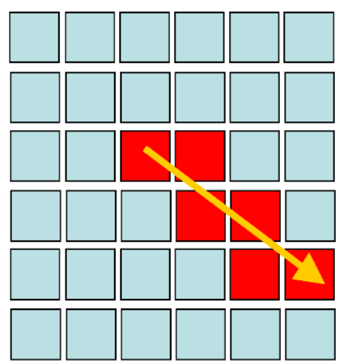


Reaction table from F. Wrobel et al., *IEEE Trans. Nucl. Phys.*, 47(6), Dec. 2000

$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n + \alpha$	10.34 MeV
$^{27}Al + n + p$	12.00 MeV
$^{26}Mg + {}^{3}He$	12.58 MeV
$^{21}Ne + 2\alpha$	12.99 MeV



Single-Bit Upset (SBU)



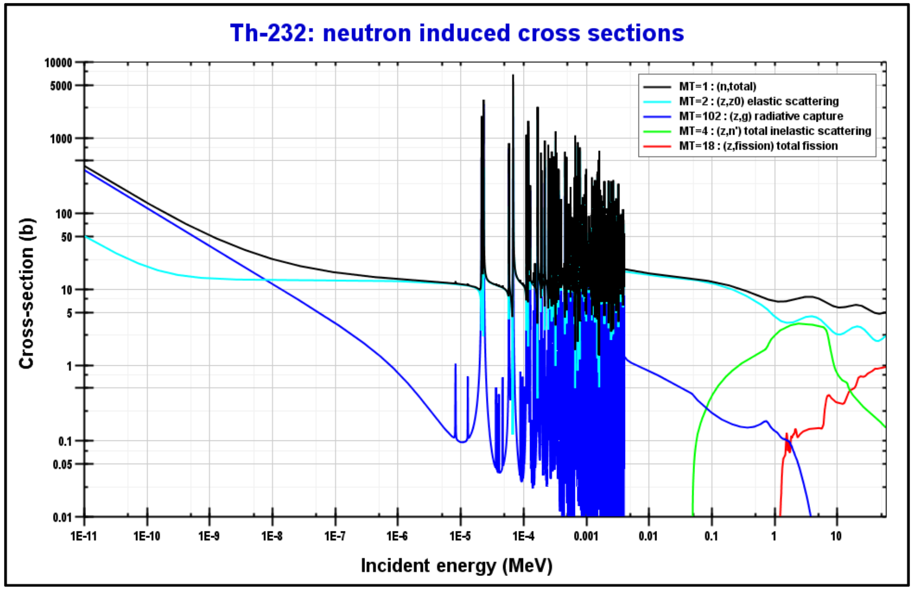
Multiple-Bit Upset (MBU)

”Wanted and unwanted memory loss”

Need: DDX data

Slide adapted from Alexander Prokofiev

- Where do the **needs** come from?
- How do we **provide** nuclear physics knowledge?
- What is currently going on and what are the **plans** for NFS?



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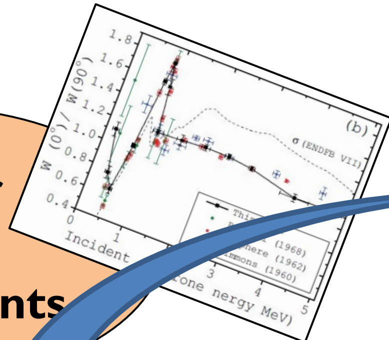
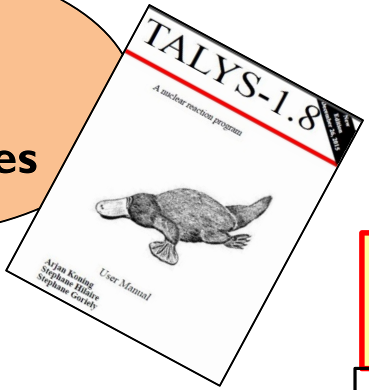
Nuclear data: how is it done?

Requirements
(sensitivity analysis)

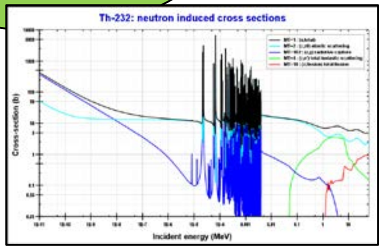


Nuclear physics **experiments**

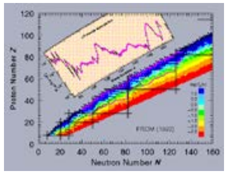
Nuclear physics **model codes**



Nuclear data **evaluation**



End-user **applications**

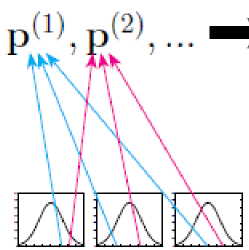


Covariances! QA: Reproducibility, etc.
(see, e.g., the TENDL project)

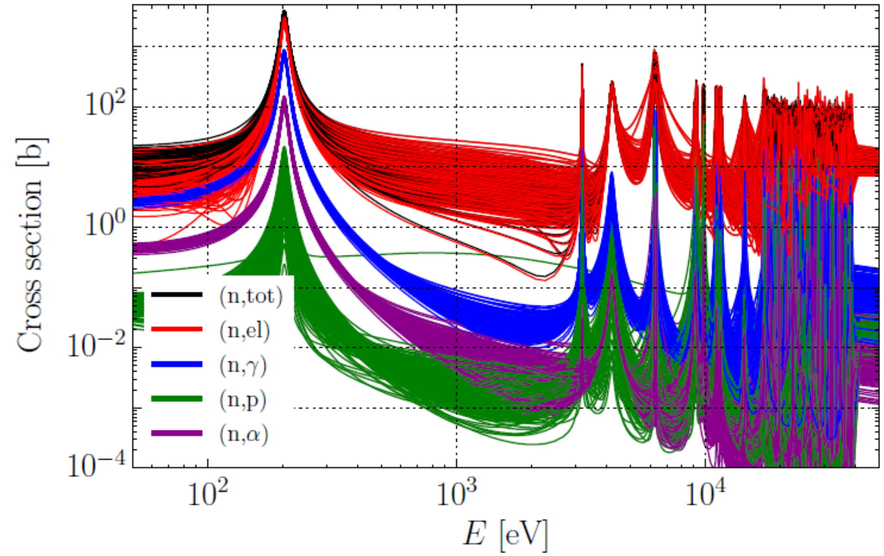
Koning and Rochman, Nucl. Data Sheets 113 (2012) 2841

Total Monte Carlo evaluation and UQ

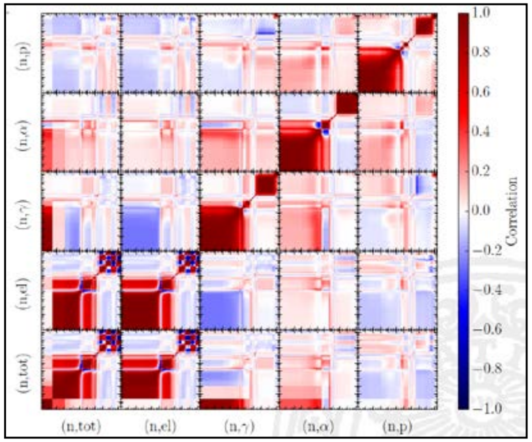
Sampling input parameters to nuclear reaction model



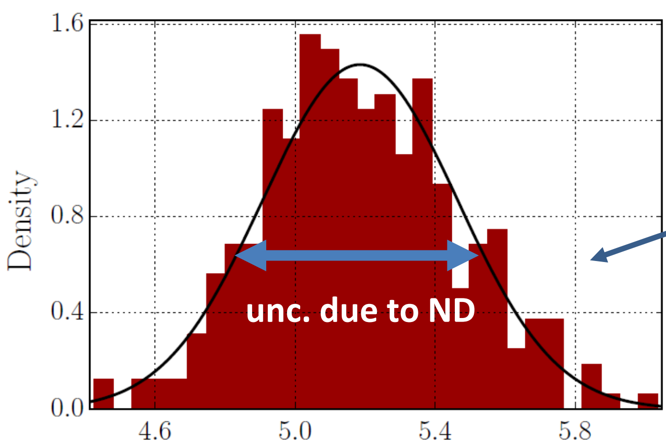
TALYS+ Resonances + Error components



New **Ni59** evaluation produced by UU in JEFF 3.3



Uncertainty propagation.

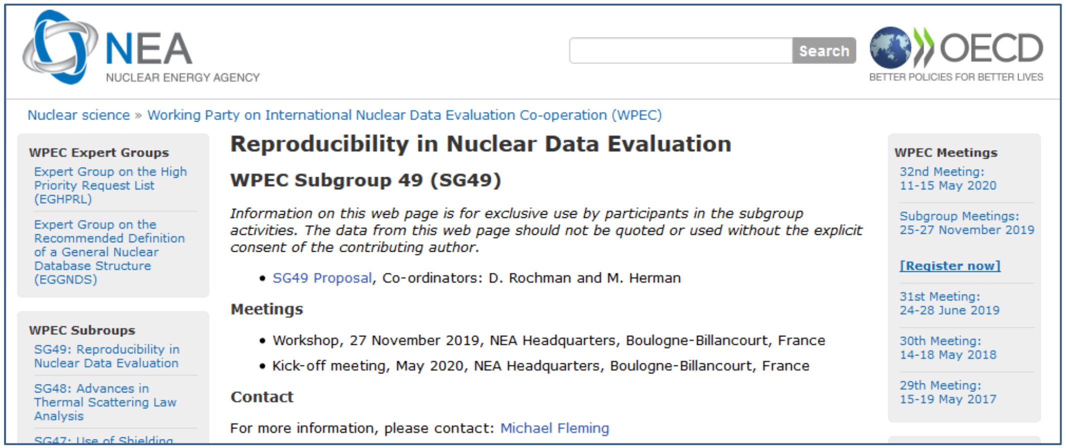


He production (a.u.) in aged reactor material

Slide adapted from Henrik Sjöstrand

Data quality assurance

- NEA is setting up a new SG in *Reproducibility in Nuclear Data Evaluation*.


NEA NUCLEAR ENERGY AGENCY
Search
OECD BETTER POLICIES FOR BETTER LIVES
Nuclear science » Working Party on International Nuclear Data Evaluation Co-operation (WPEC)

WPEC Expert Groups
Expert Group on the High Priority Request List (EGHPRL)
Expert Group on the Recommended Definition of a General Nuclear Database Structure (EGGNDS)

WPEC Subroups
SG49: Reproducibility in Nuclear Data Evaluation
SG48: Advances in Thermal Scattering Law Analysis
SG47: Use of Shielding

Reproducibility in Nuclear Data Evaluation

WPEC Subgroup 49 (SG49)

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- SG49 Proposal, Co-ordinators: D. Rochman and M. Herman

Meetings

- Workshop, 27 November 2019, NEA Headquarters, Boulogne-Billancourt, France
- Kick-off meeting, May 2020, NEA Headquarters, Boulogne-Billancourt, France

Contact

For more information, please contact: Michael Fleming

WPEC Meetings
32nd Meeting: 11-15 May 2020
Subgroup Meetings: 25-27 November 2019
[Register now]
31st Meeting: 24-28 June 2019
30th Meeting: 14-18 May 2018
29th Meeting: 15-19 May 2017

WPEC SG 49

- A key to reproducibility is the possibility of *automatic interpretation* of the experiments.
- Today, many of the r… e, but differ in the co-variance fil…

Tough challenge for the experimentalist but important!

- *Detailed documentation of sources of uncertainties and correlations, as well as correlations between experiments, is essential to produce well-founded co-variances in new evaluations.*
- This information needs also to be available in EXFOR.

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Modern nuclear data evaluation

TALYS-based evaluated nuclear data library

Home | Reference & us | Citations | TALYS

TENDL-2019beta: (release date: end of 2019)

Last update: 19 august 2019

TENDL is a nuclear data library which provides the output of the **TALYS** nuclear model code system for direct use in both basic physics and applications. The 10th version is **TENDL-2019**, which is based on both default and adjusted **TALYS** calculations and data from other sources (previous releases can be found here: 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015), and . 2017).

Up to 2014, TENDL was produced at NRG Petten. Since 2015, TENDL is mainly developped at PSI and the IAEA (Nuclear Data Section). Still, many people contributes to TENDL with the testing and processing of the files.

TENDL contains evaluations for seven types of incident particles, for all isotopes living longer than 1 second (about 2800 isotopes), up to 200 MeV, with covariances.

TENDL is not a default or shadow library. Not a single neutron evaluation is based on default calculations. With the HFR approach, all resonances are unique, following statistical rules. For important isotopes, great care was used in the evaluations.

https://tendl.web.psi.ch/tendl_2019/tendl2019.html

Nuclear Data Sheets 155 (2019) 1-55

TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology

A.J. Koning,[1,2,*] D. Rochman,[3] J.-Ch. Sublet,[1] N. Dzysiuk,[4,5] M. Fleming,[6,7] and S. van der Marck[4]

[1]*Nuclear Data Section, International Atomic Energy Agency, P.O. Box 100, 1400 Vienna, Austria*
[2]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*
[3]*Laboratory for Reactor Physics Systems Behaviour, Paul Scherrer Institut, Villigen, Switzerland*
[4]*NRG, Westerduinweg 3, 1755 LE Petten, Netherlands*
[5]*Taras Shevchenko National University of Kyiv, Kyiv, Ukraine*
[6]*Nuclear Energy Agency, OECD, 92100 Boulogne-Billancourt, France*
[7]*United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*
(Received 3 August 2018; revised received 7 November 2018; accepted 29 November 2018)

The TENDL library is now established as one of the major nuclear data libraries in the world, striving for completeness and quality of nuclear data files for all isotopes, evaluation methods, processing and applied performance. To reach this status, some basic principles have been applied which sets it apart from other libraries: reproducible dedicated evaluations when differential data are available, through determination of nuclear models implemented in TALYS and their parameters, completeness (with or without experimental data), format and processing standardization, automation of production and reproducibility. In this paper, we will outline how such an approach has become a reality, and recall some of the past successes since the first TENDL release in 2008. Next, we will demonstrate the performance of the latest TENDL releases for different application fields, as well as new approaches for uncertainty quantification based on Bayesian inference methods and possible differential and integral adjustments. Also, current limitations of the library performances due to modelling and needs for new and more precise experimental data will be outlined.

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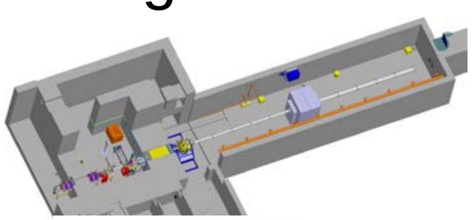
- Where do the **needs** come from?
- How do we **provide** nuclear physics knowledge?
- What is currently going on and what are the **plans** for NFS?

Facilities!

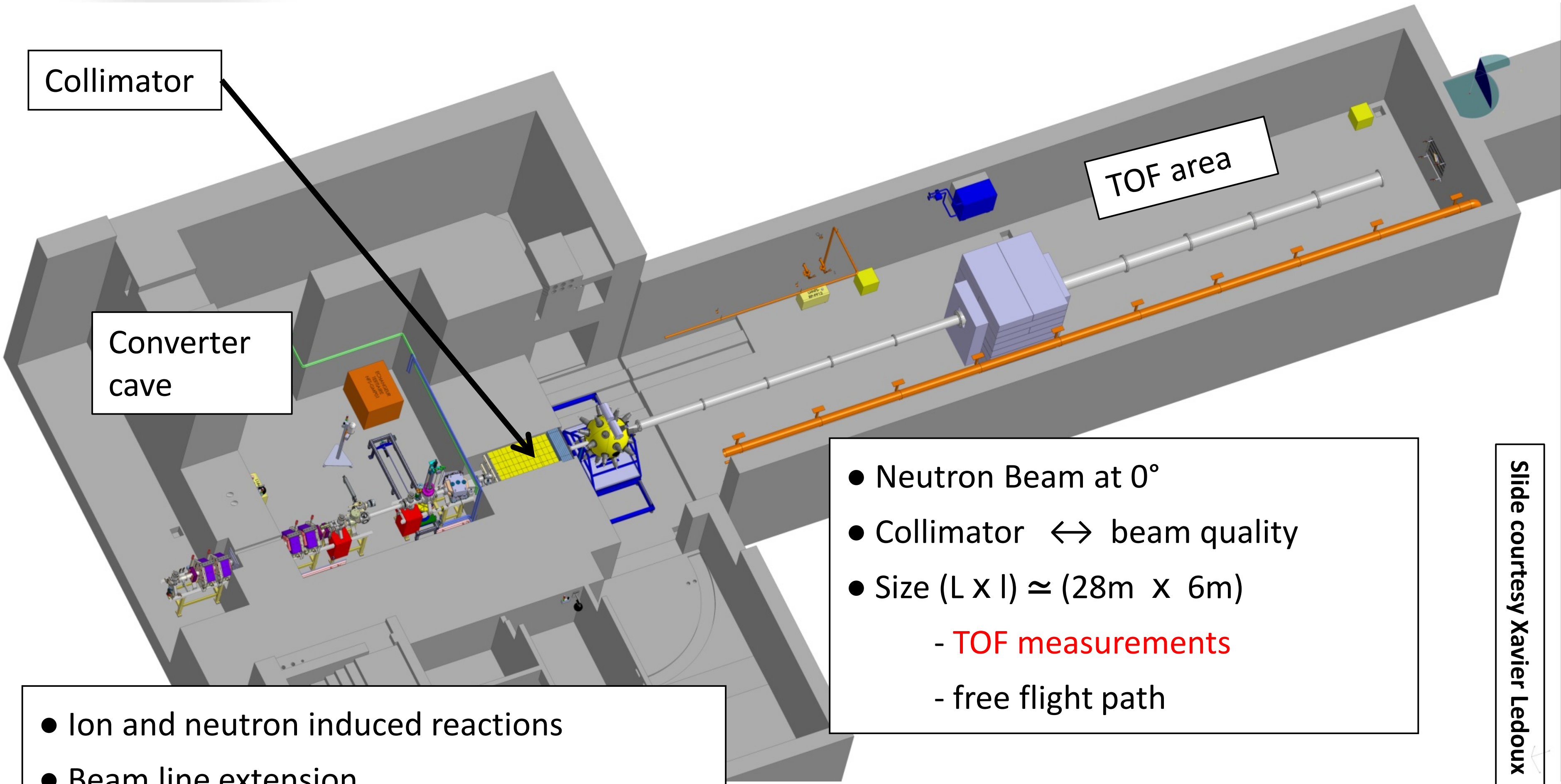
Some background:

- Currently no (!) neutron facility in the Nordic countries; no research reactor, no accelerator, not even a 14 MeV generator (but soon …)

- Few facilities worldwide (QMN over 20 MeV < 5)
- NFS is filling a gap and meets the needs to a large extend
- Flexibility is one of the great assets



NFS layout



- Neutron Beam at 0°
- Collimator ↔ beam quality
- Size (L x l) ≃ (28m x 6m)
  - TOF measurements
  - free flight path

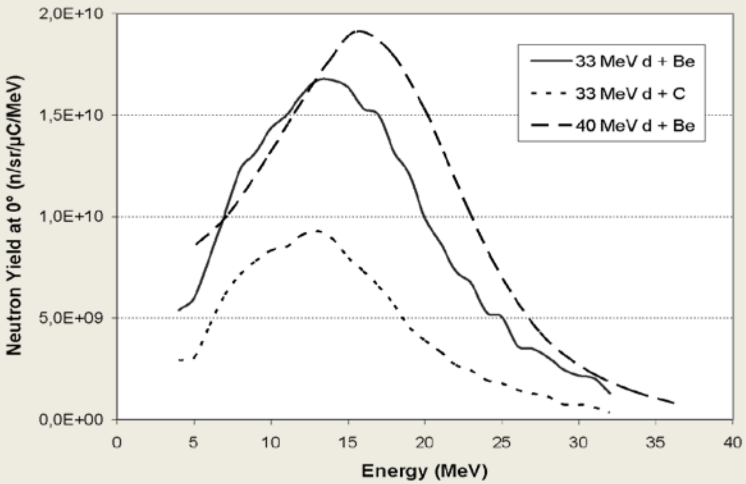
- Ion and neutron induced reactions
- Beam line extension
- Irradiation station (n, p, d)

Slide courtesy Xavier Ledoux

Neutron production at NFS

Continuous spectrum

Deuteron + thick converter (1cm)

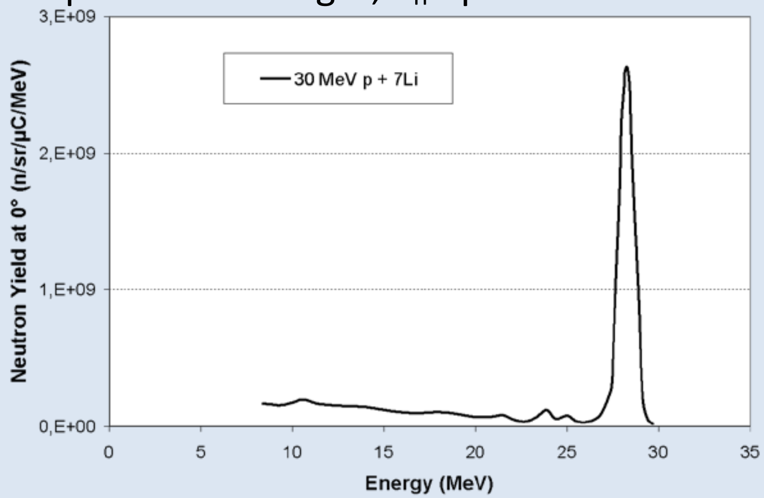


40 MeV d + Be à 50 µA

E MeV	Flux at 5 m
0-40	8.10^7 n/cm^2/s
5	2.10^6 n/cm^2/MeV/s
14	5.10^6 n/cm^2/MeV/s
30	6.10^5 n/cm^2/MeV/s

Quasi-mono-energetic

p + ^{7}Li thin target; E_n up to 31 MeV



p + Li at 20 µA

Li thickness ⇔ Δep=1MeV

E MeV	Flux at 5 m
5	1,7.10^4 n/cm^2/MeV/s
10	5.10^3 n/cm^2/MeV/s
20	2,3.10^4 n/cm^2/MeV/s
30	1,2.10^5 n/cm^2/MeV/s

Slide courtesy Xavier Ledoux

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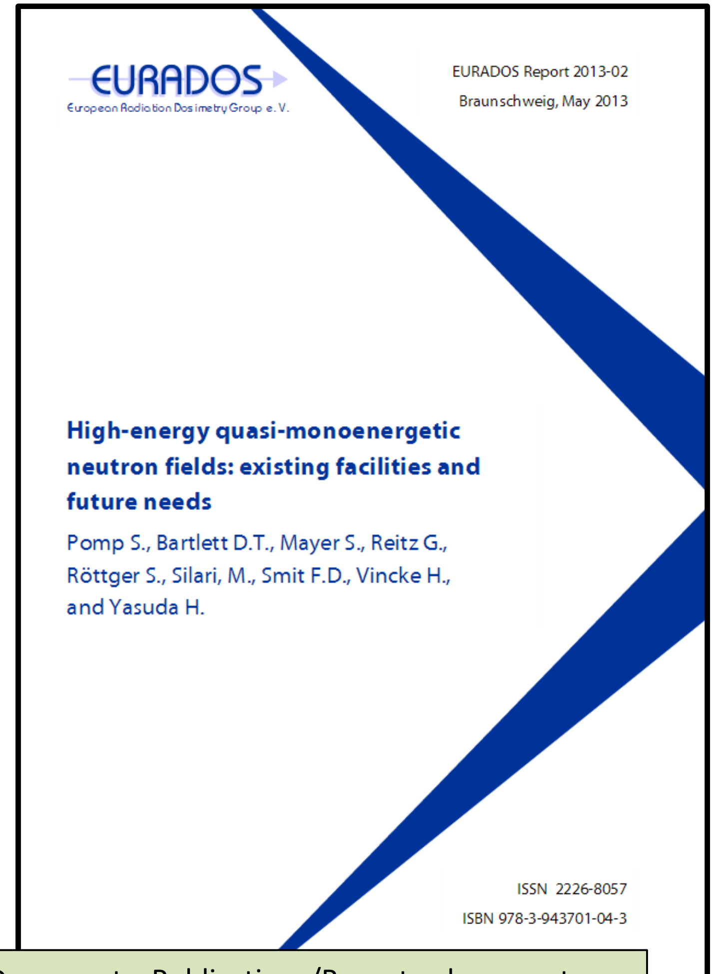
NFS is …

… one of a few QMN facilities …

Facility	Energy range [MeV]	Peak neutron fluence rate at standard irradiation position [$cm^{-2}s^{-1}$]	Beam angle relative to primary beam	Remarks
iThemba[a]	35 – 200	10^4	0°, 4°, 8°, 12°, 16°	
~~TSL[b]~~	11 – 175	10^6 for E_p < 100 MeV 10^5 for E_p > 100 MeV	0°	large experimental area
TIARA[c]	40-90	10^4	0°	large irradiation room
CYRIC[d]	20-90	10^6	0°	
RCNP[e]	100 - 400	10^5	0° - 30°	up to 100 m ToF
NPI[f]	18 – 36	Up to 10^9	0°	Standard irradiation very close to source
NFS[g]	20 – 33	n.a. yet	0°	Start late 2014

Rad. Prot. Dosim. 161 (2014) 62-66.


EURADOS
European Radiation Dosimetry Group e. V.

EURADOS Report 2013-02
Braunschweig, May 2013

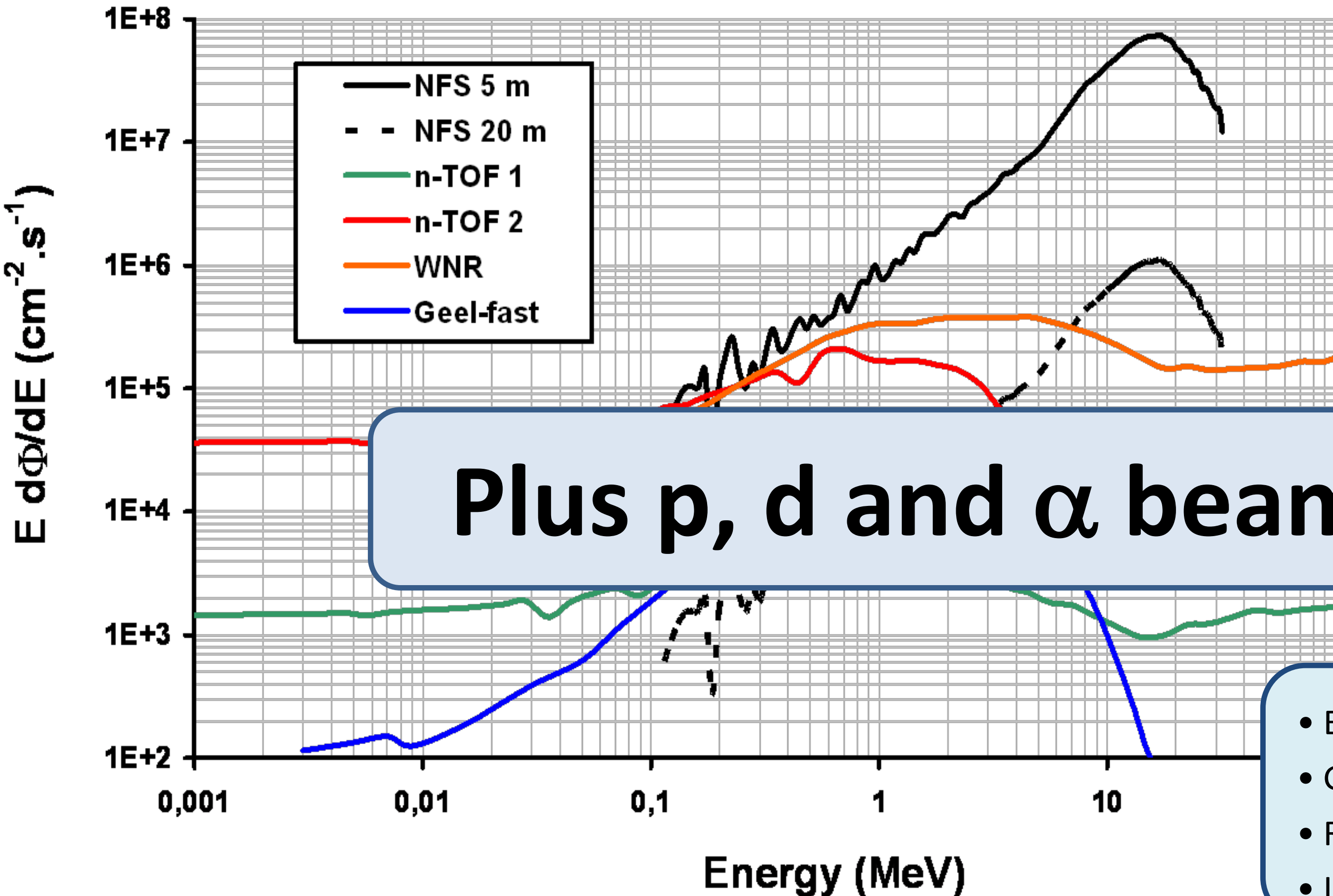
High-energy quasi-monoenergetic neutron fields: existing facilities and future needs

Pomp S., Bartlett D.T., Mayer S., Reitz G., Röttger S., Silari, M., Smit F.D., Vincke H., and Yasuda H.

ISSN 2226-8057
ISBN 978-3-943701-04-3

http://www.eurados.org/en/Documents_Publications/Reports_documents

… and a complement to other white neutron beams



Plus p, d and α beams!

NFS : 40 MeV d + Be

WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

: Geel

Slide courtesy Xavier Ledoux

- E_n: from 0,1 MeV to 40 MeV
- Good energy resolution
- Reduced γ flash
- Low instantaneous flux

Complementary to the existing facilities

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Rich experimental program at NFS

Connection to Euratom via the H2020 projects SANDA and ARIEL

Fission stuc
σ, FY, $\overline{\nu}$(A), PFN

-induced reaction studies
(n), (n,lcp), …

Astrophysics

Materials

Dosimetry

Model development

Charged-particle induced reactions
σ(E), …

Medicine

Biology

Detector development

Rich experimental program at NFS

Fission studies
σ, FY, $\overline{\nu}$(A), PFN, PFG, …

Energy

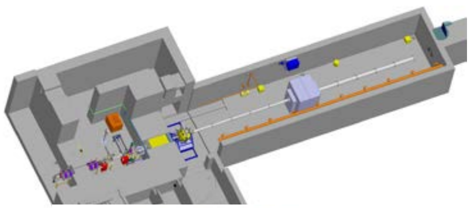
Neutron-induced reaction studies
(n,xn), (n,lcp), …

Astrophysics

Materials

Dosimetry

Charged-particle induced reactions
σ(E), …



Medicine

Detector development

Biology

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LoI and proposals for Day 1 exp.

- Neutron induced reactions studies :
  - LoI_13 : Study of pre-equilibrium process in (n,xn) reaction, *X. Ledoux*
  - LoI_14 : Comparison between activation and prompt spectroscopy as means of (n,xn) cross section measurements, *M. Kerveno*
  - LoI_20 : Direct measurement of (n,xn) reaction cross sections on ^{239}Pu, *G. Bélier*
  - LoI_21 : Light-ion production studies with Medley, *S. Pomp*
  - SCALP - Scintillating ionization Chamber for ALpha particle Production in neutron induced reaction, G. Lehaut
- Fission :
  - LoI_15 : Fission fragment distributions and neutron multiplicities, D. Doré
  - LoI_22 : Fission fragment angular distribution and fission cross section measurements relative to elastic np scattering with Medley, S. Pomp
  - LoI_28 : Study of the fission process and fission cross-section measurements, G. Bélier
  - Measurements of prompt fission neutron energy spectra for fast neutron induced fission on major and minor actinides, A. Sardet
  - Measurement of prompt fission gamma-ray spectra in fast neutron induced-fission of actinides, J.M. Laborie
  - Gamma-rays spectroscopy and lifetime measurements at NFS, A. Dijon
- Cross-section reaction measurements by activation technique :
  - LoI_16 : Proton and deuteron induced activation reactions, *P. Bem*
  - LoI_24 : Neutron-induced activations reactions, A. Klix
  - Measurement of cross-sections of deuteron-induced reactions on Ni and Zn, J. Grinyer
- Biology :
  - LoI_23 : Response of Mammalian cells to neutron exposure, *C. Hellweg*
  - R&D for the production of radioisotopes for medical applications at NFS, G. De France
  - Investigation of 211At and 64Cu medical radioisotope production at NFS, J. Grinyer
- Detector development :
  - LoI_29 : Neutron spectrometer characterization for LMJ project, *B. Rossé*
  - Characterization of neutron signal in Si-CsI telescope and measurement of the absolute neutron detection efficiency, E. Bonnet

Slide courtesy Xavier Ledoux

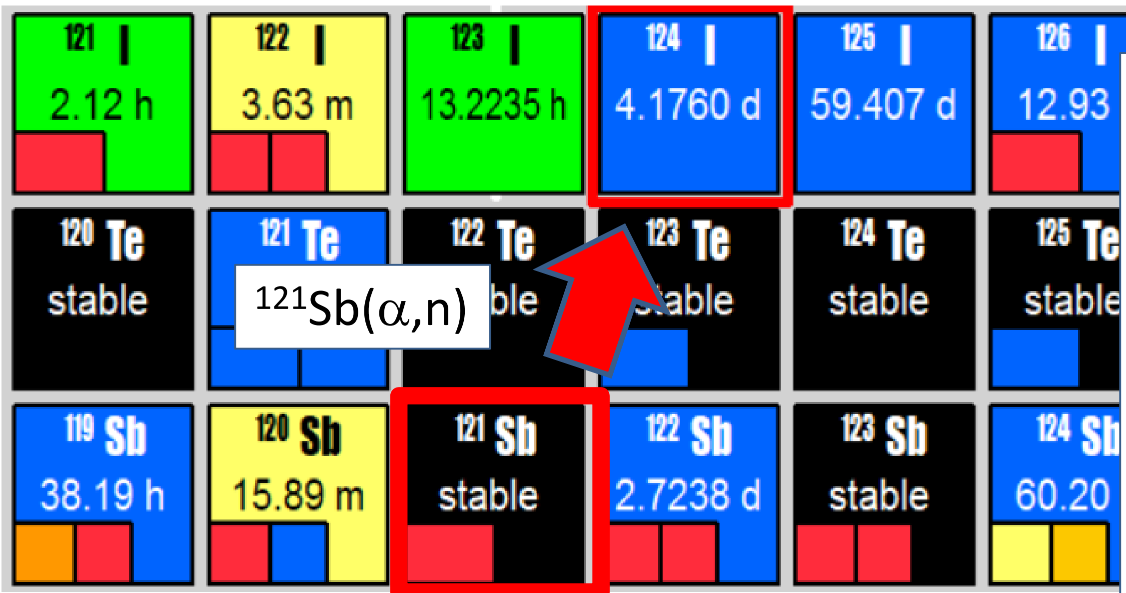
10 submitted proposal:
7 accepted in this first round

	NUM	Title	Spokesperson
Reaction model	E712	Measurement of (n,xn) reaction cross sections on U238	G. Bélier, CEA-DAM
	E721	LIONS - Light-Ion Production Studies with Medley at the NFS facility	A.V. Prokofiev, Uppsala University
Fission	E713	Prompt fission neutron spectra measurement in neutron induced fission reactions	B. Laurent, CEA-DAM
	E718	Fission fragment angular distribution and fission cross section measurements relative to elastic NP scattering at 30 MeV	D. Tarrio, Uppsala University
Fusion		Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez
	E715	Neutron-induced activation reactions	A. Klix, KIT
Radionuclei for medical applications		Alpha-induced reaction cross-section measurements on natural and enriched Zn	J. Grinyer, GANIL
	E717	Measurements of the excitation function for the production of possible candidates for targeted alpha therapy at SPIRAL2	G. de France, GANIL
Astrophysic	E719	Precise direct measurements of the $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ reaction rates to understand the origin of presolar nova grains	B. Bastin, GANIL
Instrumentation	E720	Measurement of the absolute neutron detection efficiency of FAZIA telescopes	E. Bonnet, GANIL

Slide courtesy Xavier Ledoux

α-induced radioisotope production (case of ^{124}I)

- Better to use (α,x) on Sb than (p,x) on Te? (impurities)



Use:
PET and RIT.
Benefit:
Lower dose, better image res.

Study cross section of
α-induced reactions
on enriched Sb targets.
E_{α} = 10-60 MeV
(X. Ledoux et al.)

α-induced radioisotope production (case of ^{68}Ge for ^{68}Ga)

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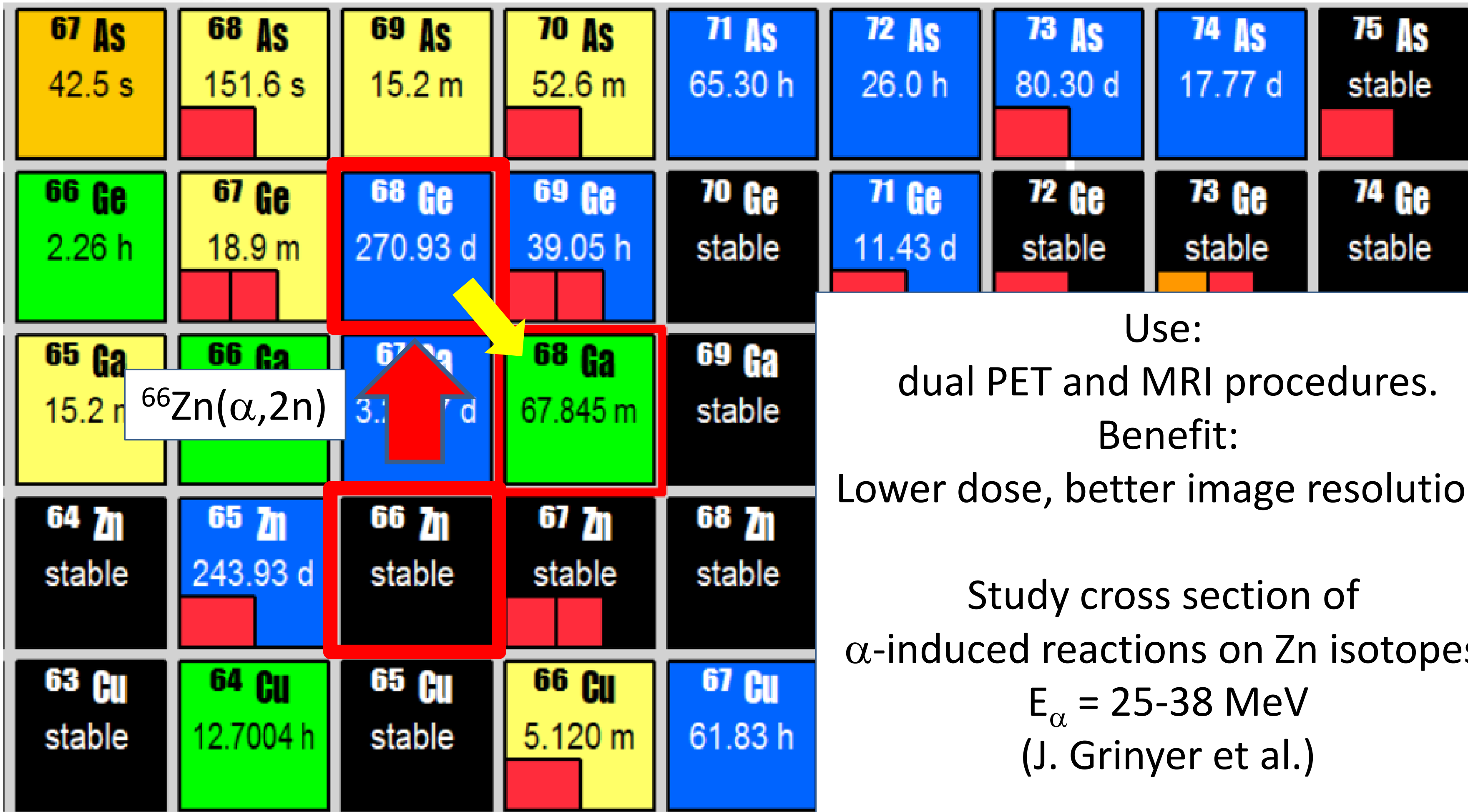

Use:
dual PET and MRI procedures.
Benefit:
Lower dose, better image resolution.

Study cross section of
α-induced reactions on Zn isotopes.
E_{α} = 25-38 MeV
(J. Grinyer et al.)

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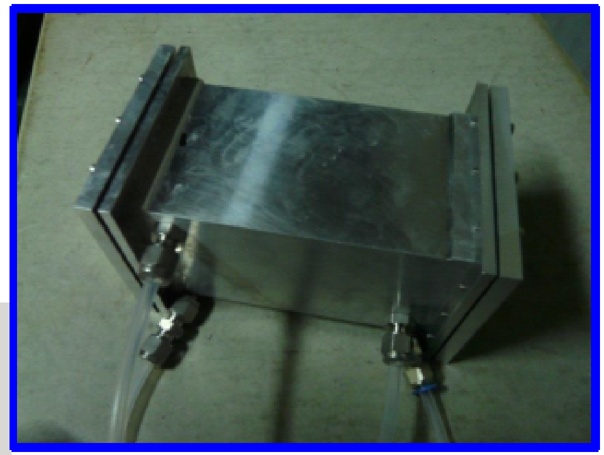
SCONE – (n,xn) vs fission

(one of several proposed n,xn exp.)

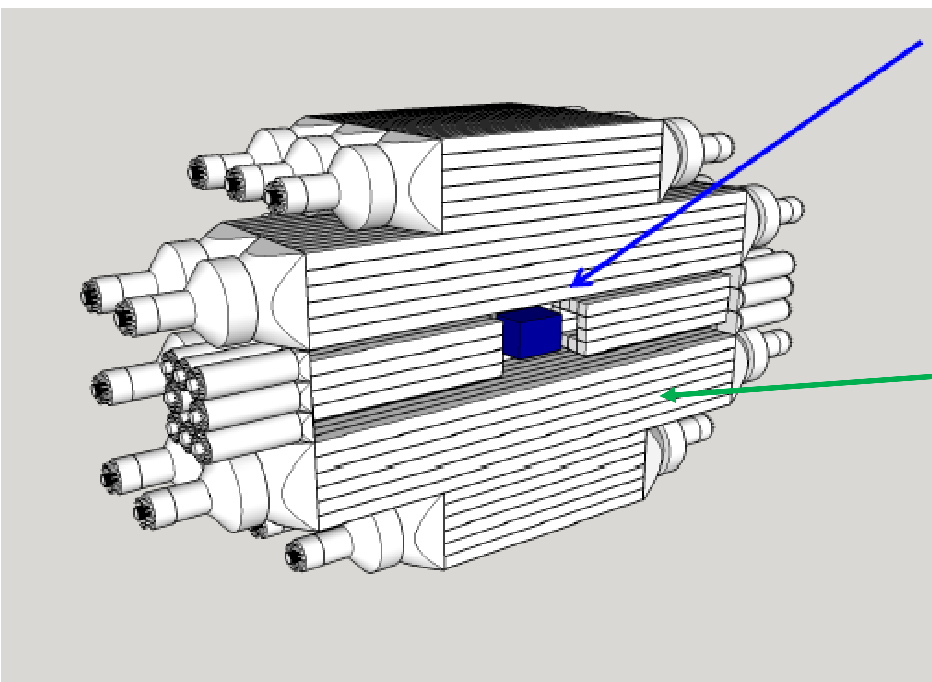
Multiplate fission chamber: **360 mg of ^{238}U** →

72 deposits, CF_4 gas, homemade dedicated preamps

→ Fission veto



SCONE (Solid COunter for NEutron)



Gd-loaded scintillators.
Require time-correlation to supress bgr.

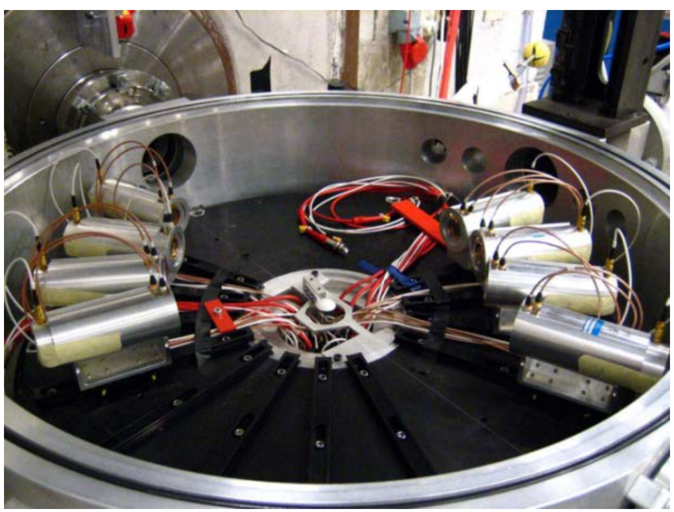
Range: 6 MeV < E_n < 20 MeV
Targets: ^{238}U, plan for ^{239}Pu

Slide adapted from Gibert Belier

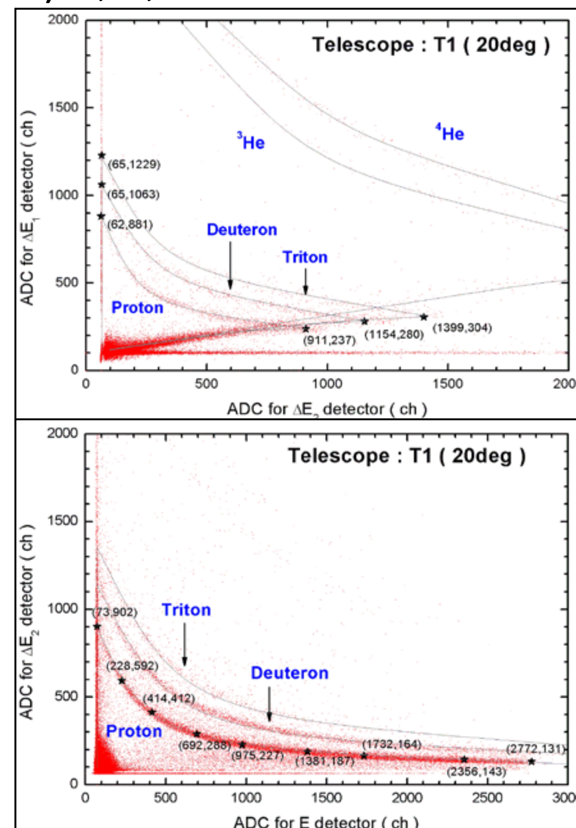
Medley – Light-ion production …

E721

- Cancer therapy and dosimetry (H, C, O, Ca, ...)
- Radiation effects in microelectronics (*SEU; single event upsets*) Si, O, ... **Silicon** and **oxygen** data is needed for:
- Energy applications (GenIV, fusion)
  - Construction material: Fe, Cr, …
  - Fuel: U, Th, …
  - Coolant: Pb, Bi, Na, …
  - ^{16}O(n,α) affects reactor reactivity, 25% of the helium production



Medley
Evacuated chamber
ΔE-ΔE-E technique + angles
⇒ double differential xs



Tippawan et al., Phys. Rev. C ***79****, 064611 (2009).*

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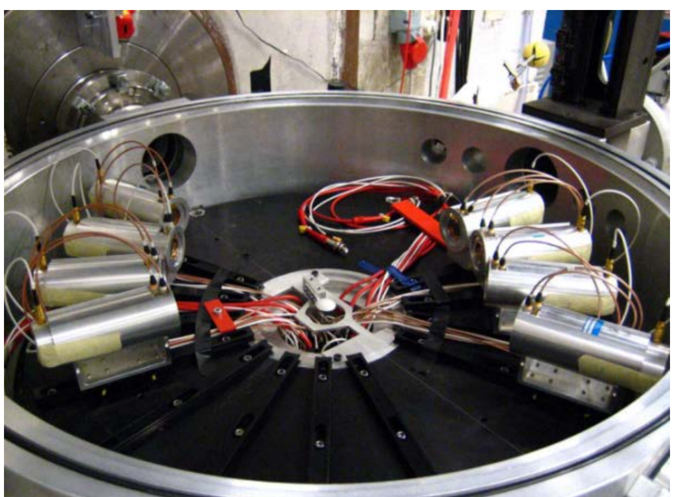
Medley – Light-ion production …

E721

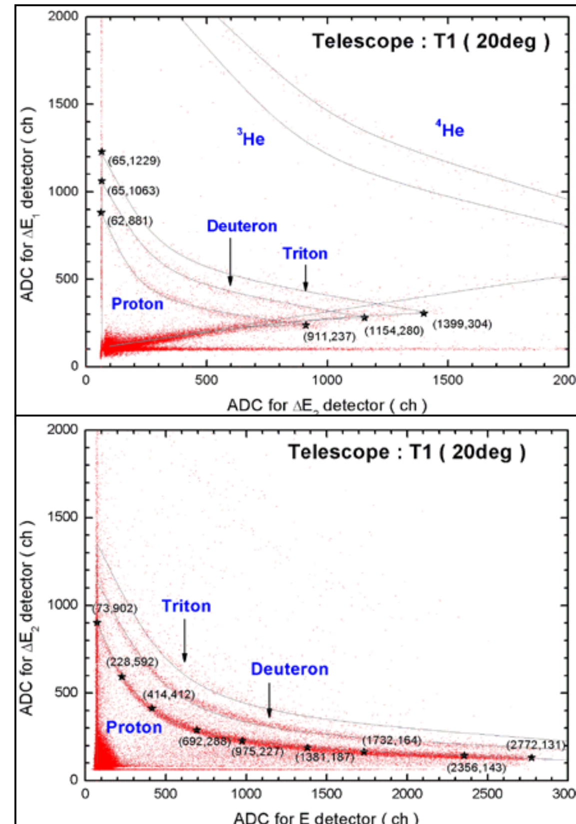
- Cancer therapy and dosimetry (H, C, O, Ca, ...)
- …ets) Si, O, ... **Silicon** and

Study DDX for $^{nat}C(n,lcp)$ in the 10 to 30 MeV range;

Improve theoretical understanding of competition of different reaction mechanisms (multi particle, pre-equilibrium)



Medley
Evacuated chamber
ΔE-ΔE-E technique + angles
⇒ double differential xs



Tippawan et al., Phys. Rev. C ***79****, 064611 (2009).*

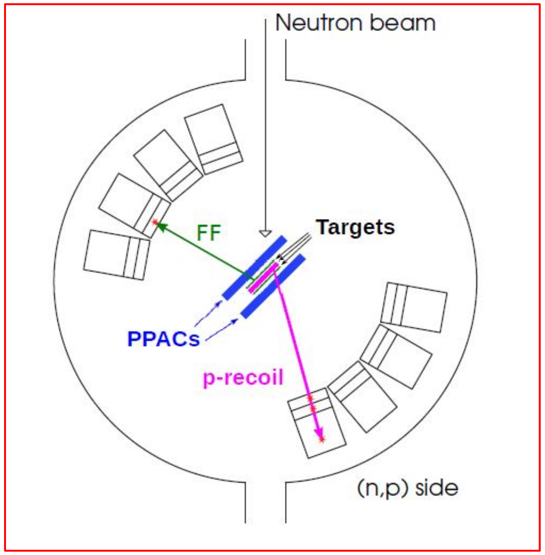
… neutron spectra and standards

Add PPACs, and a target arrangement of

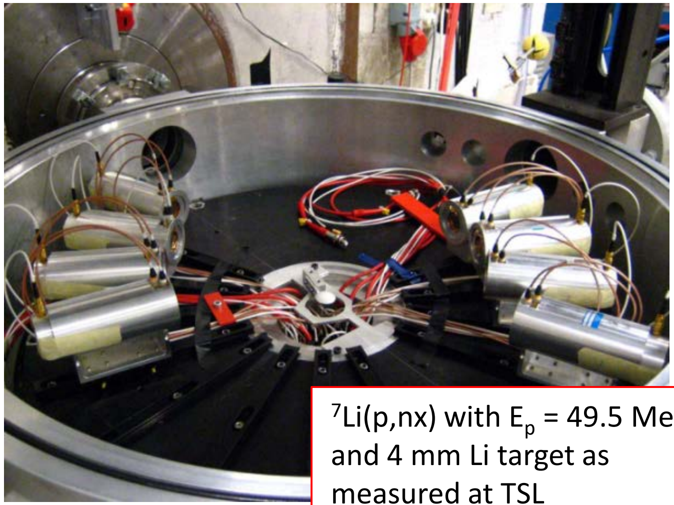
$^{235}U – CH_2 – ^{238}U$

for simultaneous measurement of neutron standards vs primary H(n,n) standard with minimal syst. uncert.

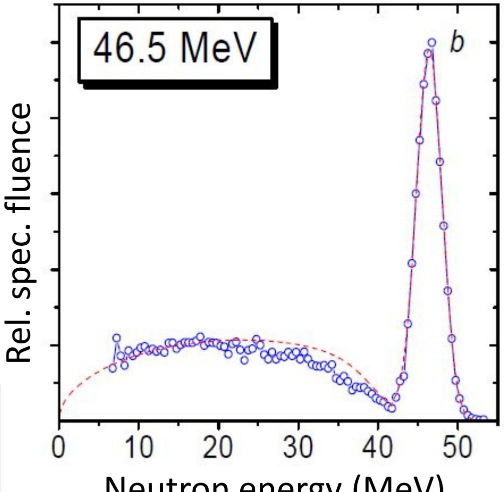
(+ “for free”: FFAD)



Jansson et al., NIM A 794 (2015) 141, and Tarrío et al., submitted to ND2016.



^{7}Li(p,nx) with E_p = 49.5 MeV and 4 mm Li target as measured at TSL



Review on standards: A. Carlsson et al., Nuclear Data Sheets 148 (2018) 143-188.

FALSTAFF

Four arm cLover for the Study of Actinide Fission Fragments

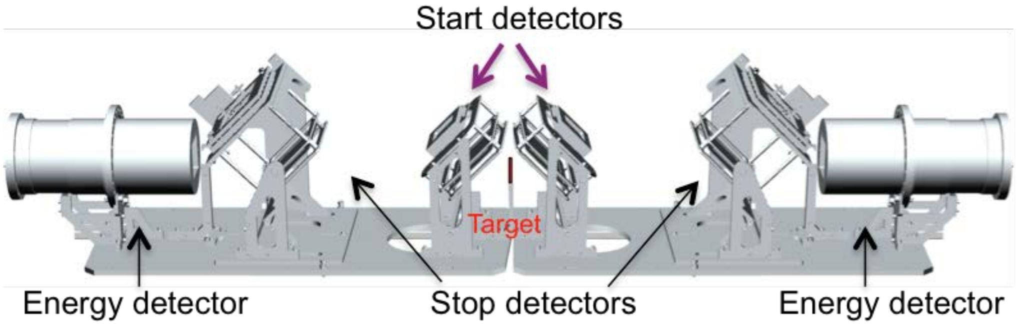
- Spectrometer for fission fragment detection in coincidence
  - Kinetic energy
  - Masses BEFORE and AFTER evaporation (-> $\overline{\nu}$(A))
  - Charge

More in the next talk!

- Mass **before** evaporation → 2V method
  TOF : *Good time resolution (σ) <150 ps*

- Mass **after** evaporation → EV method
  Energy & TOF
  - *Good energy resolution (~1%)*
  - *Charge identification (dE profile)*

- ***Large solid angle (~1% of 4π)***
- ***Good position resolution (1.2 mm)***

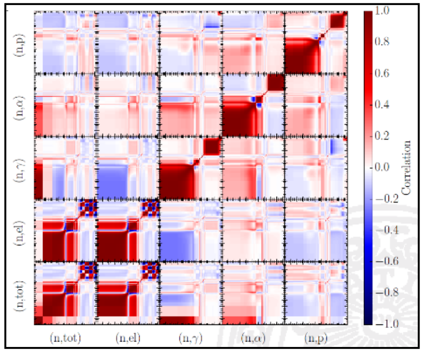


Slide courtesy Diane Doré

I hope …

… I could convince you

- that the field of nuclear data research is important,
- that NFS offers rich possibilities,
- and that there is much work ahead for **experimentalists and theorists** to provide modern, high-quality nuclear data for use in science and technology!



Thanks!

And thanks to

Maëlle Kerveno,
Xavier Ledoux,
Henrik Sjöstrand,
Alexander Prokofiev,
and the NFS collaboration!

50+ physicists from 16 labs …

… are eagerly waiting for first beam and running experiments at NFS!

CEA/DAM/DIF, F-91297, Arpajon, France
CEA/DSM/IRFU/SPhN, Saclay, France
CENBG, Gradignan, France
LPC, Caen, France
IPHC, Strasbourg, France
NPI, Řež, Czech Republic
Uppsala University, Uppsala, Sweden
KIT, Karlsruhe, Germany
GANIL, Caen, France
NIPNE, Bucharest, Romania
JRC/IRMM, Geel, Belgium
CEA/DEN, Cadarache, France
IPNO, Orsay, France
CIMAP, Caen, France
Culham Centre for Fusion Energy, United Kingdom
ELI-NP, Bucharest-Magurele, Romania