DE LA RECHERCHE À L'INDUSTRIE

RECENT DEVELOPMENTS IN NUCLEAR PHYSICS TOOLS AND TECHNIQUES APPLIED TO NUCLEAR ENERGY

SYLVIE LERAY

CEA/SACLAY, IRFU

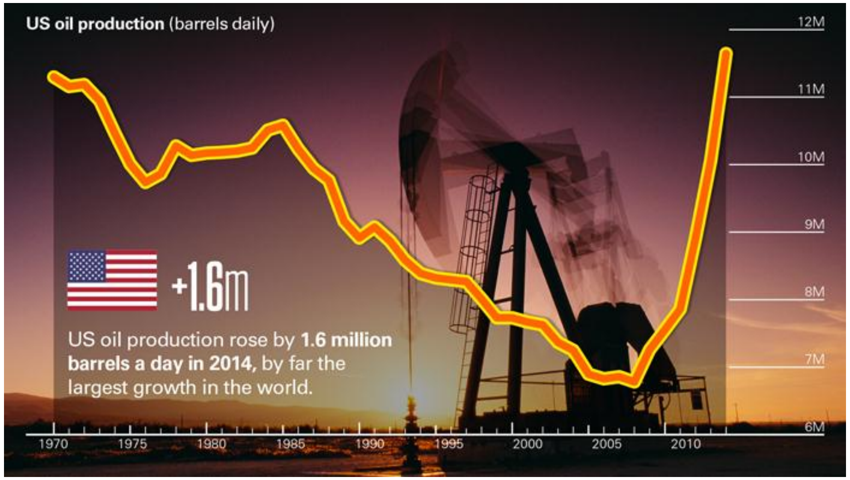
www.cea.fr

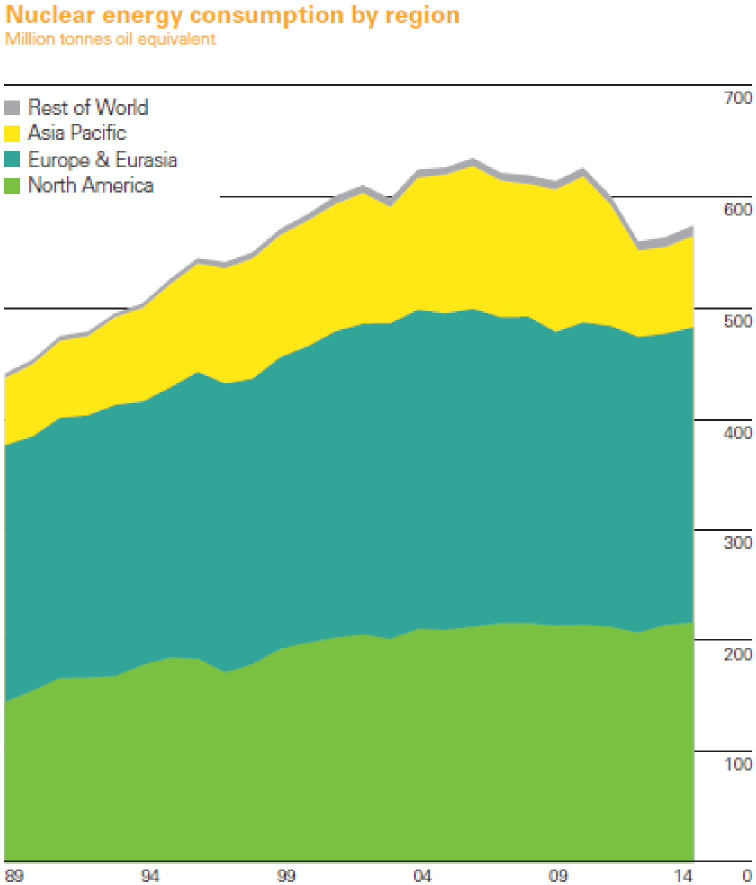
NN2015

12th INTERNATIONAL CONFERENCE ON NUCLEUS-NUCLEUS COLLISIONS

June 21-26, 2015, Catania, Italy

- The growth expected ten years ago has not happened:
  - Fukushima accident
  - Shale oil “revolution”

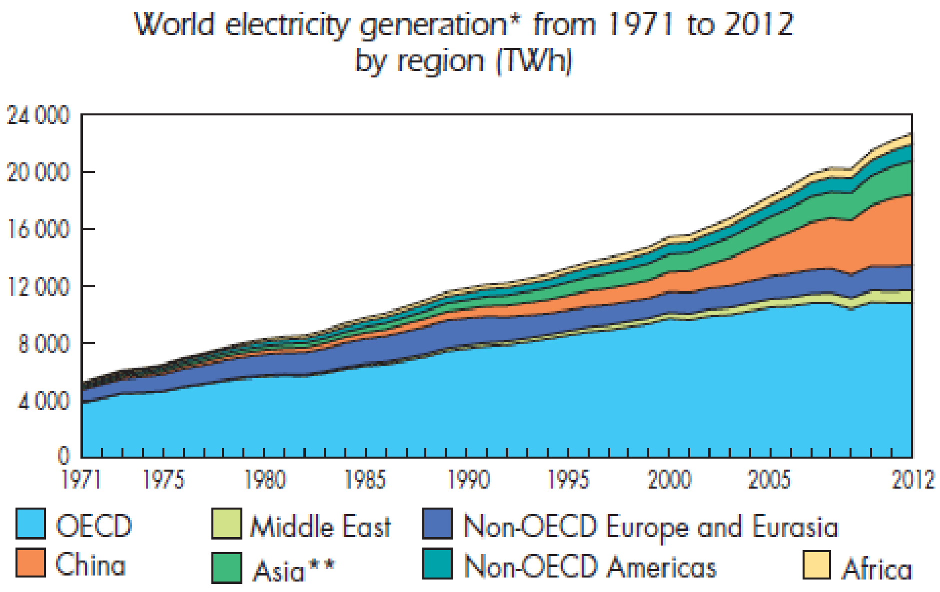




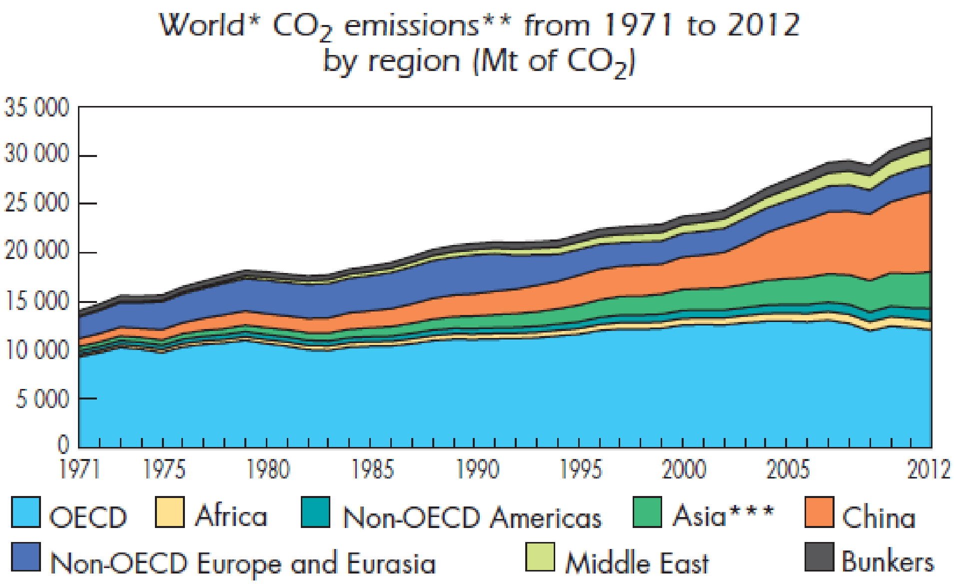
Source: BP statistical review of world energy 2015

- Increase in energy demand
- Increase of CO_2 emissions

Electricity



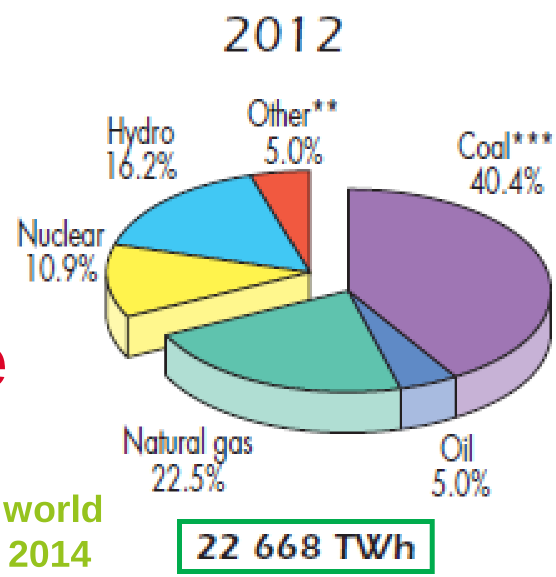
CO_2 emissions



Source: IEA Key world energy statistics 2014

NUCLEAR ENERGY

- **Mitigating CO_2 increase: no miracle solution but combination of**
  - **energy saving and increase of energetic efficiency but limited and counterbalanced by increase in developing countries**
  - **renewable energies but intermittent and expensive**
  - **nuclear energy but fear of accident and question of waste**



Source: IEA Key world energy statistics 2014

DE LA RECHERCHE À L'INDUSTRIE

NUCLEAR ENERGY

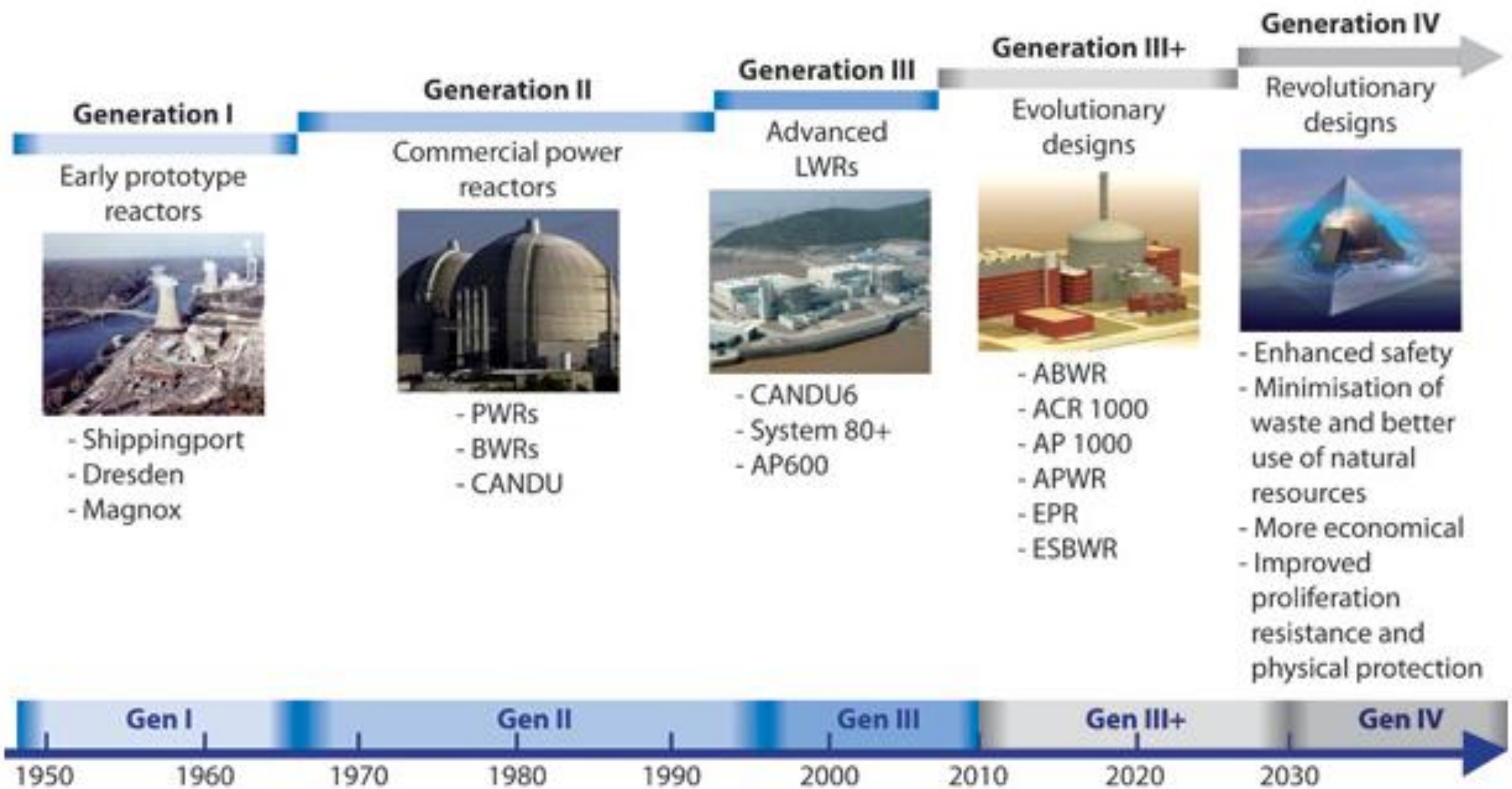
- 65 reactors in construction
  - of which 23 in China, 9 in Russia, 6 in India
- 165 reactors planned
  - of which 45 in China, 31 in Russia, 22 in India

COUNTRY	NUCLEAR ELECTRICITY GENERATION 2014		REACTORS OPERABLE Apr 2015		REACTORS UNDER CONSTRUCTION Apr 2015		REACTORS PLANNED Apr 2015		REACTORS PROPOSED Apr 2015	
	billion kWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Argentina	5.3	4.0	3	1627	1	27	0	0	3	1600
Armenia	2.3	30.7	1	376	0	0	1	1060		
Bangladesh	0	0	0	0	0	0	2	2400	0	0
Belarus	0	0	0	0	2	2400	0	0	2	2400
Belgium	32.1	47.5	7	5943	0	0	0	0	0	0
Brazil	14.5	2.9	2	1901	1	1405	0	0	4	4000
Bulgaria	15.0	31.8	2	1906	0	0	1	950	0	0
Canada	98.6	16.8	19	13553	0	0	2	1500	3	3800
Chile	0	0	0	0	0	0	0	0	4	4400
China	123.8	2.4	26	23144	23	25163	45	52200	127	150000
Czech Republic	28.6	35.8	6	3766	0	0	2	2400	1	1200
Egypt	0	0	0	0	0	0	2	2400	2	2400
Finland	22.6	34.6	4	2741	1	1700	1	1200	1	1500
France	418.0	76.9	58	63130	1	1720	1	1720	1	1100
Germany	91.8	15.8	9	12003	0	0	0	0	0	0
Hungary	14.8	53.6	4	1889	0	0	2	2400	0	0
India	33.2	3.5	21	5302	6	4300	22	21300	35	40000
Indonesia	0	0	0	0	0	0	1	30	4	4000
Iran	3.7	1.5	1	915	0	0	2	2000	7	6300
Israel	0	0	0	0	0	0	0	0	1	1200
Italy	0	0	0	0	0	0	0	0	0	0
Japan	0	0	43	40480	3	3036	9	12947	3	4145
Jordan	0	0	0	0	0	0	2	2000		
Kazakhstan	0	0	0	0	0	0	2	600	2	600
Korea DPR (North)	0	0	0	0	0	0	0	0	1	950
Korea RO (South)	149.2	30.4	24	21657	4	5600	8	11600	0	0
Lithuania	0	0	0	0	0	0	1	1350	0	0
Malaysia	0	0	0	0	0	0	0	0	2	2000
Mexico	9.3	5.6	2	1600	0	0	0	0	2	2000
Netherlands	3.9	4.0	1	485	0	0	0	0	1	1000
Pakistan	4.6	4.3	3	725	2	680	0	0	2	2000
Poland	0	0	0	0	0	0	6	6000	0	0
Romania	10.8	18.5	2	1310	0	0	2	1440	1	655
Russia	169.1	18.6	34	25264	9	7968	31	32780	18	16000
Saudi Arabia	0	0	0	0	0	0	0	0	16	17000
Slovakia	14.4	56.8	4	1816	2	942	0	0	1	1200
Slovenia	6.1	37.2	1	696	0	0	0	0	1	1000
South Africa	14.8	6.2	2	1830	0	0	0	0	8	9600
Spain	54.9	20.4	7	7002	0	0	0	0	0	0
Sweden	62.3	41.5	10	9487	0	0	0	0	0	0
Switzerland	26.5	37.9	5	3333	0	0	0	0	3	4000
Thailand	0	0	0	0	0	0	0	0	5	5000
Turkey	0	0	0	0	0	0	4	4800	4	4500
Ukraine	83.1	49.4	15	13168	0	0	2	1900	11	12000
UAE	0	0	0	0	3	4200	1	1400	10	14400
United Kingdom	57.9	17.2	16	10038	0	0	4	6680	7	8920
USA	798.6	19.5	99	98756	5	6018	5	6063	17	26000
Vietnam	0	0	0	0	0	0	4	4800	6	6700
WORLD**	2,411	c 11	437	380,77	65	67,859	165	185,92	316	363,57
	billion kWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe
	NUCLEAR ELECTRICITY GENERATION		REACTORS OPERABLE		REACTORS UNDER CONSTRUCTION		ON ORDER or PLANNED		PROPOSED	

Source: World Nuclear Association (May 2015)

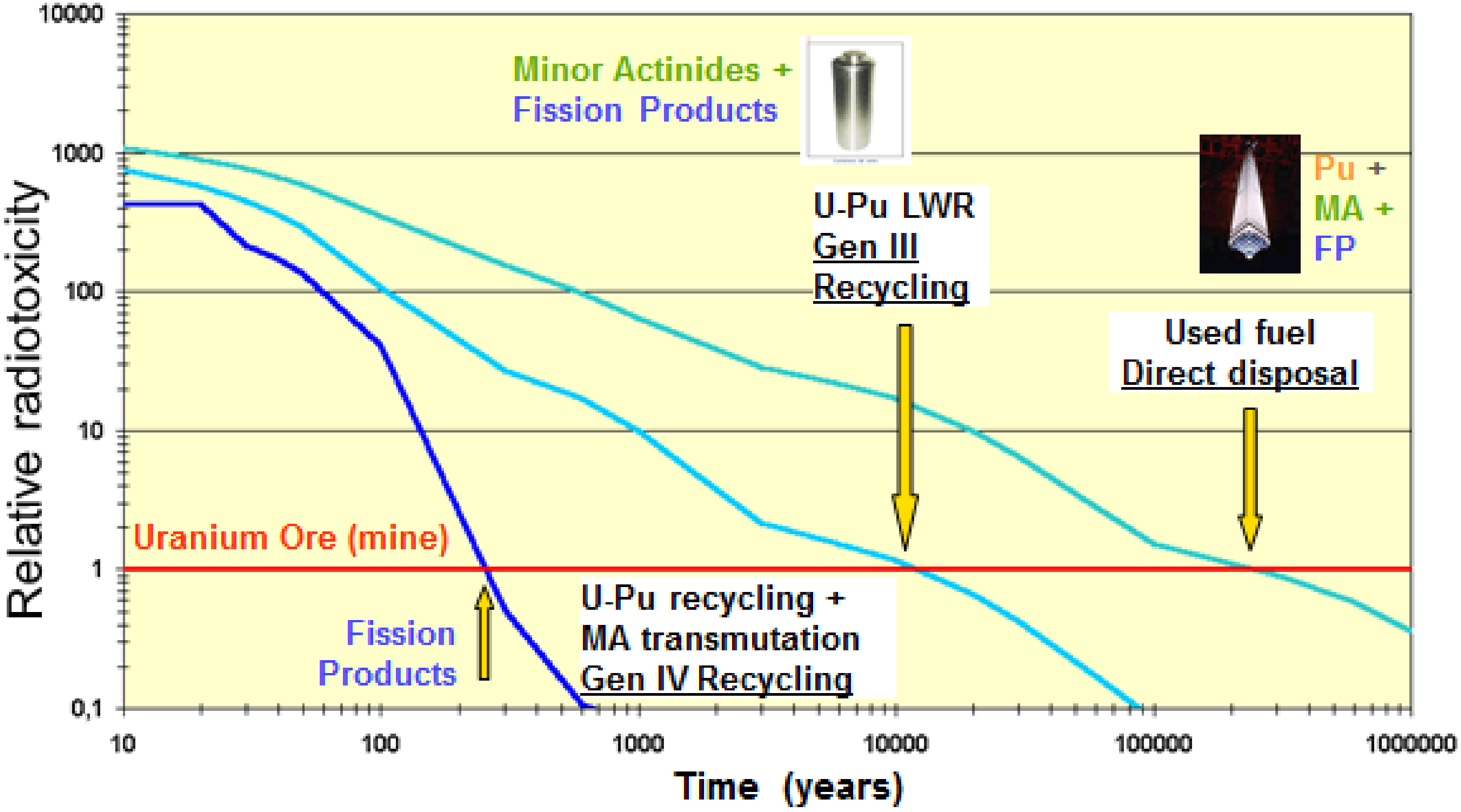
NUCLEAR ENERGY

- **Nuclear energy will develop only if confidence is restored, waste question is settled, it is economically competitive, question of long term resources in uranium is adressed**



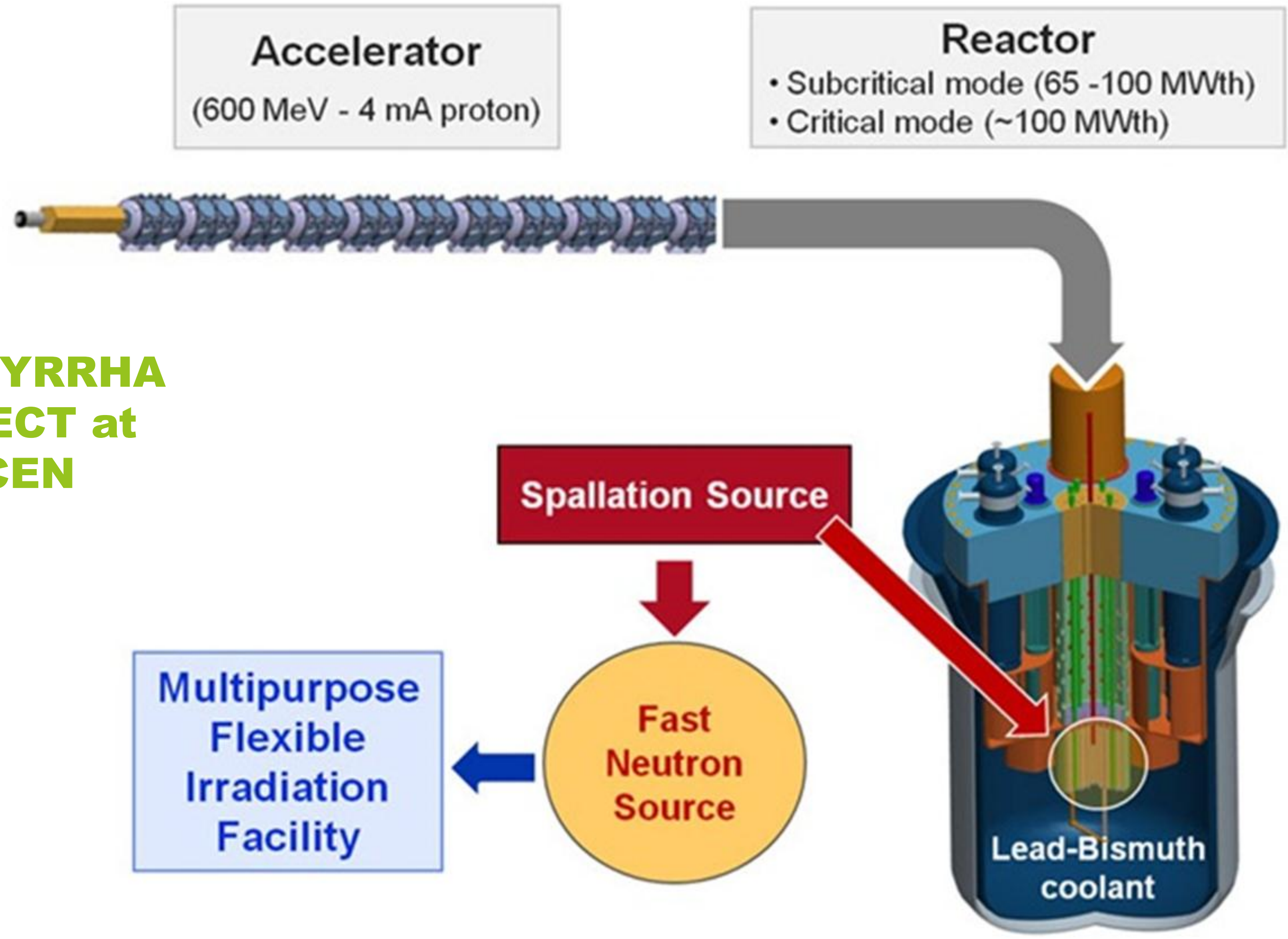
Source: Nuclear Energy Today © OECD/Nuclear Energy Agency 2012

Radiotoxicity of UOX spent fuel relative to uranium ore, versus time (years)



ADS AS A POSSIBLE CONTRIBUTOR TO WASTE MINIMISATION

The MYRRHA PROJECT at SCK•CEN



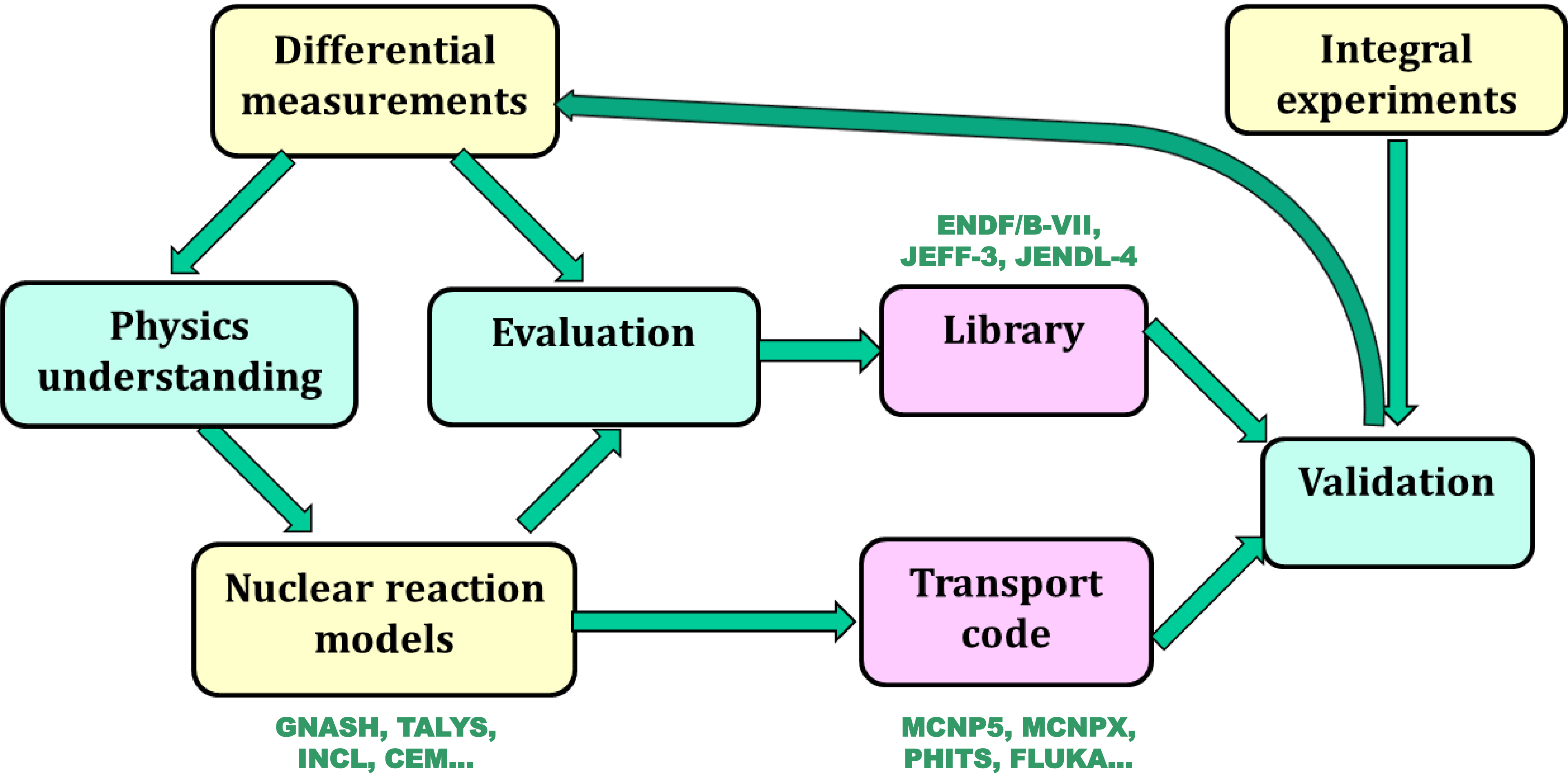
NUCLEAR DATA NEEDS

NUCLEAR DATA NEEDS

- **Existing, Gen-III reactors**
  - *Optimization of fuel burn-up*
  - *Increase of life time*
  - *Safety margin reduction: decay heat, delayed n fraction*
  - *Waste disposal*
- **Fast reactors (Gen-IV)**
  - *New fuel, cladding, coolant materials*
  - *Minor actinide transmutation*
- **ADS**
  - *Spallation target radioactive inventory*
  - *Material damage*

- **cross-sections**
  - *capture*
  - *fission*
  - *inelastic, (n,2n)*
- **multiplicities**
  - *prompt and delayed neutrons*
  - *delayed gammas*
- **characteristics of reaction products**
  - *Energy and angular distributions*
  - *fission fragments*
  - *spallation residues*

NUCLEAR DATA NEEDS



FP7 EURATOM 2013: CHANDA PROJECT

EU funding 5.4 M€

1/12/2013 – 30/11/2017

CIEMAT, ANSALDO, CCFE, CEA, CERN, CNRS, CSIC, ENEA, GANIL, HZDR, IFIN-HH, INFN, IST-ID, JRC, JSI, JYU, KFKI, NNL, NPI, NPL, NRG, NTUA, PSI, PTB, SCK, TUW, UB, UFrank, UMainz, UMan, UPC, UPM, USC, UU, UOslo.

Follow-up of the ANDES project (2010-2013)

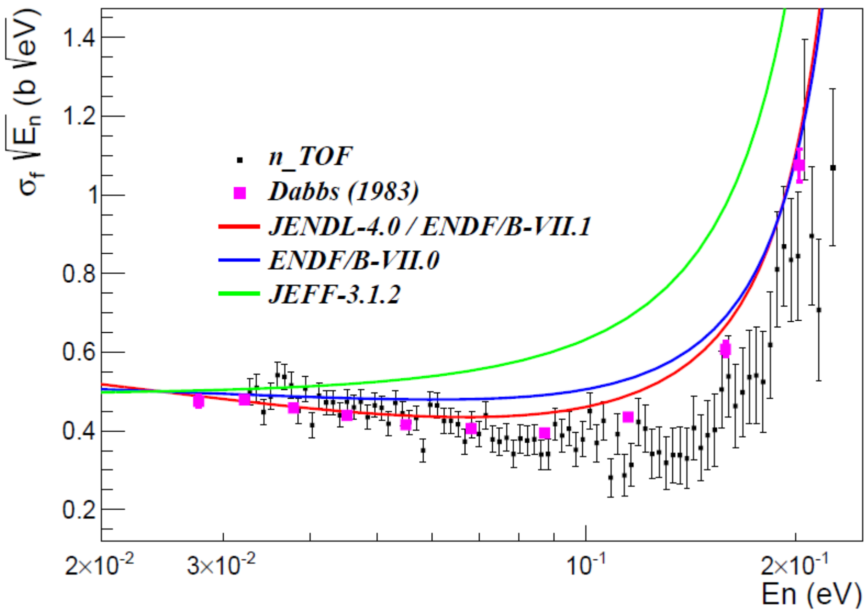
EURATOM FP7 PROJECT CHANDA

solving CHAlenge in Nuclear DAta

- access to the available EU nuclear data facilities
- upgrade of neutron facilities (nTOF and NFS) in order to allow measurements on short lived and rare materials
- support to radioactive target fabrication laboratories
- **developing new methodologies and capabilities in performing measurements, evaluation and validation of nuclear data and models**

nTOF CERN: Fission cross sections

^{241}Am(n,f) cross section

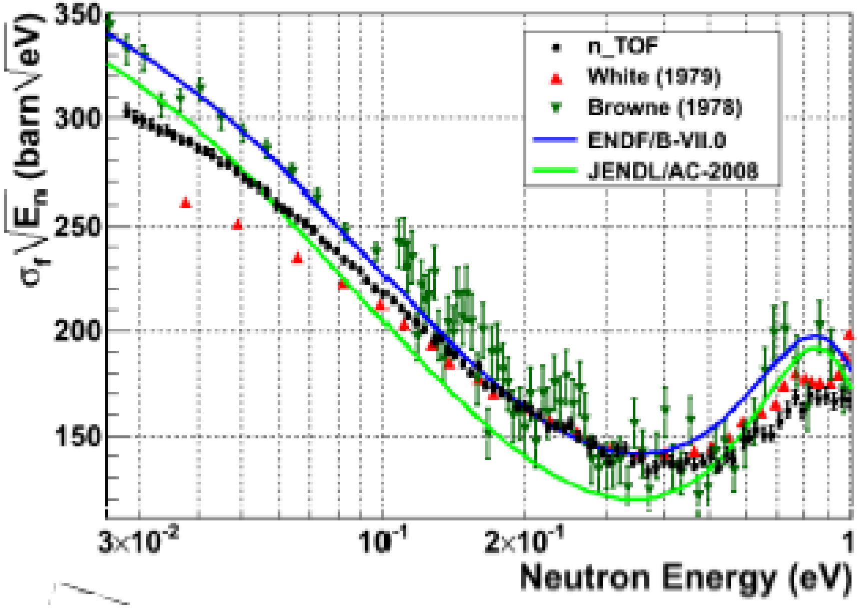


↪ major revision from JEFF-3.1 to JEFF-3.2

From N. Colonna, CHANDA Meeting April 2015

M. Mastromarco et al., in preparation

The ^{245}Cm(n,f) cross-sections



↪ Very few data with large discrepancies before nTOF measurement

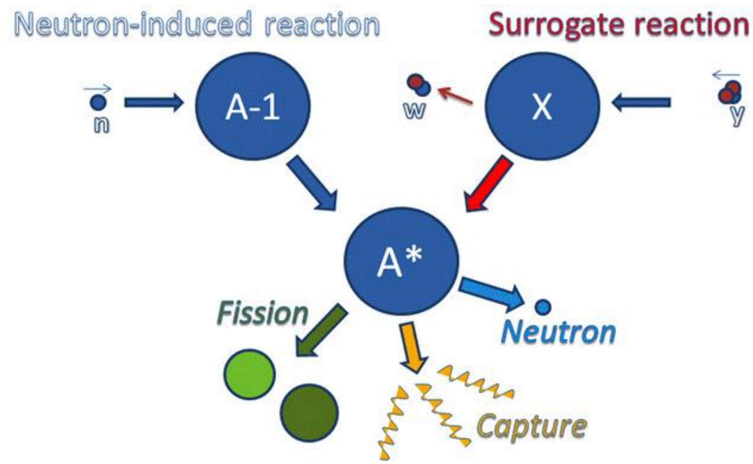
M. Calviani et al., PRC 85, 034616 (2012)

SURROGATE REACTIONS

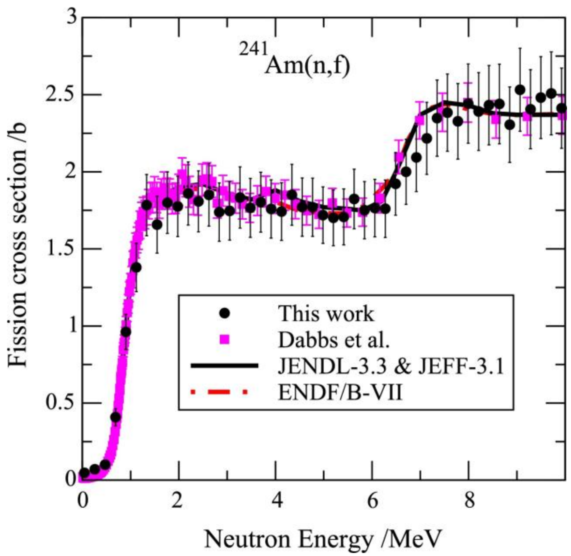
For a review: J. Escher, Rev. Mod. Phys. 84, 353–397 (2012)

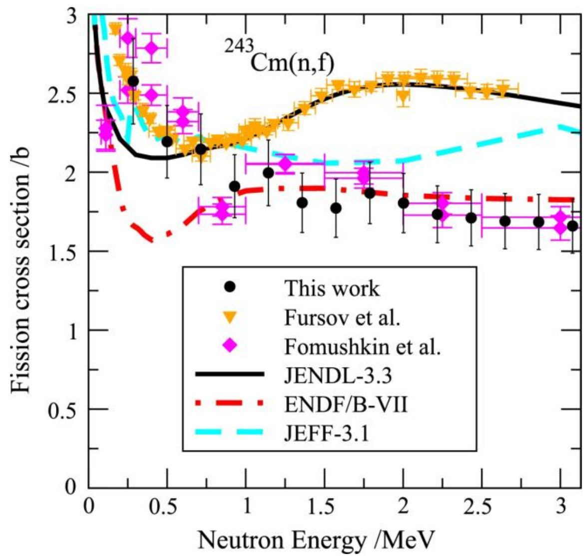
Measurement of cross-sections on isotopes difficultly available as targets

→ relevant for the transmutation of minor actinides, high burn-up reactors



$$^{243}Am + {}^{3}He \rightarrow \begin{cases} {}^{242}Am + \alpha = {}^{241}Am + n \\ {}^{243}Cm + t = {}^{242}Cm + n \\ {}^{244}Cm + d = {}^{243}Cm + n \end{cases}$$





$$\sigma_{(n,X)}(E_n) = \sigma_{(n,NC)}(E_n) \times P_{(NC,X)}(E^*)$$

calculated optical model — measured

assumes same J^π population or little dependence

↪Works well for fission cross-sections

Coll. CENBG, IPN Orsay, CEA-Bruyères, CEA-Saclay

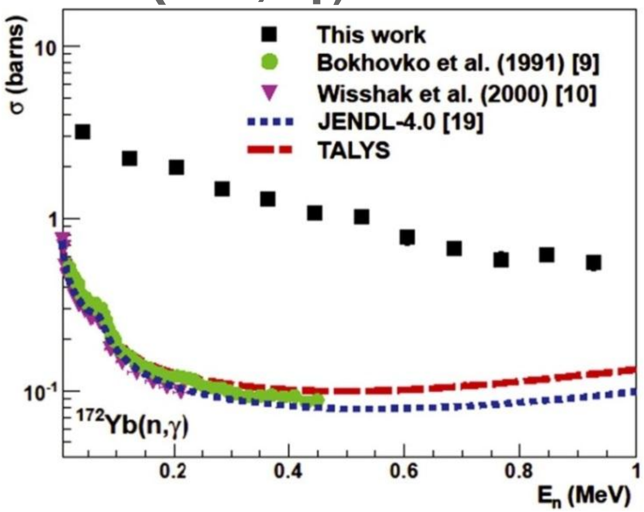
From Kessedjian et al., PLB 692 (2010) 297

SURROGATE REACTIONS

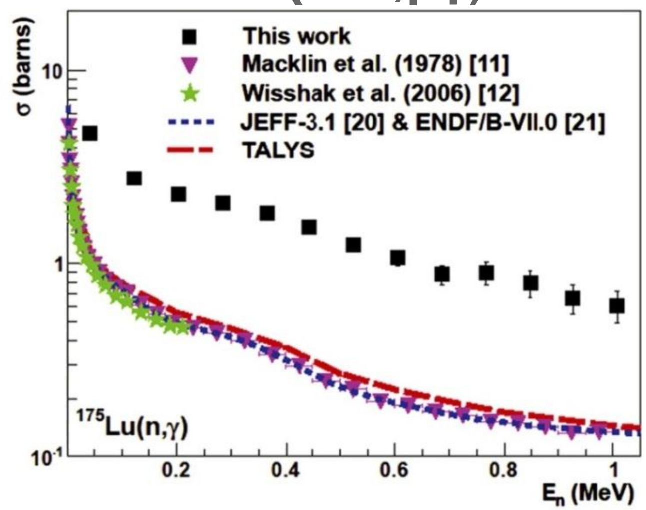
- **Measurement of capture cross-sections ?**

→ **Test on known lanthanide capture cross-sections shows that surrogate capture probability very different from direct reaction**

$^{174}Yb(^{3}He,\alpha\gamma)^{173}Yb^{*}$



$^{174}Yb(^{3}He,p\gamma)^{176}Lu^{*}$



From Boutoux et al., Phys. Lett. B 712 (2012) 319

↪ *Difference due to different J^{π} population in the direct and transfer reactions and n/γ* competition

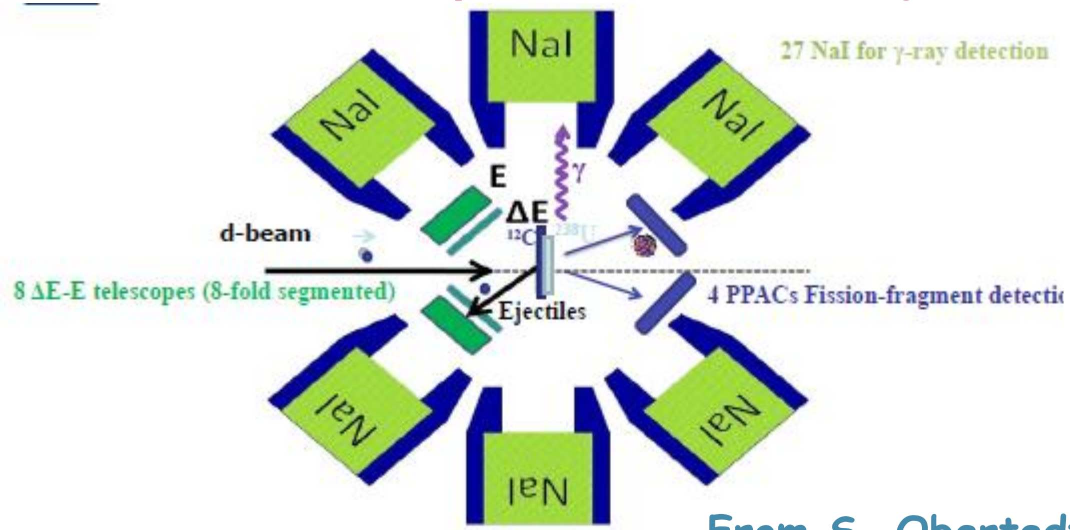
Escher et al., RMP 84(2012) 353

↪ ***Comprehensive theoretical description of direct reactions that populate highly excited states, dependence of these processes on angular momentum, parity, and energy needed***

SURROGATE REACTIONS IN CHANDA

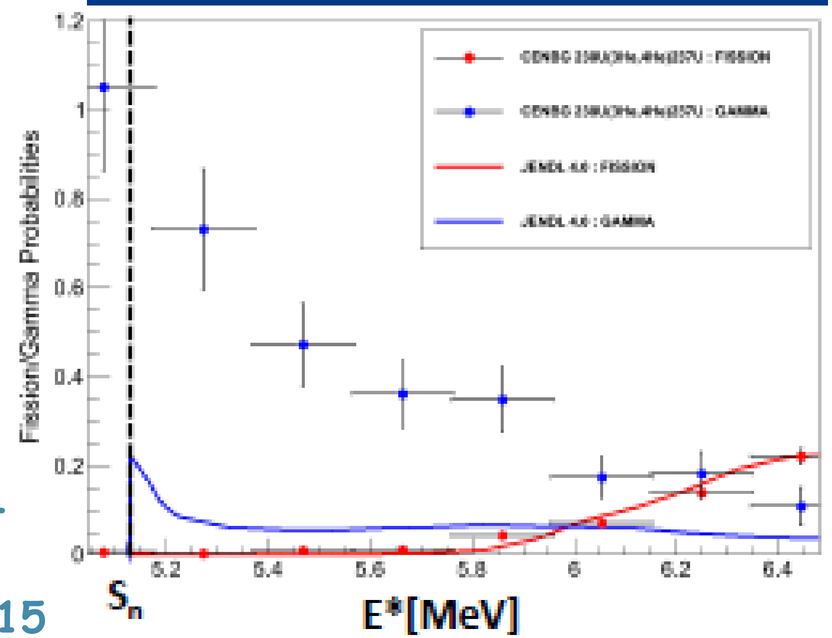
- Simultaneous measurement of fission and gamma-decay probabilies

→ Precursor experiment at OSLO cylcotro



From S. Obertedt et al., CHANDA Meeting, April 2015

$^{3}He+^{238}U \rightarrow ^{4}He+^{237}U \Leftrightarrow n+^{236}U$



➢ *Much larger differences for capture than for fission*

➢ *However large experimental uncertainties*

↪ ***New experiment at IPNO tandem with beam of higher intensity and excellent beam energy definition and with a segmented fission fragment detector***

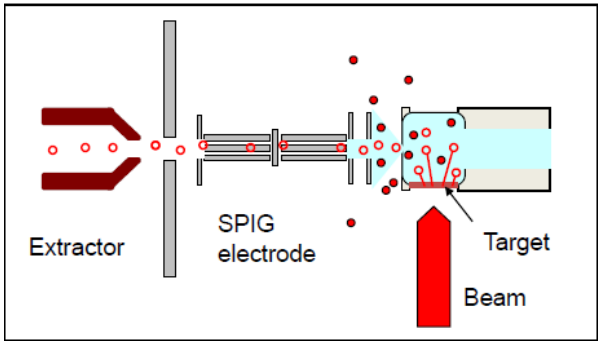
DECAY HEAT CALCULATIONS

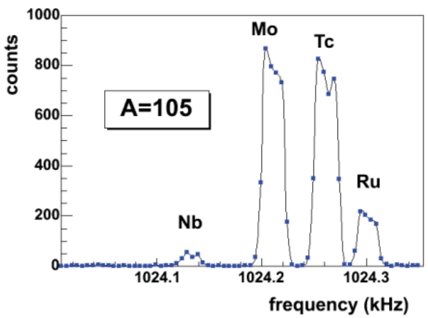
- Impact : safety, shorter refueling times, optimized shielding for transport of spent fuel, storage…→ target accuracy 10%

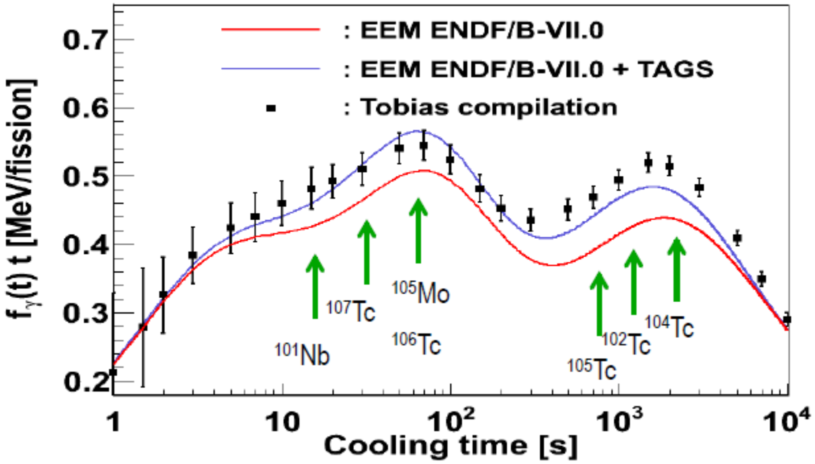
➢ need for fission yields, decay data i.e. half-lives, branching ratios, mean β, γ energies

↪Total absorption gamma-ray spectroscopy (TAGS), using large 4π scintillation detectors

– Jyvaskyla IGISOL separator + JYFLTRAP Penning trap for isotopic purification







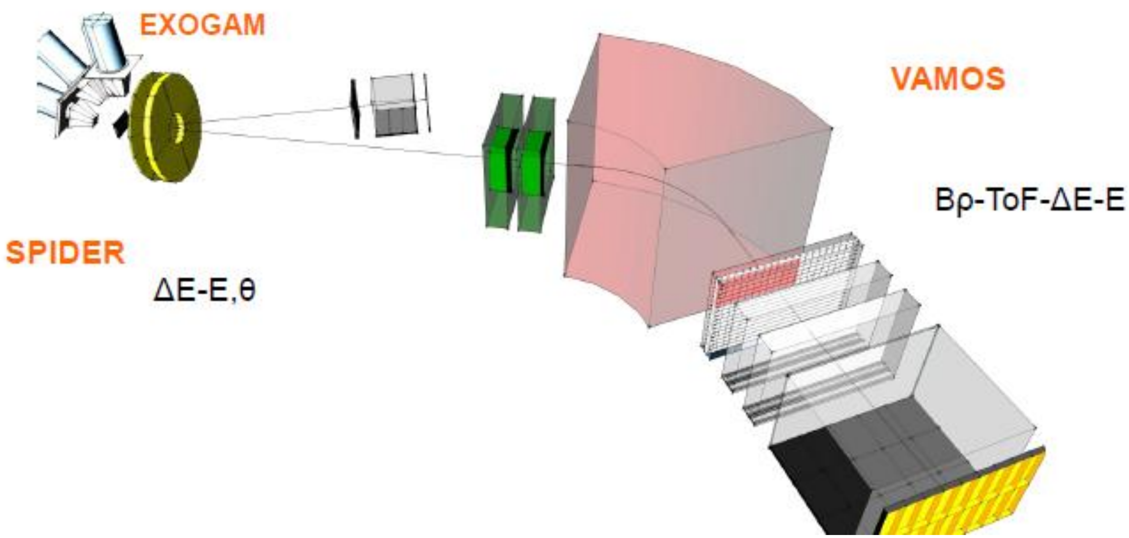
↪ Discrepancy between measurements of decay heat and calculations solved

From Algora et al., PRL 105, 202501 (2010)

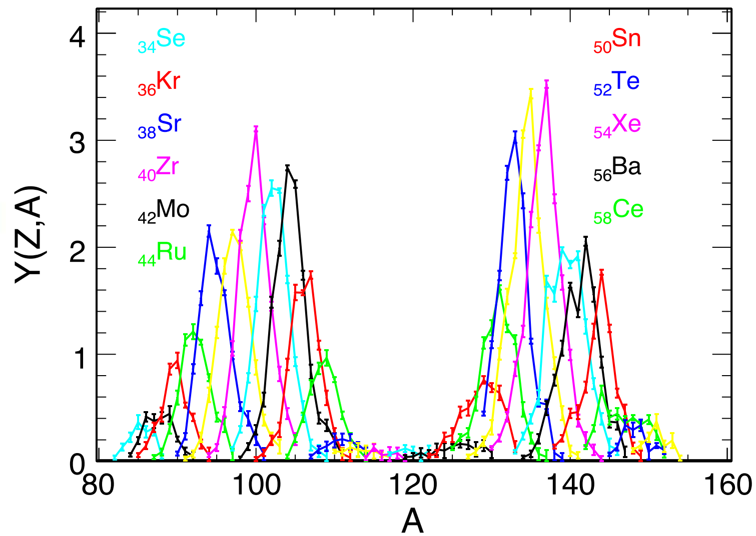
↪Also important for antineutrino spectra

FISSION FRAGMENT STUDIES

- **Isotopic fission yields from compound nuclei produced in transfer reactions at GANIL**

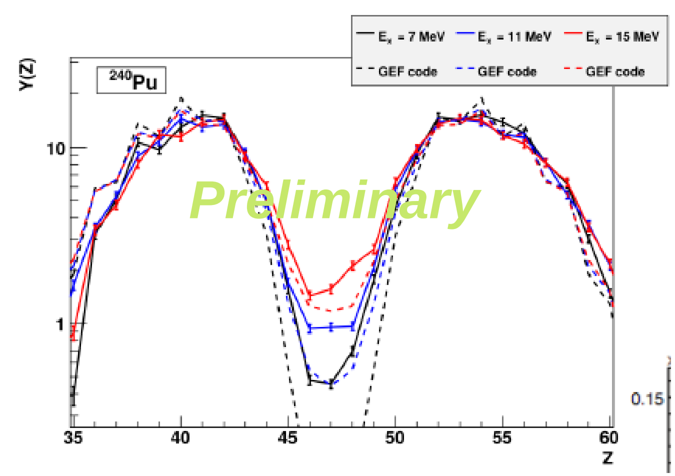


$^{12}C(^{238}U,^{240}Pu)^{10}Be$, E* = 10 MeV



M. Caamaño et al., PRC 88 (2013) 024605

- **Access to nuclei above U**
- E* determined assuming no excitation of the light tranfer partner
- High resolution using inverse kinematics
- Z, A, velocity of fragments, TKE, neutron emission as a function of E*

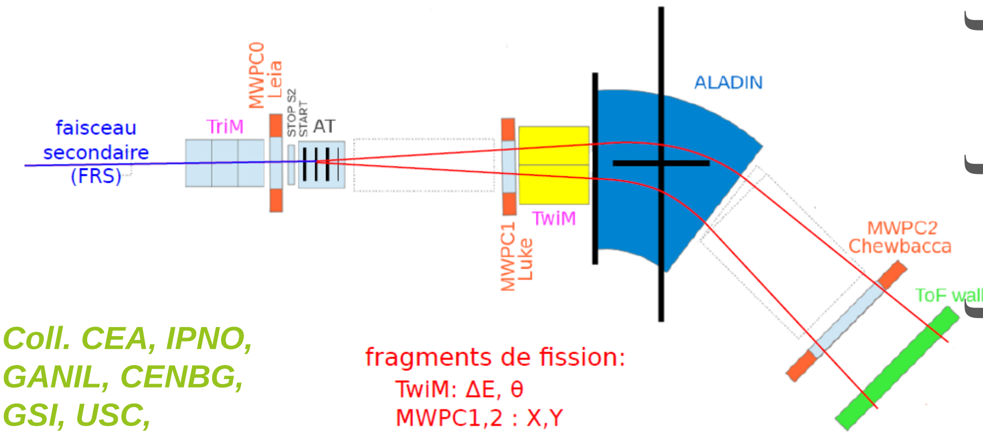


F. Farget et al., CHANDA Meeting April 2015

FISSION FRAGMENT STUDIES

SOFIA
Studies On FIssion with Aladin

- Through fission of secondary beams in the Coulomb field of a heavy target at GSI: SOFIA experiment

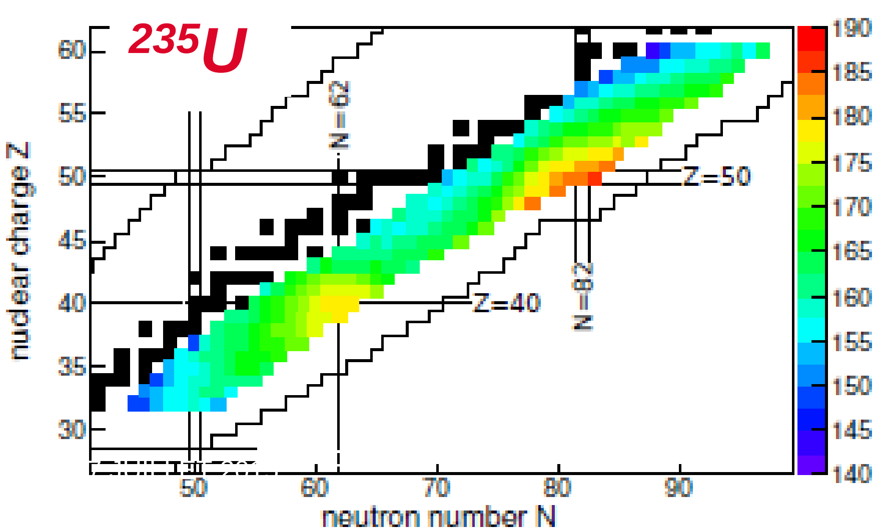


fragments de fission:
TwiM: ΔE, θ
MWPC1,2 : X,Y
plastic+ToFW: ToF

Coll. CEA, IPNO, GANIL, CENBG, GSI, USC, Chalmers

- *GDR excitation by absorption of virtual photon*
- *<E*> around 12 MeV ⇔ 6 MeV neutron*
- *Full identification (Z, A, kinetic energy) of **both FF** for actinides and pre-actinides*

From A. Chatillon et al. , CHANDA Meeting April 2015



J.F. Martin, PhD thesis

$\langle TKE \rangle$ vs (N_{FF}, Z_{FF})

- high TKE for ST1 mode
  ⇒ compact configuration
- low TKE for SL mode
  ⇒ large deformation

HIGH-ENERGY DATA

SPALLATION REACTION STUDIES FOR ADS

- radioactive inventory, in particular volatile elements (tritium, Kr, Xe, I, Hg, Po…)
  - short-lived nuclei for maintenance operation, in case of accident
  - long-lived nuclei for long-term disposal
- Gas production for damage in structural material, in particular helium

➥ **Need for highly predictive models** to be implemented into transport codes

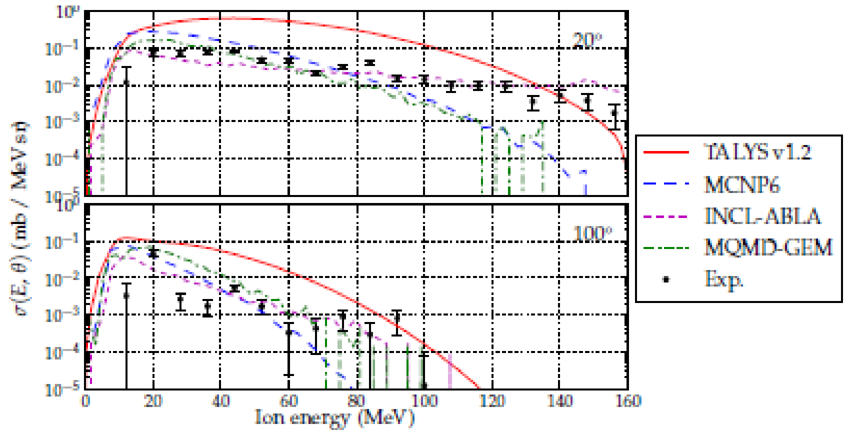
➥ High-quality data allowing benchmarking of the models and **understanding of the reaction mechanism**

Modelling of spallation reactions

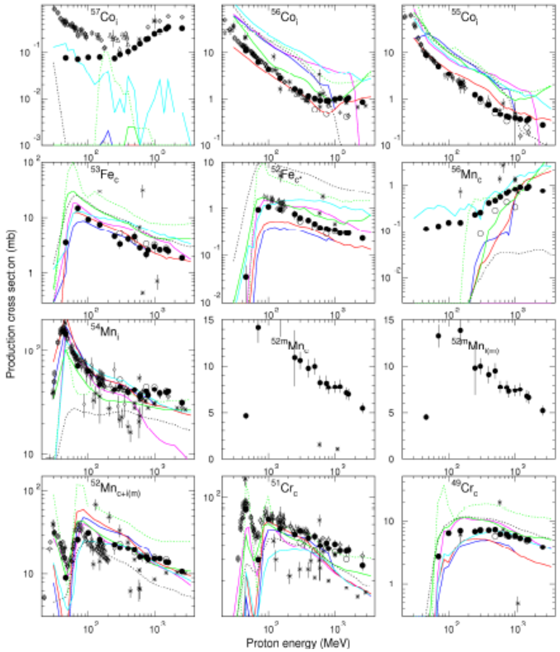
- **New high quality data**
  - excitation function measurements at ITEP
  - light charged particles DDXS in **neutron-induced reactions** measured at Uppsala

^{3}He DDXS in $p+^{56}Fe$, at 175 MeV

Bevilacqua et al., PRC (2015)

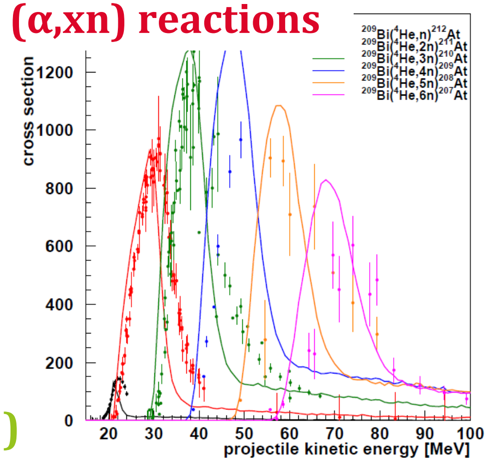


Excitation functions $p+^{56}Fe$, Titarenko et al.



- **Development of highly predictive models**
  - INCL+ABLA, CEM, FLUKA…
  - compared to all available data
  - able to predict all types of reactions and all channels

(α,xn) reactions

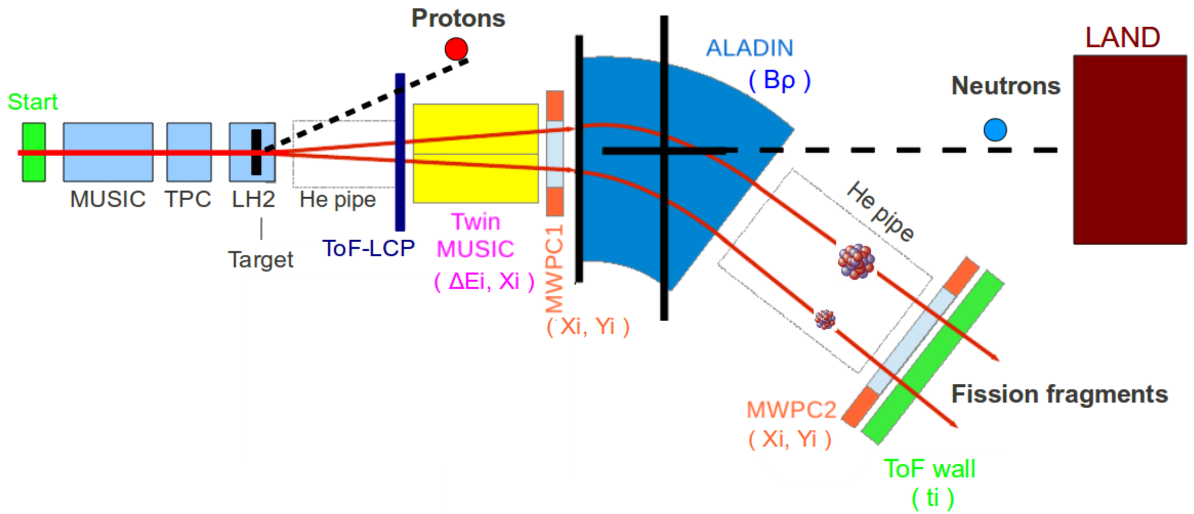


A. Boudard et al., Phys. Rev. C 87, 014606 (2013)

TOWARDS COMPLETE CHARACTERIZATION OF THE REACTION

- **To go further in model improvement more constraining data are now required**
- **Need for a complete characterization of the reaction products to understand the reaction mechanism in detail**

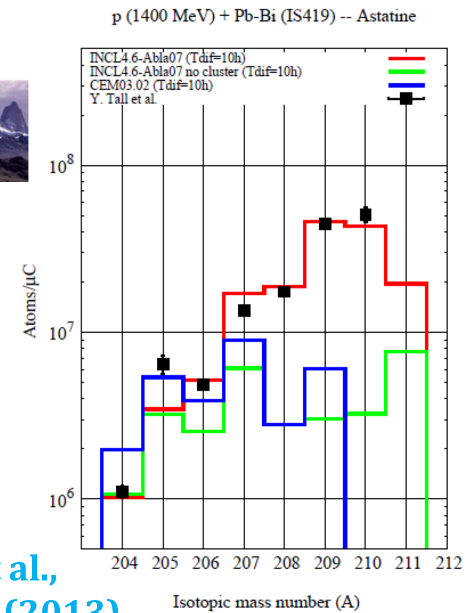
↳ **The SOFIA setup used to study fission at high energies (see talks by J. Benlliure and J.L. Rodriguez Sanchez)**



VOLATILE ELEMENT PRODUCTION

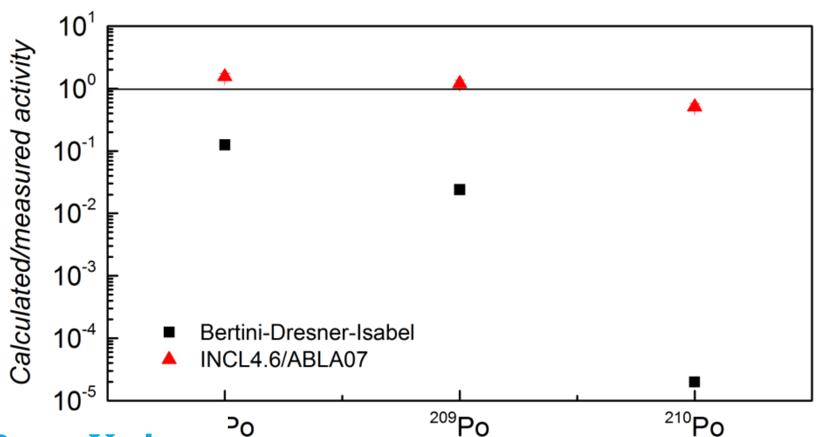
- Production of At isotopes in ISOLDE LBE target (which decay to Po isotopes) mostly due to secondary reactions induced by high-energy helium ions.

- ^{210}Po ($T_{1/2}$=138 days) observed in Pb SINQ target 10 years after irradiation due to the decay of ^{210}Pb ($T_{1/2}$=22 years) formed mostly by t+^{208}Pb reactions



J.C. David et al., EPJA 49, 29 (2013)

- **Improvement of the physics models which were unable to predict Z_{target}+2 isotopes**
  - ➥ **Importance of the coalescence mechanism**
  - ➥ **LCP+A reactions at low energies**
- Calculations: INCL4.6-ABLA07 in MCNPX2.7.b

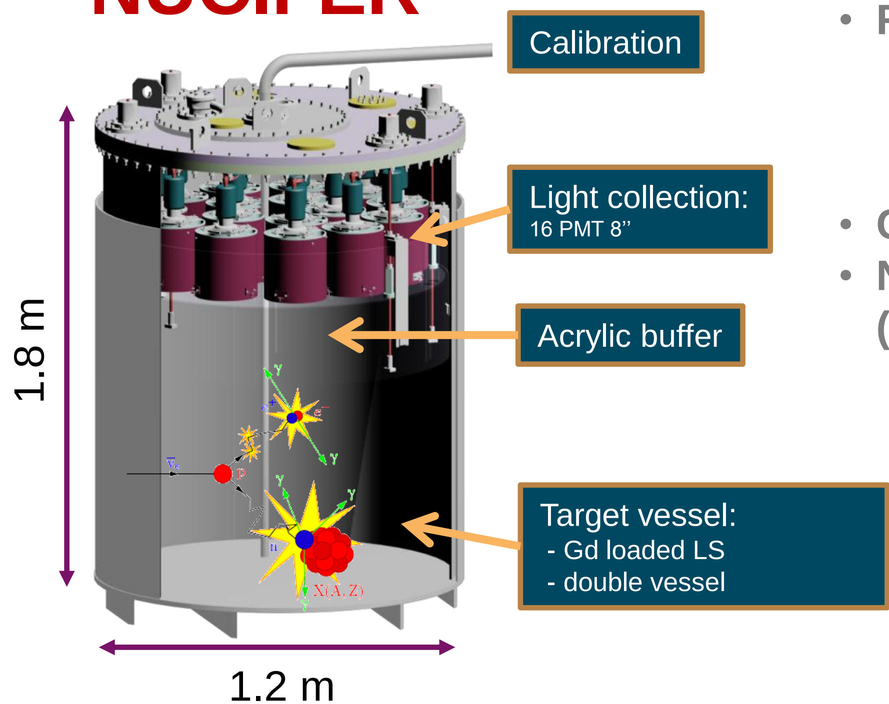


T. Lorenz, PhD Thesis, Bern Univ.

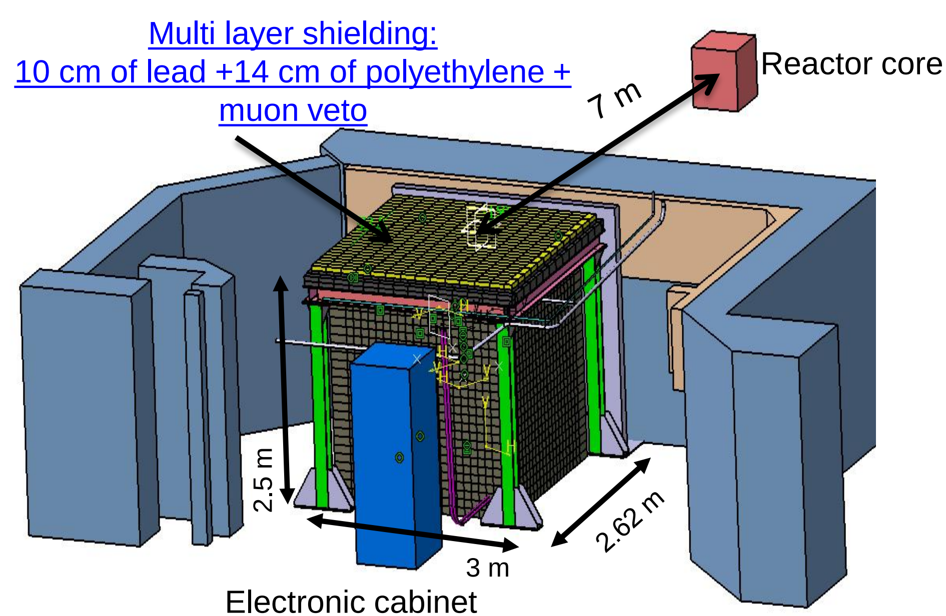
ANTI-NEUTRINOS FOR REACTOR CONTROL

NEUTRINOS: A NEW PROBE FOR NEW SAFEGUARDS APPLICATIONS

NUCIFER



- Very strong tamper resistance
- Real-time information on isotopic fission rates:
  - ON/OFF periods
  - power monitoring ?
  - fuel composition evolutions ?
- Can be operated remotely
- Non-intrusive and continuous acquisition (demonstrated over year scale)



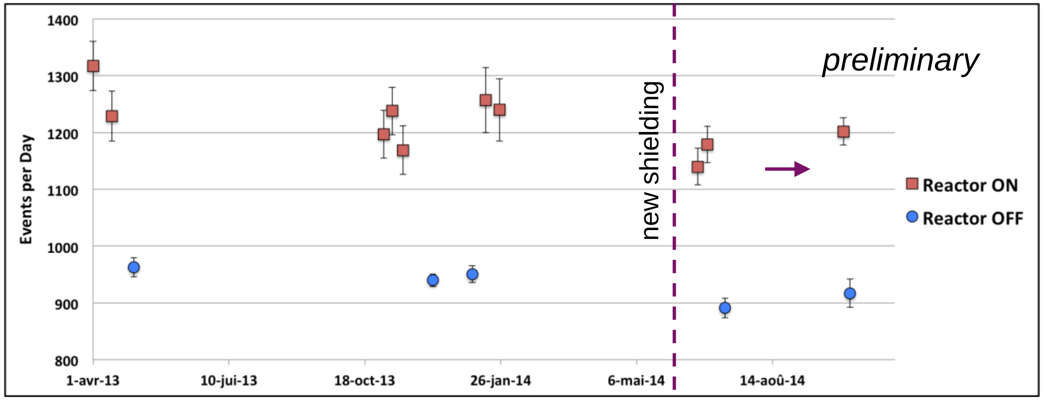
OSIRIS research reactor (70 MW)

- Compact Core: 80x70x70 cm^3
- Fuel element : U_3Si_2Al, 20% ^{235}U
- Refueling: $1/7^{th}$ each 20 days
- Baseline: ~7.0 m
- Close to the surface : overburden: ~ 5 m.w.e
- Challenging reactor induced background

From A. Letourneau et al.

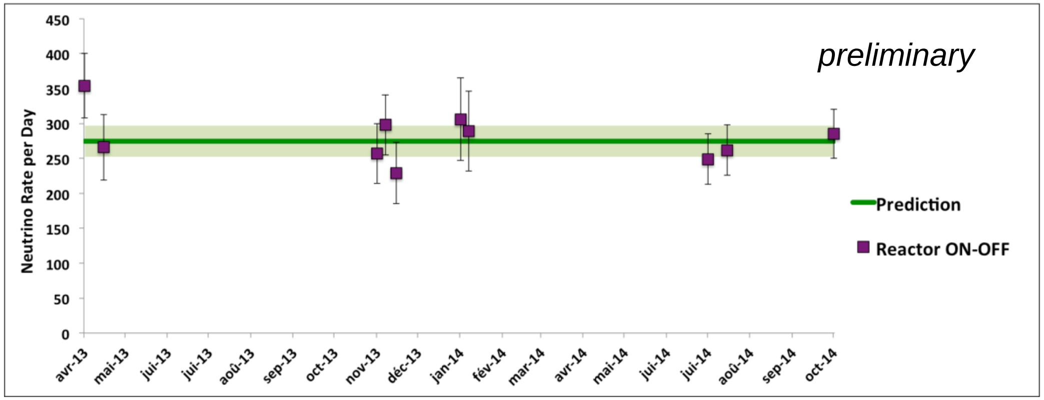
NEUTRINO-METRY

- Nucifer shows a very good **reliability** (no fake alarm), **no safety** issues and **stability** of the light response at the 1% level after 2 years of commissioning



NUCIFER

From A. Letourneau et al.



Mean = (276 ± 14) nu/day

Power = 67.5 MW,
Distance = 7 m
Target volume = 1 m^3

- A clear **ON-OFF effect** (detected in 12 hours at 95% C.L.) despite the [very high background](#) at the OSIRIS site

CONCLUSIONS

- The expected renaissance has not happened but nuclear energy will very likely grow faster in the future, in particular in developing countries
- Enhanced requirements for safety, economical competitiveness, minimisation / transmutation of waste imply further needs for high quality nuclear data and predictive models
- Nuclear physicists have played and will still play a major role by providing facilities, innovative experimental techniques and theoretical models