DE LA RECHERCHE À L'INDUSTRIE

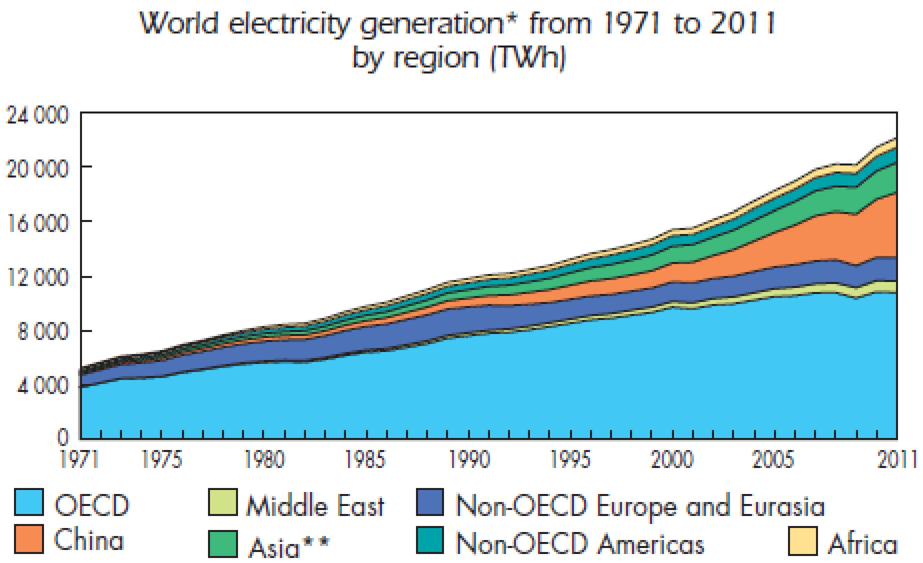
NUCLEAR PHYSICS FOR ENERGY PRODUCTION AND WASTE TRANSMUTATION

n_TOF collaboration meeting | Sylvie Leray

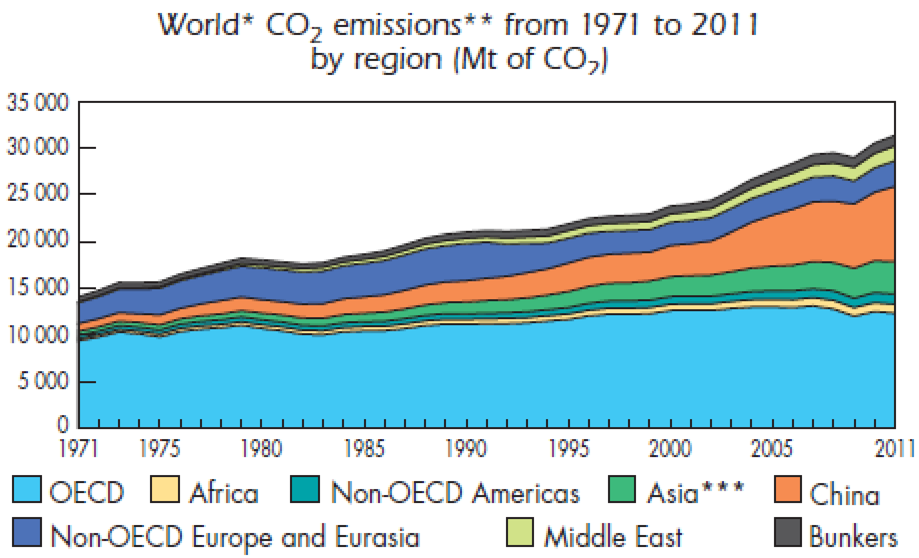
NOVEMBER 28, 2013

- Increase in energy demand
- Increase of CO_2 emissions

Electricity Generation by Region



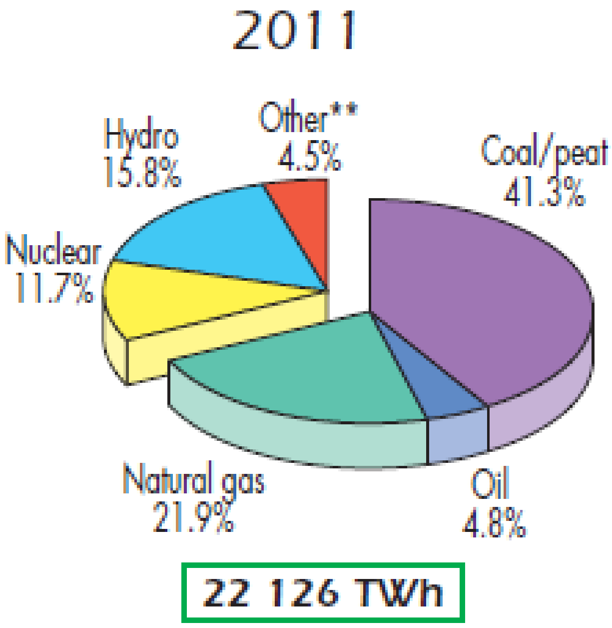
CO_2 Emissions by Region



Source: IEA Key world energy statistics 2013

NUCLEAR ENERGY

- No single solution but combination of:
  - energy saving and increase of energetic efficiency
  - renewable energies,
  - nuclear energy



Source: IEA Key world energy statistics 2013

NUCLEAR ENERGY FUTURE

435 reactors operable, 374MWe
66 reactors under construction, 68 MWe
160 reactors planned, 176 MWe
310 reactors proposed, 360 MWe

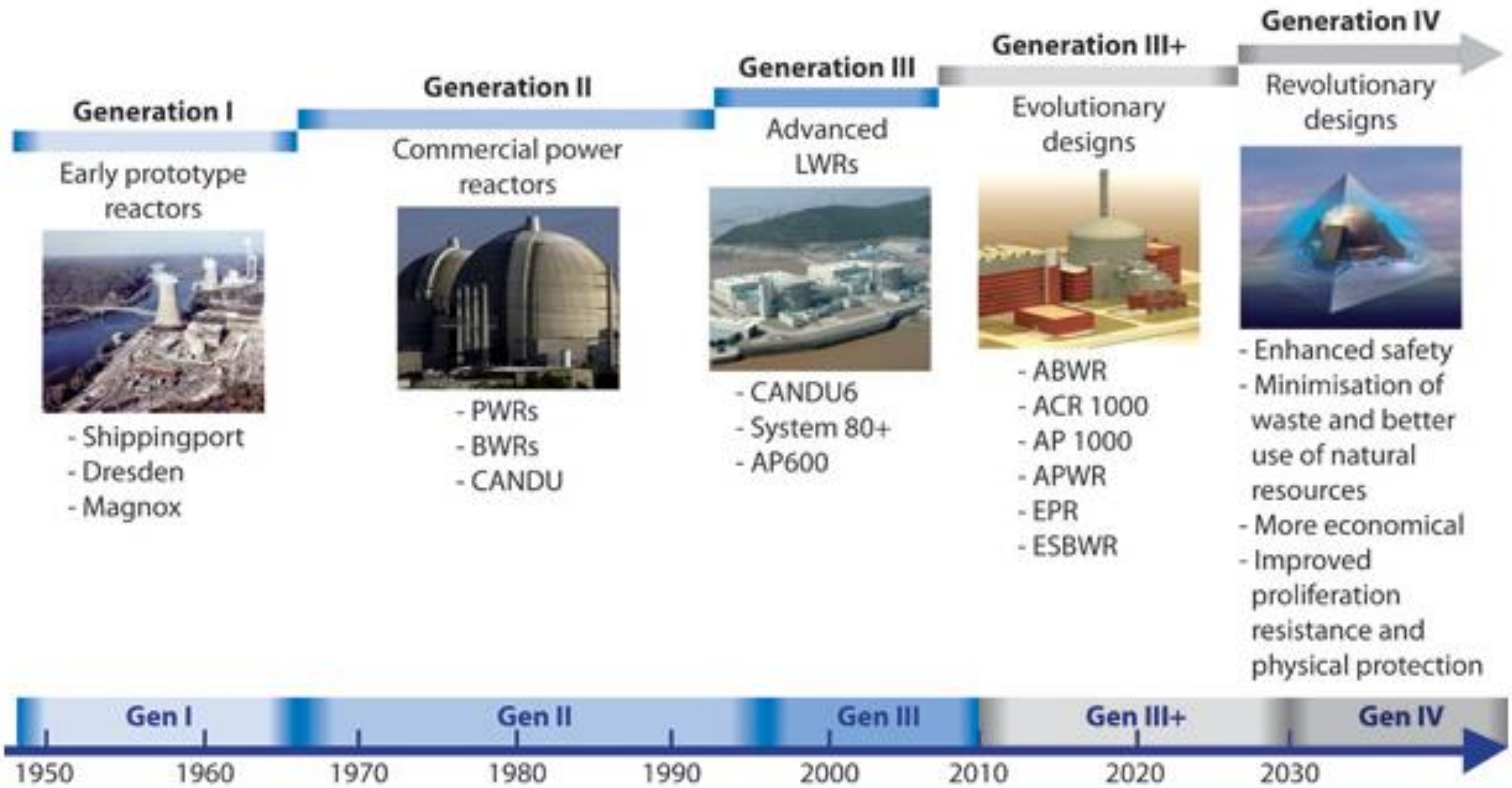
Commercial Operation*		REACTOR	TYPE	MWe (net)
2013	Iran, AEOI	Bushehr 1*	PWR	950
2013	India, NPCIL	Kudankulam 1	PWR	950
2013	India, NPCIL	Kudankulam 2	PWR	950
2013	China, CGNPC	Hongyanhe 1*	PWR	1080
2013	China, CGNPC	Ningde 1*	PWR	1080
2013	Korea, KHNP	Shin Wolsong 2	PWR	1000
2013	Korea, KHNP	Shin-Kori 3	PWR	1350
2013	Russia, Rosenergoatom	Leningrad II-1	PWR	1070
2013	Argentina, CNEA	Atucha 2	PHWR	692
2013	China, CGNPC	Ningde 2	PWR	1080
2013	China, CGNPC	Yangjiang 1	PWR	1080
2013	China, CGNPC	Taishan 1	PWR	1700
2013	China, CNNC	Fangjiashan 1	PWR	1080
2013	China, CNNC	Fuqing 1	PWR	1080
2013	China, CGNPC	Hongyanhe 2	PWR	1080
2014	Russia, Rosenergoatom	Novovoronezh II-1	PWR	1070
2015	Russia, Rosenergoatom	Rostov 3	PWR	1070
2014	Slovakia, SE	Mochovce 3	PWR	440
2014	Slovakia, SE	Mochovce 4	PWR	440
2014	Taiwan Power	Lungmen 1	ABWR	1300
2014	China, CNNC	Sanmen 1	PWR	1250
2014	China, CPI	Haiyang 1	PWR	1250
2014	China, CGNPC	Ningde 3	PWR	1080
2014	China, CGNPC	Hongyanhe 3	PWR	1080
2014	China, CGNPC	Yangjiang 2	PWR	1080
2014	China, CGNPC	Taishan 2	PWR	1700
2014	China, CNNC	Fangjiashan 2	PWR	1080
2014	China, CNNC	Fuqing 2	PWR	1080
2014	Korea, KHNP	Shin-Kori 4	PWR	1350
2014?	Japan, Chugoku	Shimane 3	ABWR	1375
2014	India, Bhavini	Kalpakkam	FBR	470
2014	Russia, Rosenergoatom	Beloyarsk 4	FNR	750
2015	USA, TVA	Watts Bar 2	PWR	1180
2015	Taiwan Power	Lungmen 2	ABWR	1300
2015	China, CNNC	Sanmen 2	PWR	1250
2015	China, CGNPC	Hongyanhe 4	PWR	1080
2015	China, CGNPC	Yangjiang 3	PWR	1080
2015	China, CGNPC	Ningde 4	PWR	1080
2015	China, CGNPC	Fangchenggang 1	PWR	1080
2015	China, CNNC	Changjiang 1	PWR	650
2015	China, CNNC	Changjiang 2	PWR	650
2015	China, CNNC	Fuqing 3	PWR	1080
2015	India, NPCIL	Kakrapar 3	PHWR	640
2015?	Japan, EPDC/J Power	Ohma 1	ABWR	1350
2016	Finland, TVO	Olkiluoto 3	PWR	1600
2016	France, EdF	Flamanville 3	PWR	1600
2016	Russia, Rosenergoatom	Novovoronezh II-2	PWR	1070
2016	Russia, Rosenergoatom	Leningrad II-2	PWR	1200
2016	Russia, Rosenergoatom	Vilyuchinsk	PWR x 2	70
2016	India, NPCIL	Kakrapar 4	PHWR	640
2016	India, NPCIL	Rajasthan 7	PHWR	640
2016	Pakistan, PAEC	Chashma 3	PWR	300
2016	China, China Huaneng	Shidaowan	HTR	200
2016	China, CPI	Haiyang 2	PWR	1250
2016	China, CGNPC	Yangjiang 4	PWR	1080
2016	China, CGNPC	Hongyanhe 5	PWR	1080
2015	China, CNNC	Hongshiding 1	PWR	1080
2015	China, CGNPC	Fangchenggang 2	PWR	1080
2016	China,	several others	PWR	
2017	USA, Southern	Vogtle 3	PWR	1200
2017	Russia, Rosenergoatom	Baltic 1	PWR	1200
2017	Russia, Rosenergoatom	Rostov 4	PWR	1200
2017	Russia, Rosenergoatom	Leningrad II-3	PWR	1200
2017	Ukraine, Energoatom	Khmelnitsky 3	PWR	1000
2017	Korea, KHNP	Shin-Ulchin 1	PWR	1350
2017	India, NPCIL	Rajasthan 8	PHWR	640
2017	Romania, SNN	Cernavoda 3	PHWR	655
2017?	Japan, JAPC	Tsuruga 3	APWR	1538
2017	Pakistan, PAEC	Chashma 4	PWR	300
2017	USA, SCEG	Summer 2	PWR	1200
2017	China,	several		
2018	Korea, KHNP	Shin-Ulchin 2	PWR	1350
Commercial Operation*		REACTOR	TYPE	MWe (net)

Source: World Nuclear Association (updated March 2013)

NUCLEAR ENERGY

- But necessity to increase public acceptance
  - Enhanced safety
  - Acceptable solution for the management of nuclear waste
  - Sustainability on the long term

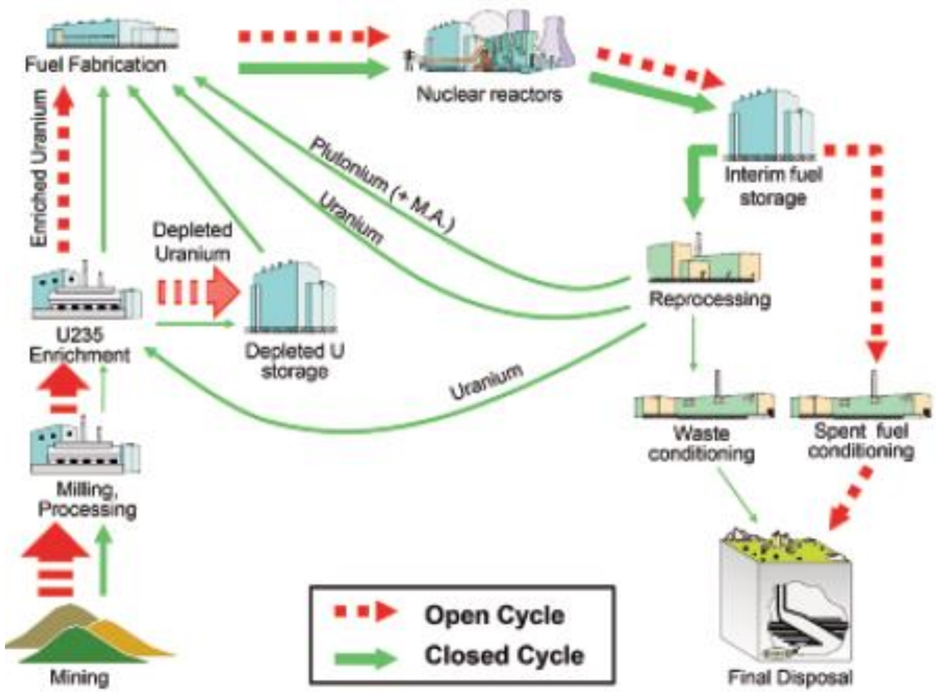
FUTURE OF NUCLEAR ENERGY



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

NUCLEAR WASTE MANAGEMENT

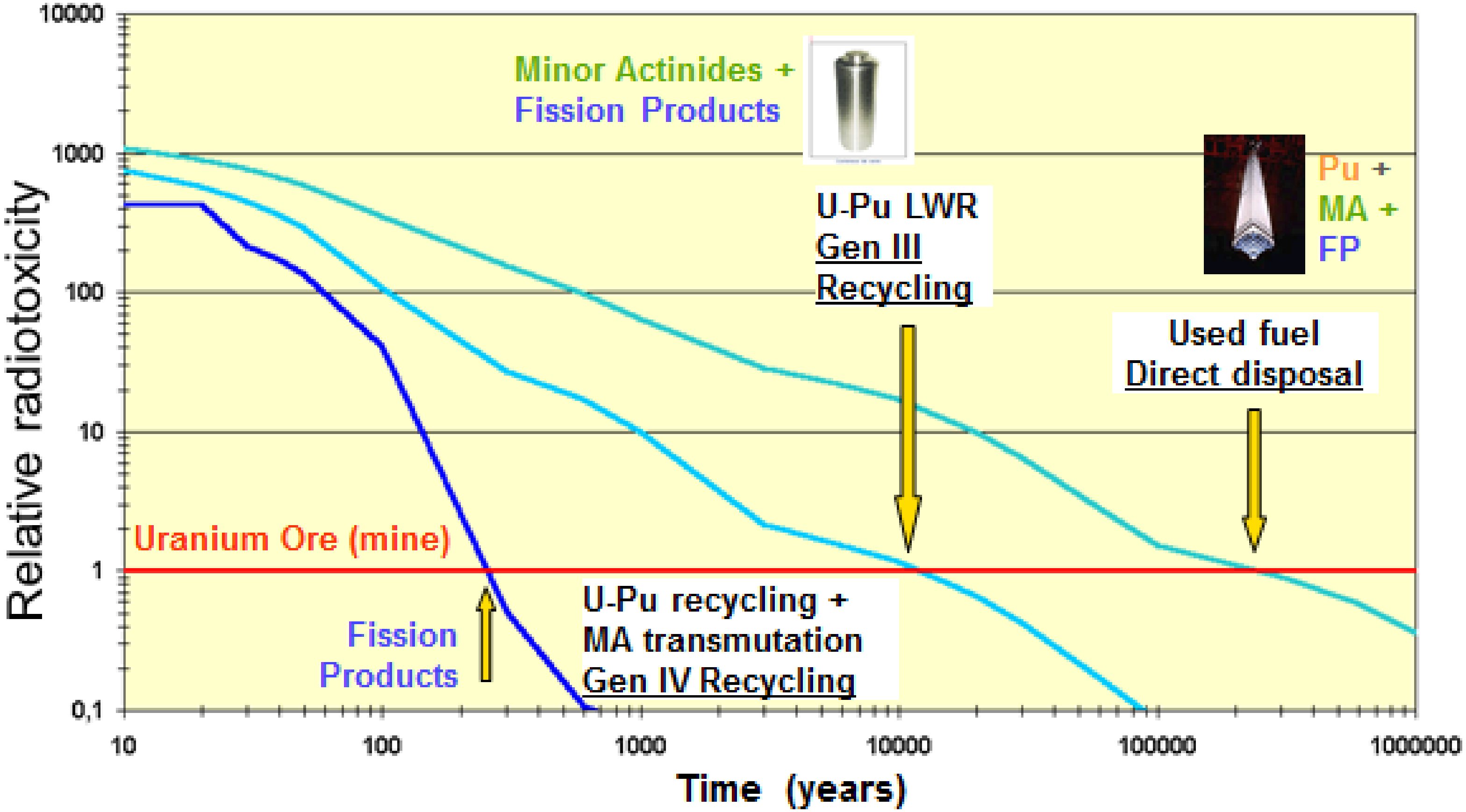
- Presently, depending on the countries:
  - Open cycle: direct disposal of spent fuel
  - Partially closed cycle: reprocessing to extract Pu, MOX fuels
- Possibly in the future
  - Multirecycling
  - Transmutation of minor actinides either in critical or in sub-critical fast reactors (ADS)



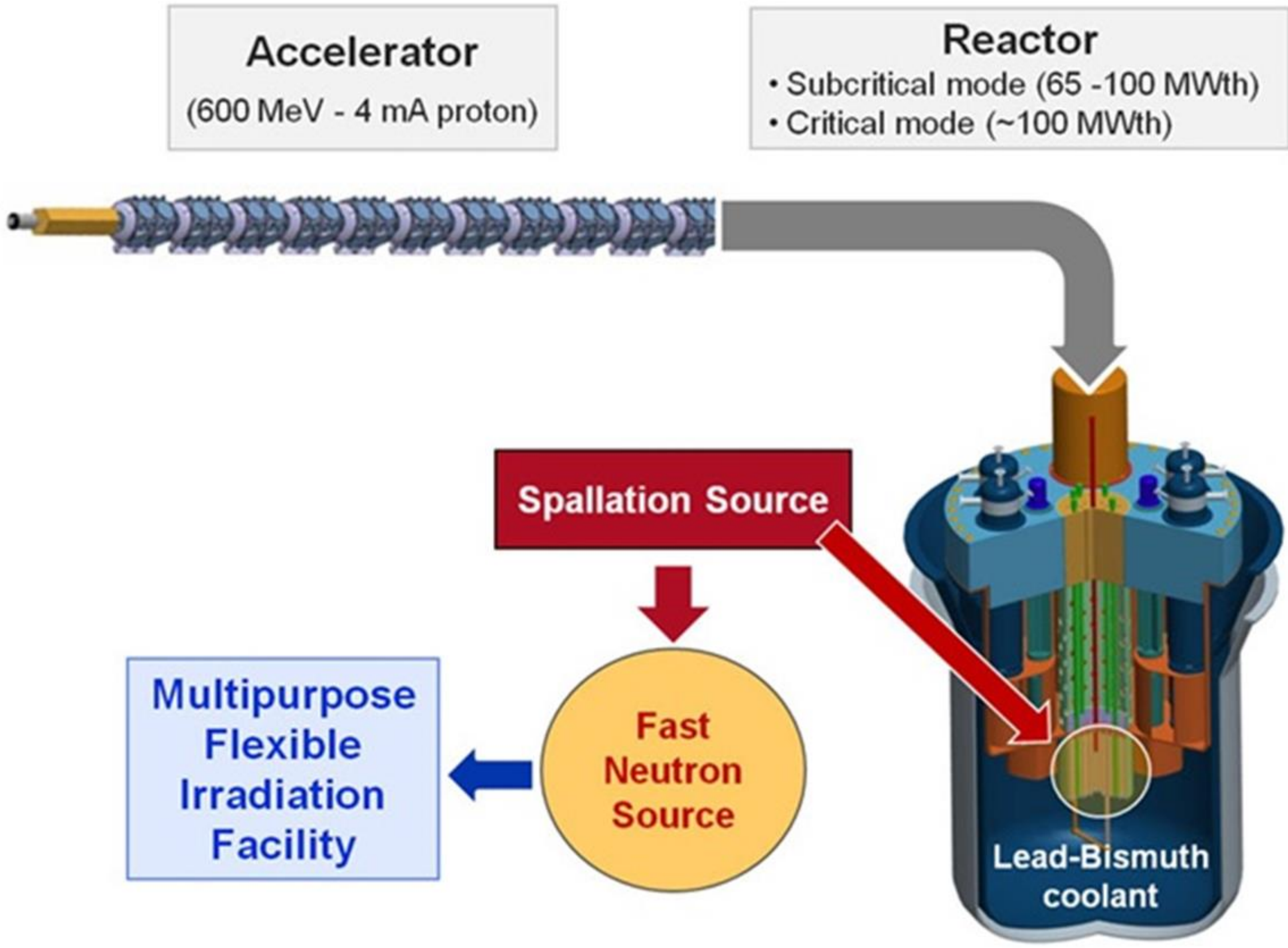
➥ **But ultimate disposal will anyhow be necessary**

NUCLEAR WASTE MANAGEMENT

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



THE MYRRHA PROJECT AT SCK•CEN



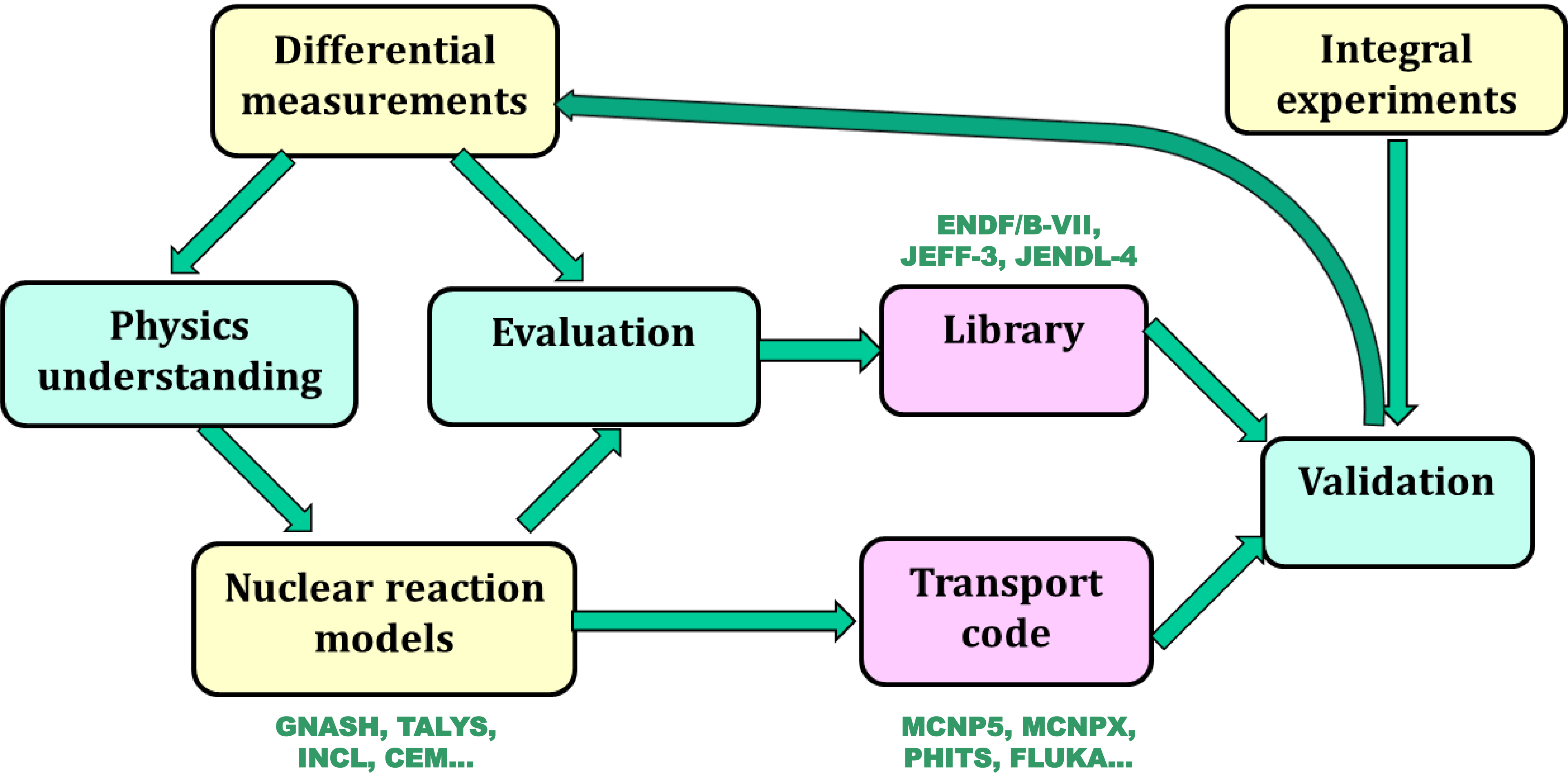
NUCLEAR PHYSICS FOR ENERGY PRODUCTION

NUCLEAR DATA NEEDS

- *Existing, Gen-III reactors*
  - *Optimization of fuel burn-up*
  - *Increase of life time*
  - *Safety margin reduction: decay heat, delayed n fraction*
- *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

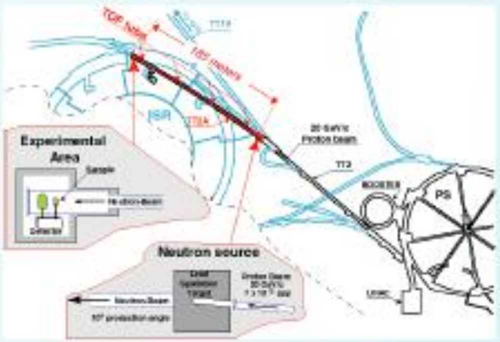


ANDES FP7 PROJECT

www.andes-nd.eu

ANDES main experimental facilities

Accurate Nuclear Data for nuclear Energy Sustainability



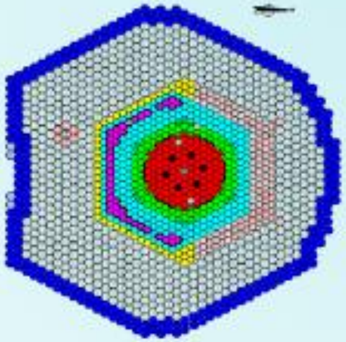
CERN n_TOF

IRMM in the JRC

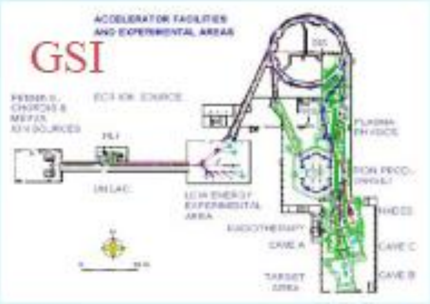
GANIL

IFIN-HH

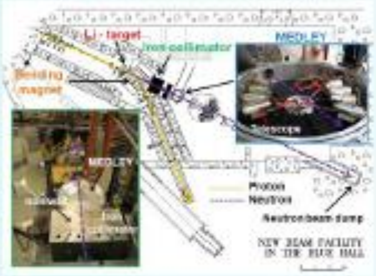
IGISOL at Jyväskylä



PROFIL at PHENIX



GSI



TSL

SURROGATE REACTIONS

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

Measurement of cross-sections on isotopes difficultly available as targets

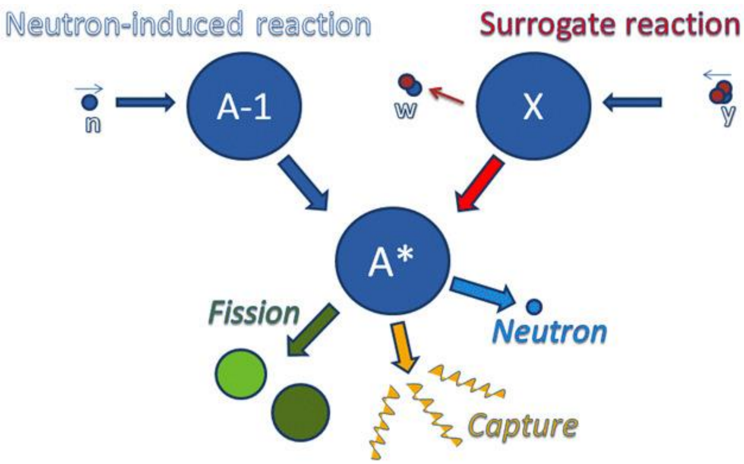
→ relevant for the transmutation of minor actinides, high burn-up reactors

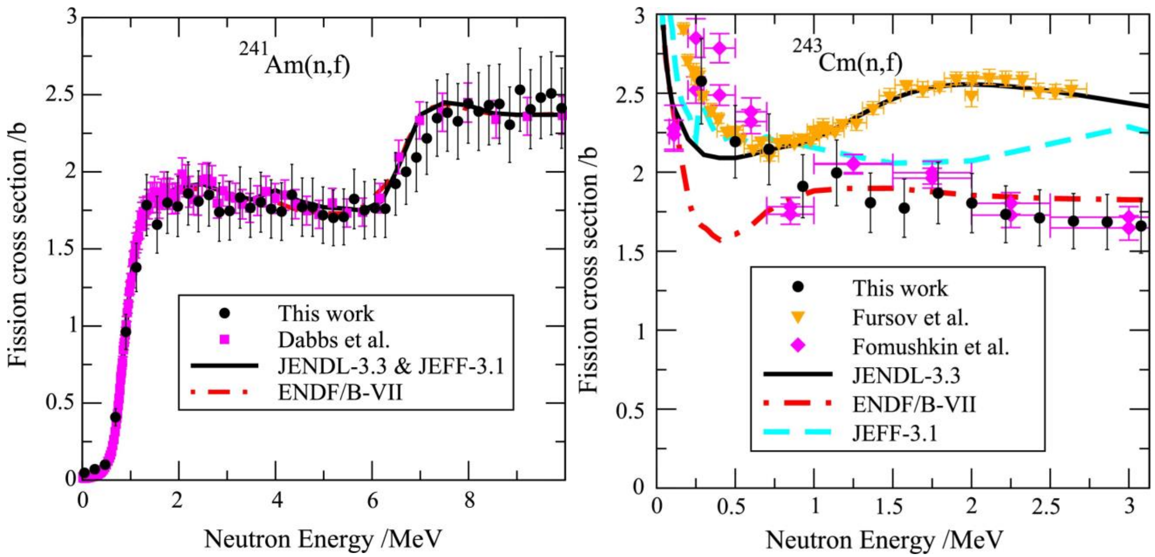
$^{243}Am + {}^{3}He \rightarrow$

$^{242}Am + \alpha = {}^{241}Am + n$

$^{243}Cm + t = {}^{242}Cm + n$

$^{244}Cm + d = {}^{243}Cm + n$





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

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

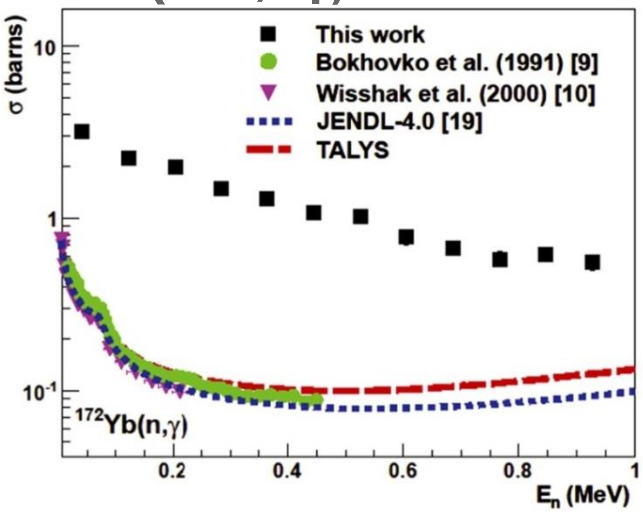
From Kessedjian et al., PL 105, 202501 (2010)

SURROGATE REACTIONS

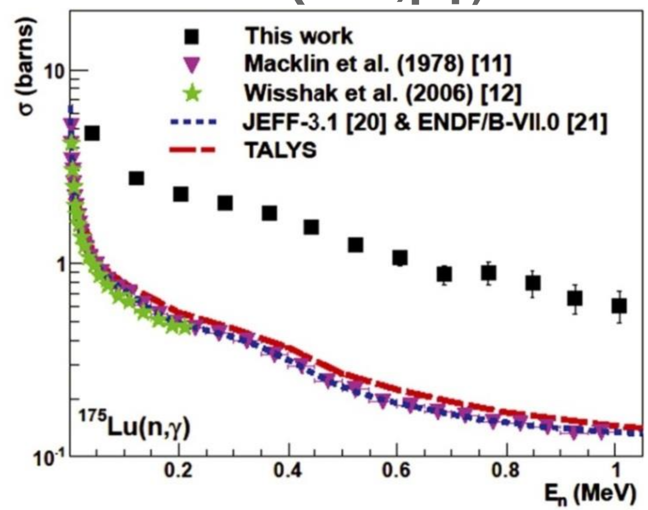
- **Measurement of capture cross-sections ?**

→ 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. (2012)

↳*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***

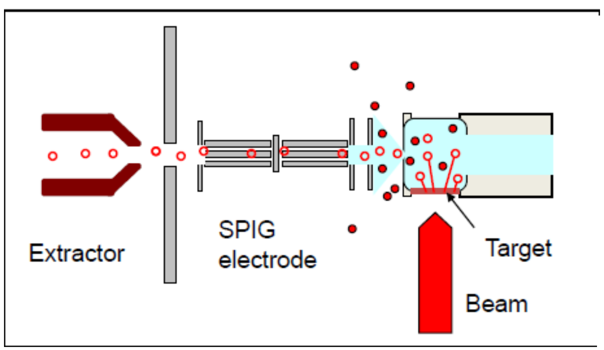
DECAY HEAT CALCULATIONS

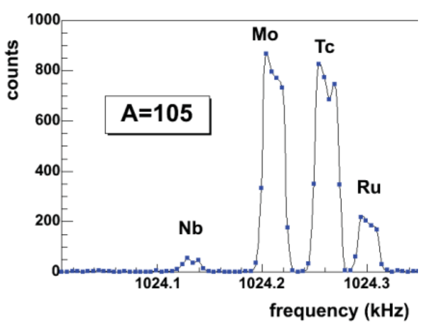
- **Impact : safety, shorter refueling times, optimized shielding for transport of spent fuel, storage…→ target accuracy 10%**

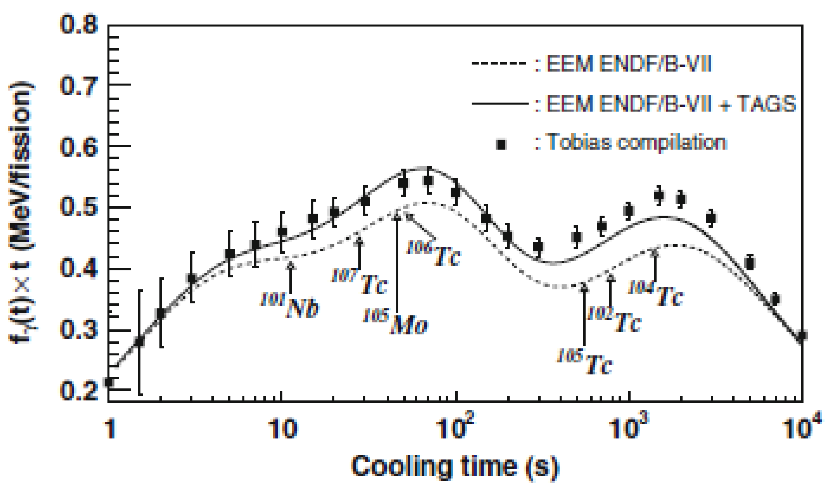
➢ **need for fission yields, decay data i.e. half-lives, branching ratios, mean β, γ energies**

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

– **Jyvaskyla IGISOL separator + JYFLTRAP Penning trap for isotopic purification**







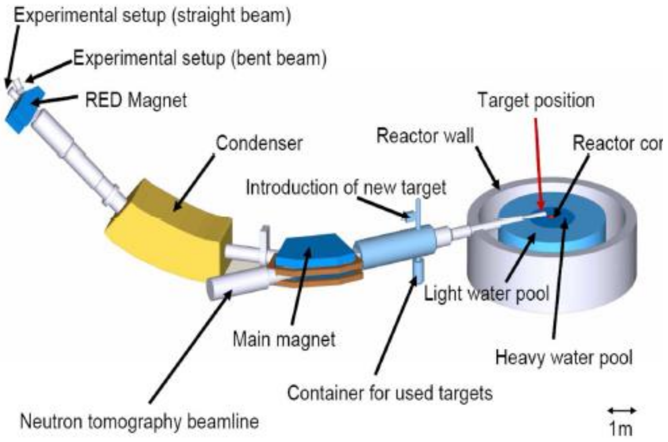
From Algora et al., PRL 105, 202501 (2010)

↳ Also delayed neutron probability measurements with the BELEN-20 detector

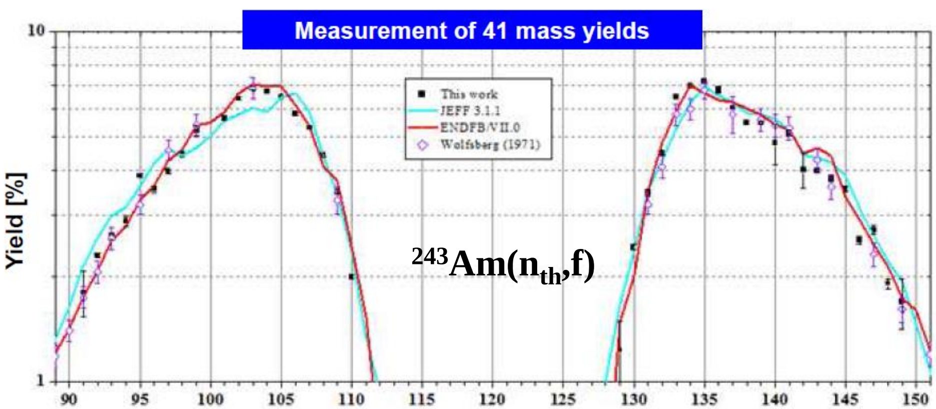
FISSION FRAGMENT YIELDS

➢ *Measurements of fission-fragment characteristics*

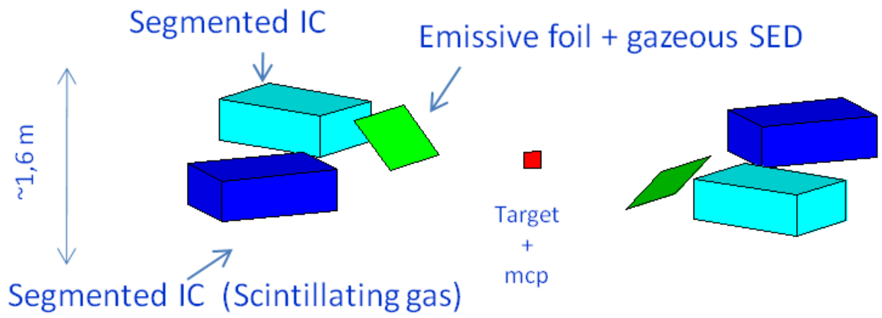
♦ *with thermal neutrons*
Lohengrin@ILL



C. Amouroux PhD thesis

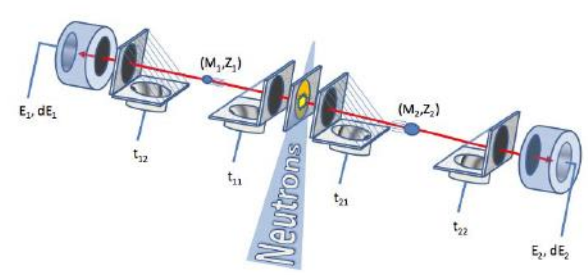


♦ *with fast neutrons*
Falstaff@NFS-SPIRAL2



2E-2v spectrometer for NFS, D. Dore et al.

Spectrometer for ion detection in fission research (SPIDER)

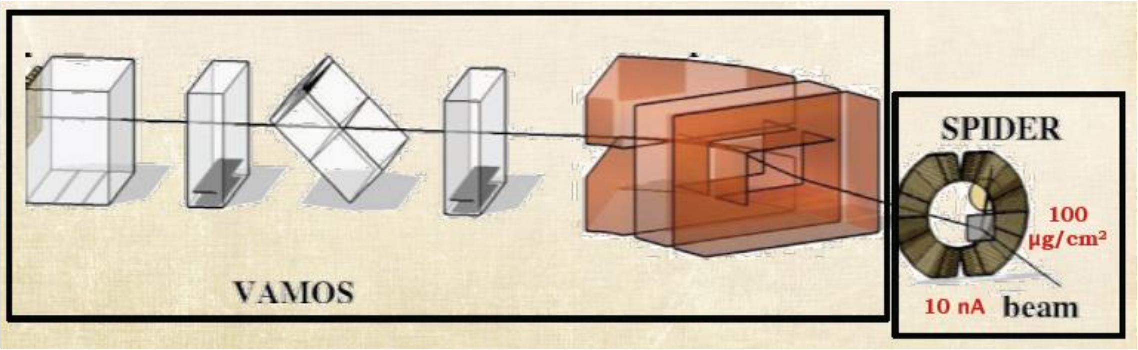


Los Alamos, F. Tovesson et al.

FISSION FRAGMENT STUDIES

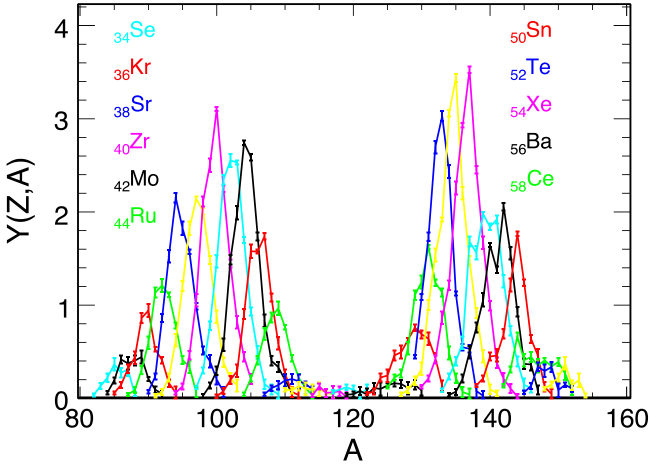
- Through surrogate reactions at GANIL

↳ *FF isotopic distribution of nuclei above U*



F. Farget, C. Rodríguez-Tajes et al.

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

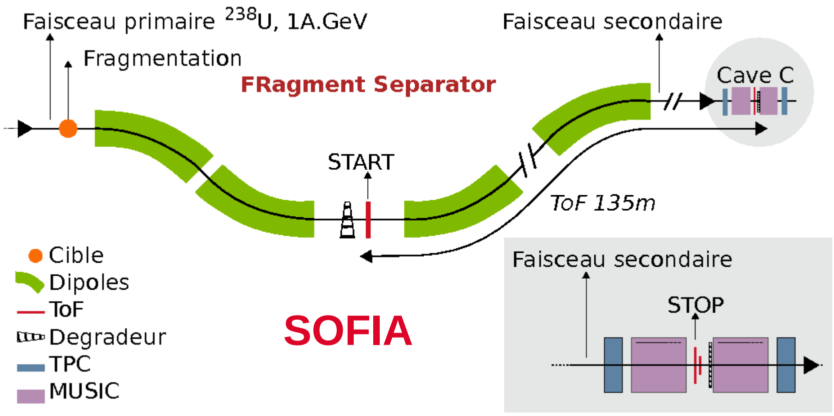


- Through fission of secondary beams in the Coulomb field of a heavy target at GSI

↳ *SOFIA experiment: Identification of both FF for actinides and pre-actnides*

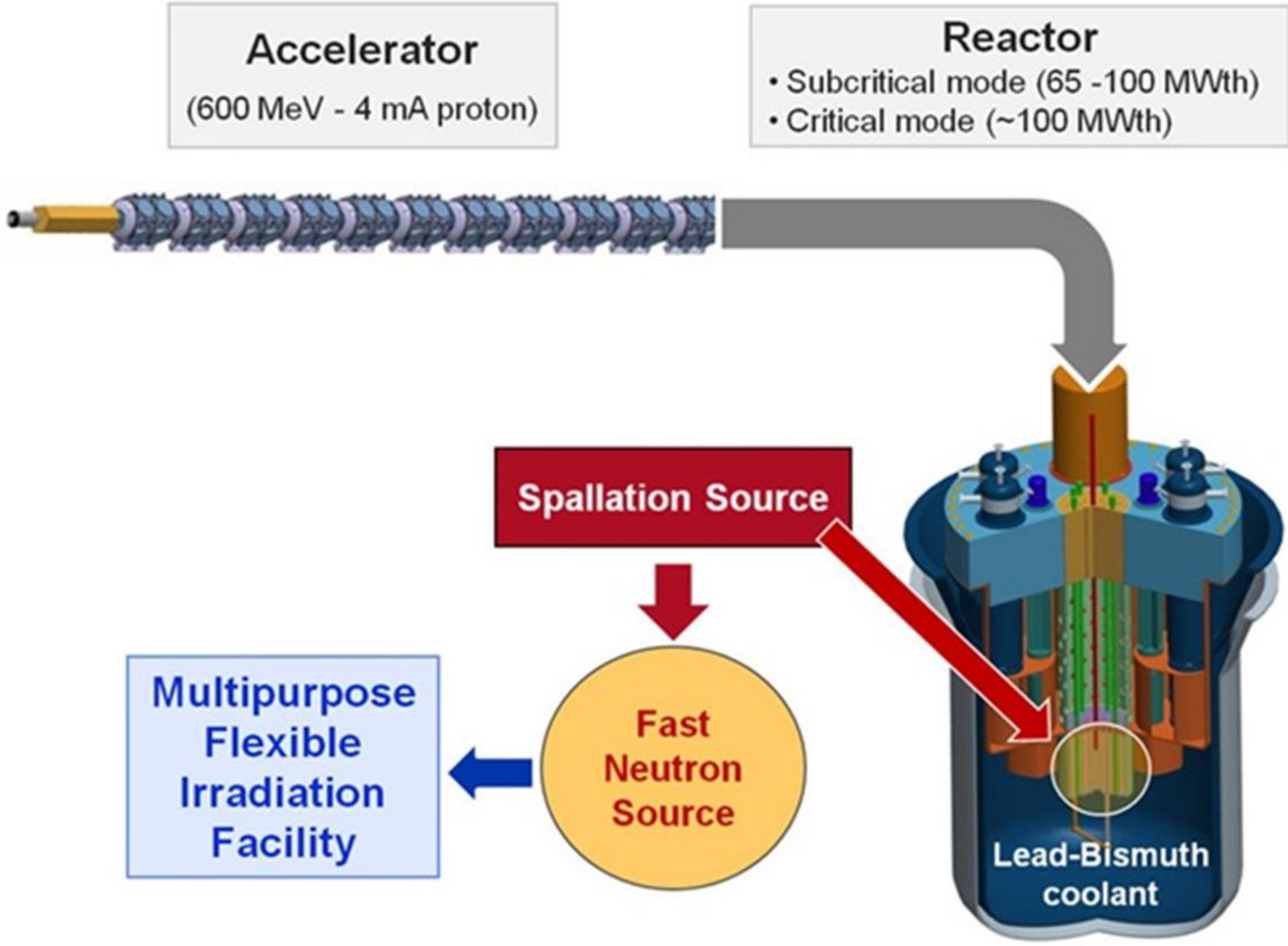
<E> = 10 MeV ⇔ 6 MeV neutron*

J. Taieb et al.



NUCLEAR PHYSICS FOR ADS

THE MYRRHA PROJECT AT SCK•CEN

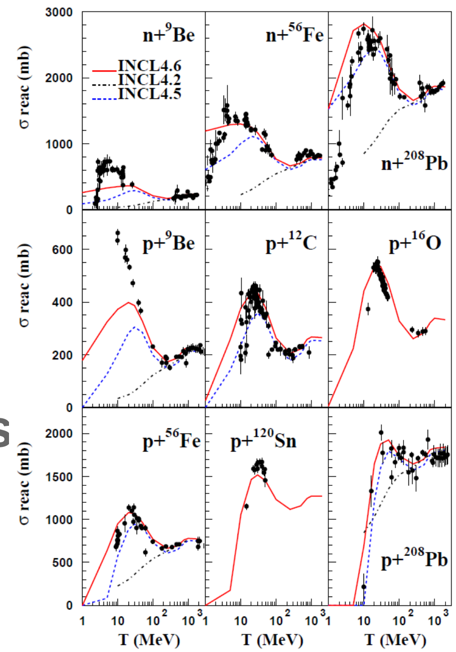


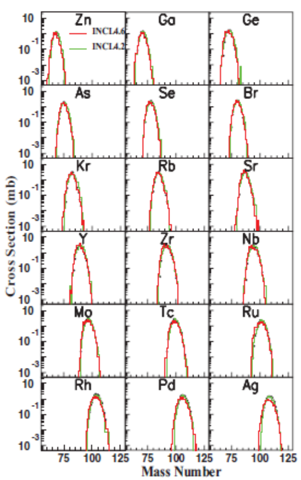
Modelling of spallation reactions

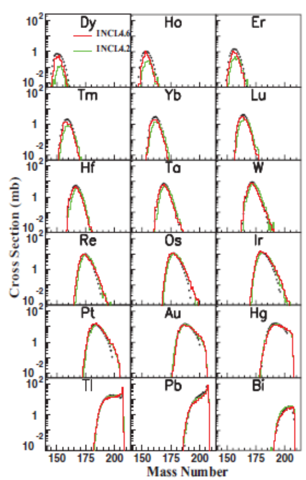
New high quality data

- isotopic distributions of residues at FRS
- excitation function measurements (Michel et al., Titarenko et al.)
- light charged particles DDXS and neutrons multiplicities by the NESSI / PISA collaborations

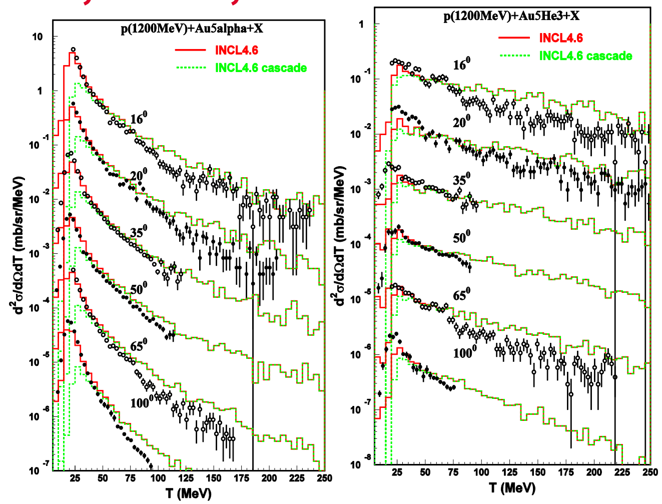
↪ **Highly predictive models for implementation into transport codes: INCL+ABLA, CEM, FLUKA…**



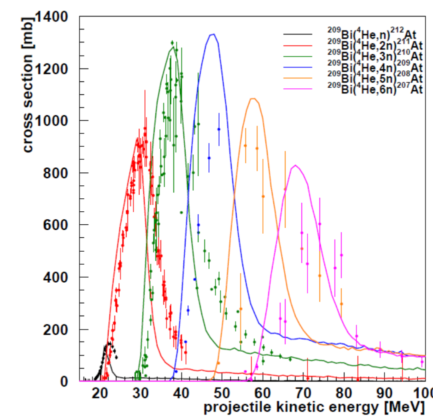




Data fromEnqvist et al.



Data from Herbach et al.

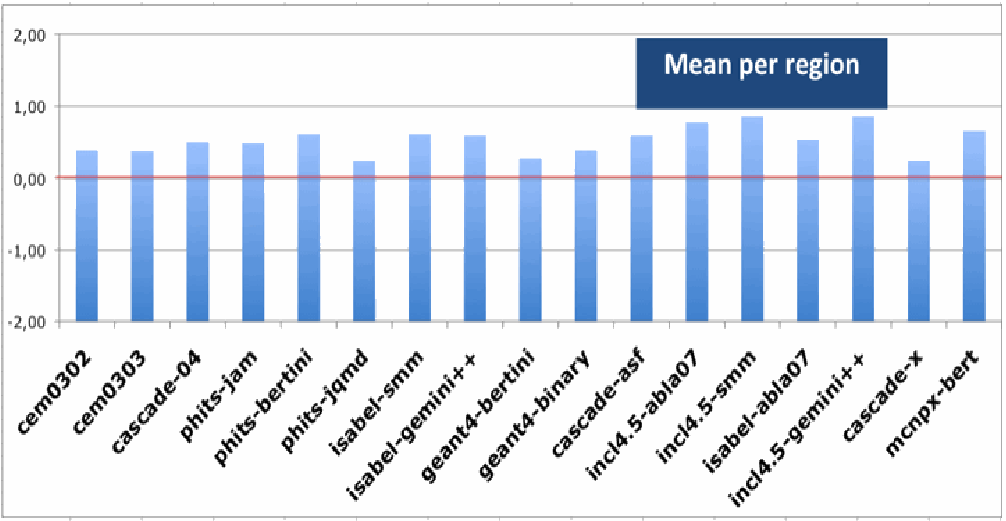


From A. Boudard et al., Phys. Rev. C 87, 014606 (2013)

IAEA benchmark of spallation models

Neutron double differential cross-sections global analysis:

Division of the spectra in 4 energy regions: evaporation, pre-equilibrium, pure cascade and quasi-elastic

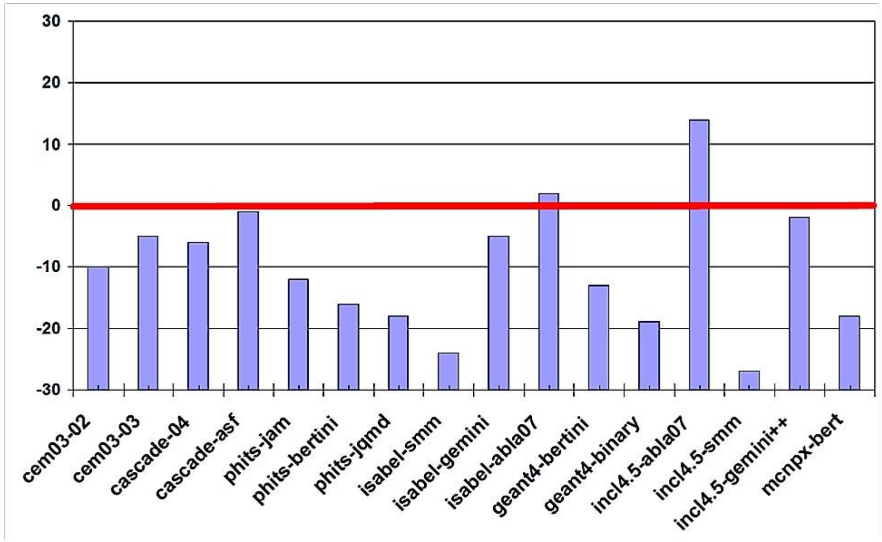


http://www-nds.iaea.org/spallations

Residue global analysis:

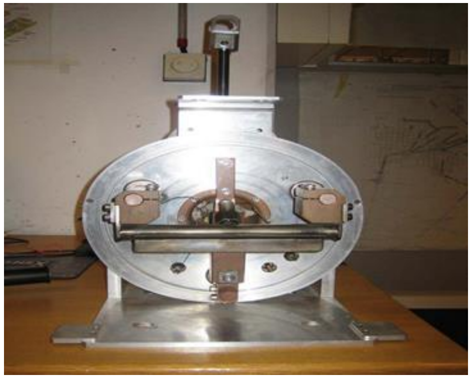
Division of the distributions in mass/charge regions: evaporation residues, deep spallation, fission and intermediate mass fragments

Isotopic distributions



Quality	Points
Good	2
Moderately good, minor problems	1
Moderately bad, particular problems	-1
Unacceptably bad, systematically wrong	-2

PRODUCTION OF AT IN THE ISOLDE LBE TARGET



Measurement of At isotopes released from a liquid lead-bismuth (LBE) target irradiated by a proton beam of 1.4 and 1 GeV at ISOLDE (Y. Tall et al., ND2007)

♦ **not reproduced by any calculation**

Two production channels:

➢ **Double charge exchange (p,π⁻) induced by primary protons**

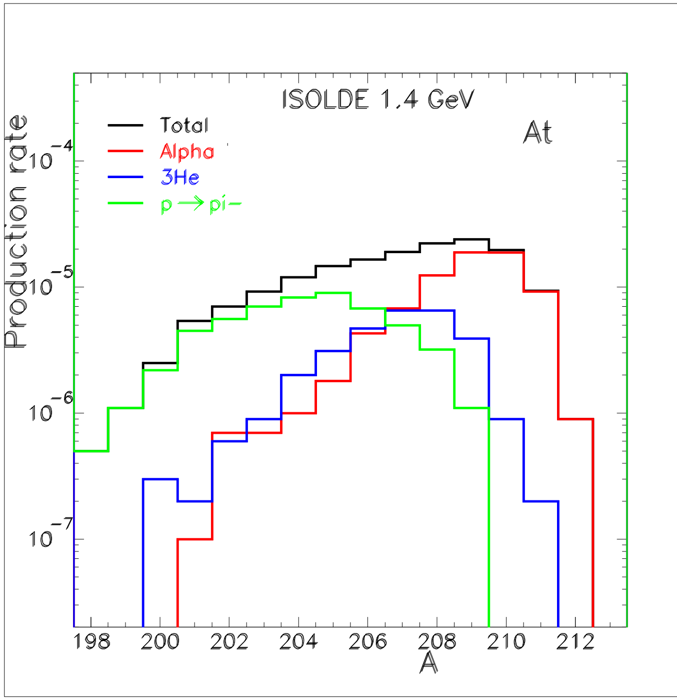
$$p + {}_{83}Bi \rightarrow {}_{85}At + xn + \pi^-$$

➥ **dominant for light isotopes (A ≤ 206)**

➢ **Secondary reactions induced by helium nuclei**

$${}_2He + {}_{83}Bi \rightarrow {}_{85}At + xn$$

➥ **dominant for heavy isotopes**

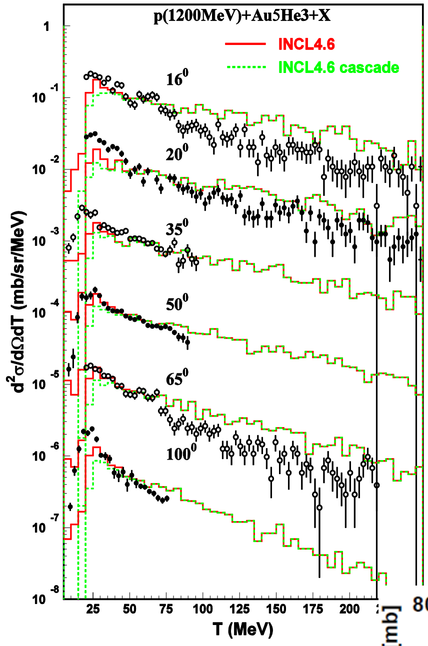


From David et al. EPJA (2013)

Calculations with INCL4.6-ABLA07 in MCNPX2.7.b

SECONDARY HELIUM-INDUCED REACTIONS

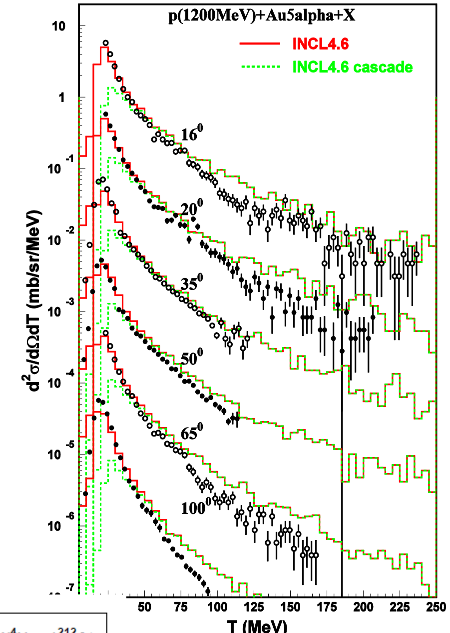
Helium production in primary reactions



^{3}He

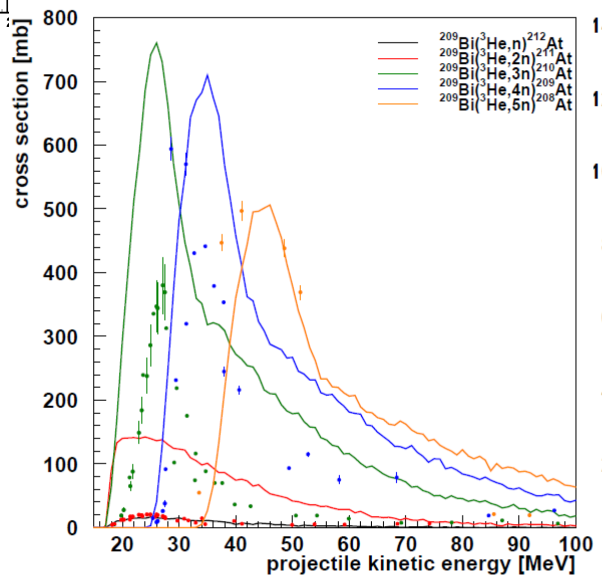
p(1200 MeV) + Ta
(Herbach et al.)

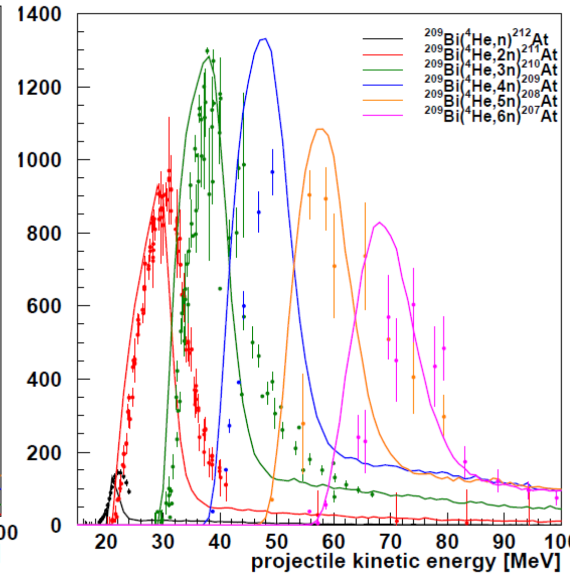
^{4}He



Calculation: INCL4.6 coupled to ABLA07

Excitation functions (^{3}He,xn) (^{4}He,xn)





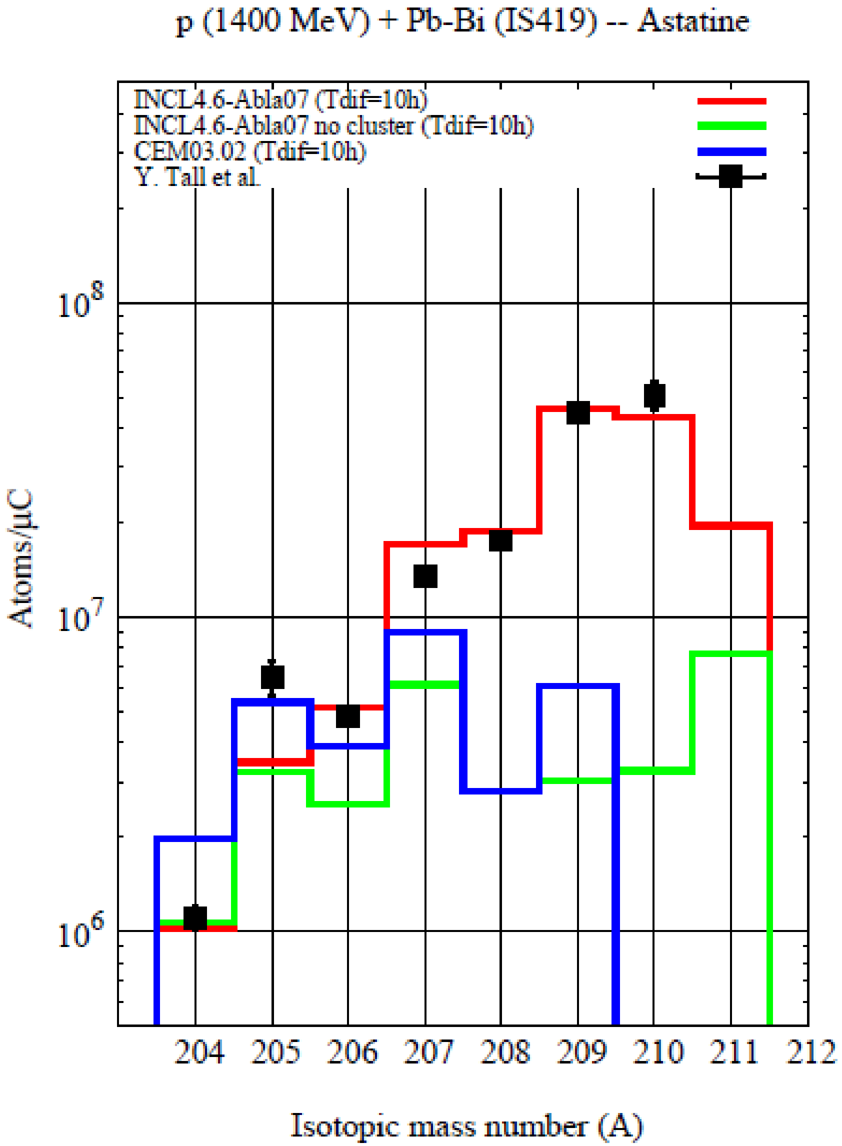
PRODUCTION OF At IN ISOLDE LBE TARGET

Calculations: INCL4.6-ABLA07 in MCNPX2.7.b

- Importance of predicting correctly high-energy helium
- Much better than CEM03

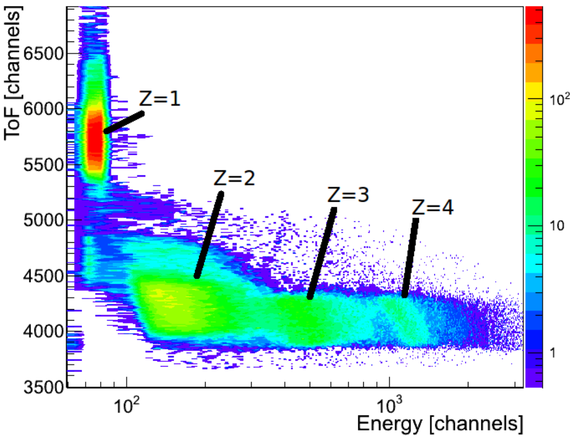
Data from Y. Tall et al., ND2007

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



- aiming at a full kinematical reconstruction of the reaction by measuring in coincidence all the reaction products

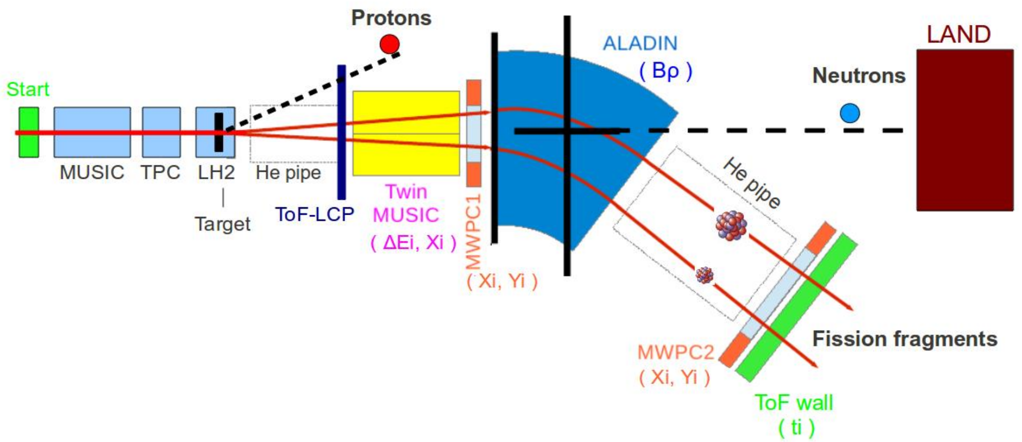
- providing a deeper understanding of the reaction mechanism and severe constraints on the models

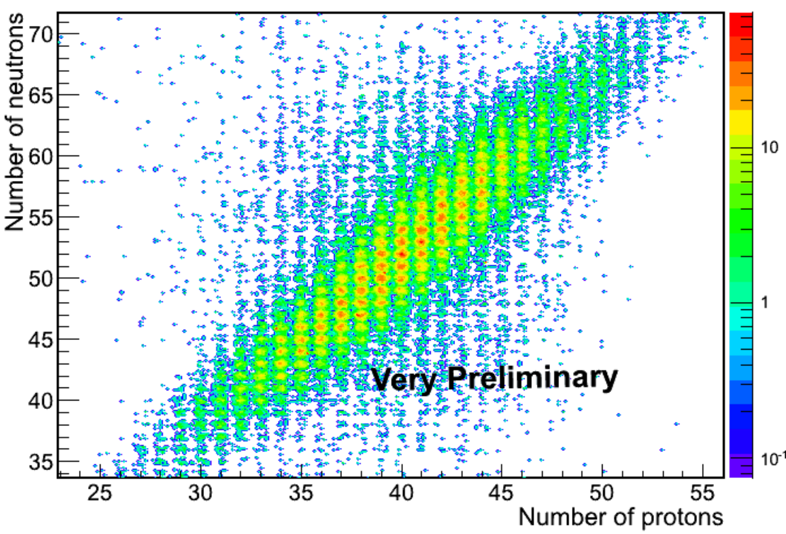


From J. Benlliure, ANDES meeting Oct. 2013)

The SOFIA experiment

(coll. CEA/Bruyères, IPNO, Univ. Santiago de Compostella)





CONCLUSIONS

- Nuclear energy will continue developing in the future
- Enhancement of safety, new types of reactors (Gen-IV), minimisation/transmutation of waste requires high quality nuclear data and models
- Nuclear physicists have played and will still play a major role by providing facilities, innovative experimental techniques and theoretical models

solving CHAlenge in Nuclear DAta

- access to the available EU nuclear data facilities
- upgrade of neutron facilities 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 nuclear models