New trends in nuclear physics applications

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Importance of Nuclear Physics applications

From the beginning of its history, Nuclear Physics always closely tied to applications, in particular energy and medicine

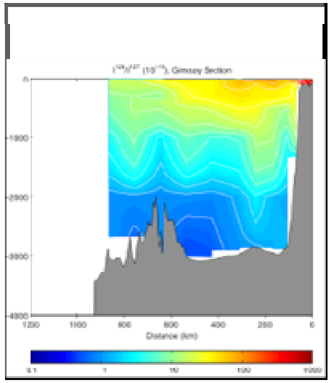
Marie Curie and her daughter Irène at the Hoogstade Hospital in Belgium, 1915. Copyright © Association Curie Joliot-Curie

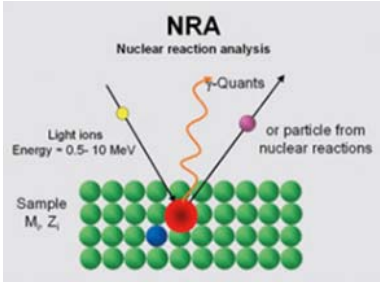
The Birth of the Atomic Age was captured by Gary Sheahan to remember Enrico Fermi, Chicago Pile-1 and the first sustained nuclear chain reaction. Used with permission of the Chicago Historical Society.

Today, both renewed interest from nuclear physicists and new opportunities provided by innovating methods and tools

Domains of applications

- ***Nuclear energy***
- ***Security***
- ***Life science***
- ***Space***
- ***Environment***
- ***Material science***
- ***Cultural heritage, arts and archaeology***





Della Robbia sculptures
Museo del Bargello (Firenze)

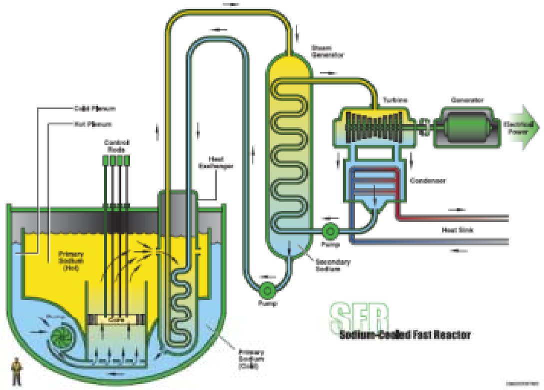
Nuclear energy

- ***Increase in energy demand, need for CO_2-free energies***

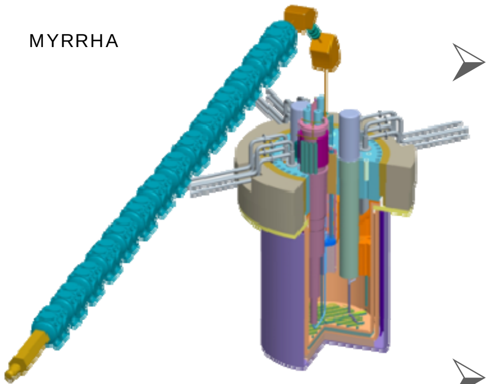
➔ ***development of nuclear energy (despite Fukushima)***

↳ ***Advanced options for nuclear energy generation***

- ***Next generation fission reactors (Gen-IV)***
  - *inherent safety*
  - *sustainability*
  - *economics*
  - *proliferation resistance*

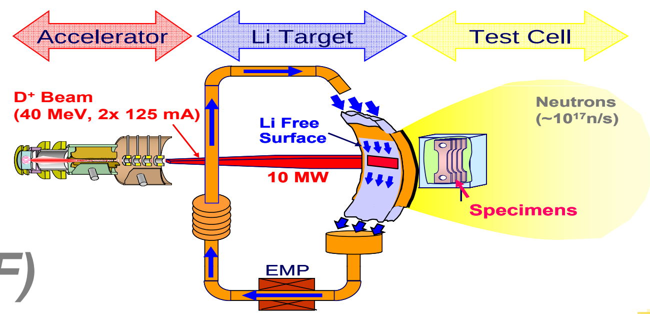


MYRRHA



- ***Accelerator-driven sub-critical reactors***
  - *Transmutation of nuclear waste in dedicated systems*
  - *Demonstrator (MYRRHA)*

IFMIF



- ***Fusion reactors***
  - *ITER, DEMO*
  - *Material test facility (IFMIF)*

COUNTRY	REACTORS OPERABLE May 2012		REACTORS UNDER CONSTRUCTION May 2012		REACTORS PLANNED May 2012		REACTORS PROPOSED May2012	
	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Argentina	2	935	1	745	2	773	1	740
Armenia	1	376	0	0	1	1060		
Bangladesh	0	0	0	0	2	2000	0	0
Belarus	0	0	0	0	2	2000	2	2000
Belgium	7	5943	0	0	0	0	0	0
Brazil	2	1901	1	1405	0	0	4	4000
Bulgaria	2	1906	0	0	1	950	0	0
Canada	17	12044	3	2190	3	3300	3	3800
Chile	0	0	0	0	0	0	4	4400
China	15	11881	26	27640	51	57480	120	123000
Czech Republic	6	3764	0	0	2	2400	1	1200
Egypt	0	0	0	0	1	1000	1	1000
Finland	4	2741	1	1700	0	0	2	3000
France	58	63130	1	1720	1	1720	1	1100
Germany	9	12003	0	0	0	0	0	0
Hungary	4	1880	0	0	0	0	2	2200
India	20	4385	7	5300	16	14300	40	49000
Indonesia	0	0	0	0	2	2000	4	4000
Iran	1	915	0	0	2	2000	1	300
Israel	0	0	0	0	0	0	1	1200
Italy	0	0	0	0	0	0	10	17000
Japan	50	44396	3	3036	10	13772	5	6760
Jordan	0	0	0	0	1	1000		
Kazakhstan	0	0	0	0	2	600	2	600
Korea DPR (North)	0	0	0	0	0	0	1	950
Korea RO (South)	23	20787	3	3800	6	8400	0	0
Lithuania	0	0	0	0	1	1350	0	0
Malaysia	0	0	0	0	0	0	2	2000
Mexico	2	1600	0	0	0	0	2	2000
Netherlands	1	485	0	0	0	0	1	1000
Pakistan	3	725	2	680	0	0	2	2000
Poland	0	0	0	0	6	6000	0	0
Romania	2	1310	0	0	2	1310	1	655
Russia	33	24164	10	9160	17	200000	24	24000
Saudi Arabia	0	0	0	0	0	0	16	20000
Slovakia	4	1816	2	880	0	0	1	1200
Slovenia	1	696	0	0	0	0	1	1000
South Africa	2	1800	0	0	0	0	6	9600
Spain	8	7448	0	0	0	0	0	0
Sweden	10	9399	0	0	0	0	0	0
Switzerland	5	3252	0	0	0	0	3	4000
Thailand	0	0	0	0	0	0	5	5000
Turkey	0	0	0	0	4	4800	4	5600
Ukraine	15	13168	0	0	2	1900	11	12000
UAE	0	0	0	0	4	5600	10	14400
United Kingdom	16	10038	0	0	4	6680	9	12000
USA	104	101607	1	1218	11	13260	19	25500
Vietnam	0	0	0	0	4	4000	6	6700
WORLD**	433	371,422	63	62,174	160	179,655	329	376,255
	No.	MWe	No.	MWe	No.	MWe	No.	MWe
	REACTORS OPERABLE		REACTORS UNDER CONSTRUCTION		ON ORDER or PLANNED		PROPOSED	

Source: World Nuclear Association to 1/5/12

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Nuclear energy

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➔ ***development of nuclear energy (despite Fukushima)***

↪ ***Advanced options for nuclear energy generation***

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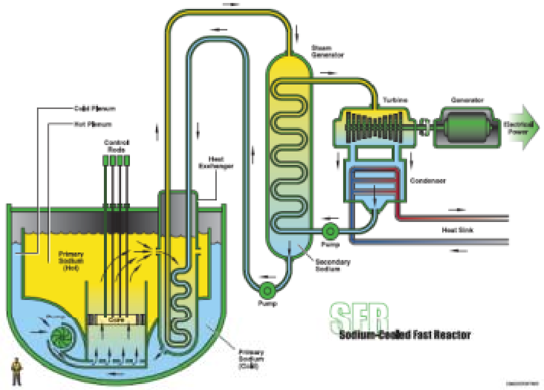

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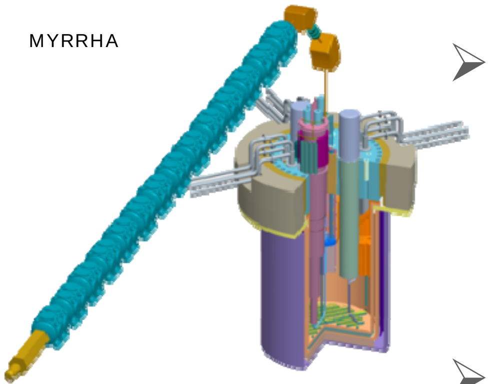

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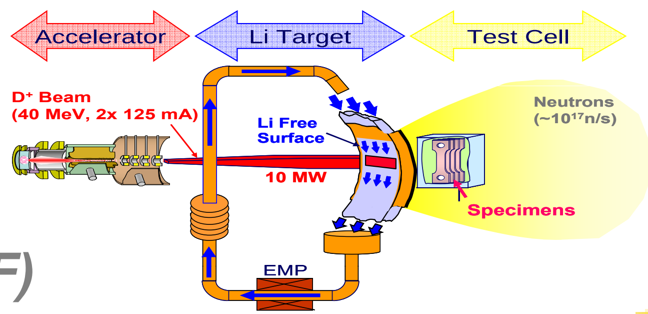
IFMIF



Nuclear energy

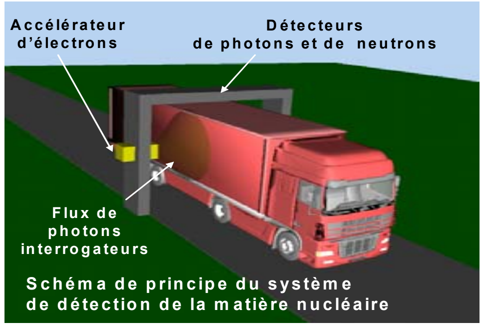
- ***need for accurate nuclear data for:***
  - ***Existing, GenIII reactors***
    - *Optimization of fuel burn-up*
    - *Increase of life time*
    - *Safety margin reduction (decay heat, delayed n fraction)*
  - ***Fast reactors (GenIV)***
    - *Cross-sections on new materials*
    - *Minor actinide transmutation…*
  - ***ADS***
    - *Spallation target radioactive inventory, material damage*
    - *Minor actinide transmutation…*
  - ***Fusion reactors***
    - *Activation data*
    - *(n,xn) for n multiplication, tritium breeding….*

Security

➢ **Detection of concealed fissionable or other radioactive material in airports, ship containers, trucks….**

– *Neutron/photon interrogation techniques*

– *Detection of delayed or prompt gammas or neutrons*



➢ **Detection of explosives, mines**

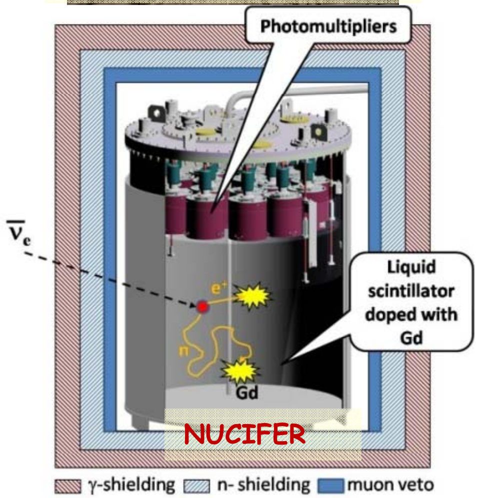
– *technology based on neutron bombardment allows identifying the elemental composition*


From Nebbia et al., LNL

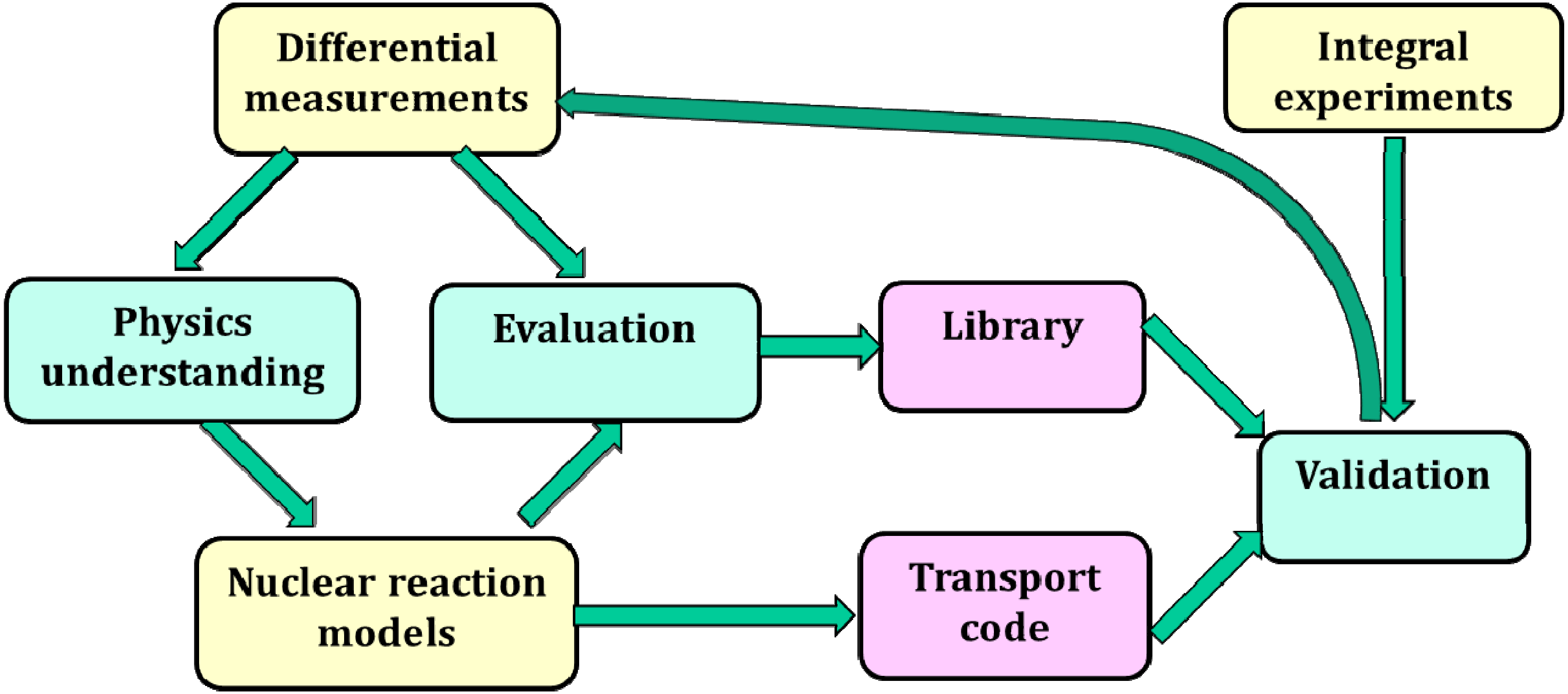
➢ **Non-proliferation control**

– *Use of anti-neutrinos to control possible illicit use of reactors (neutrino spectrum sensitive to the composition of the fuel (Pu/U))*

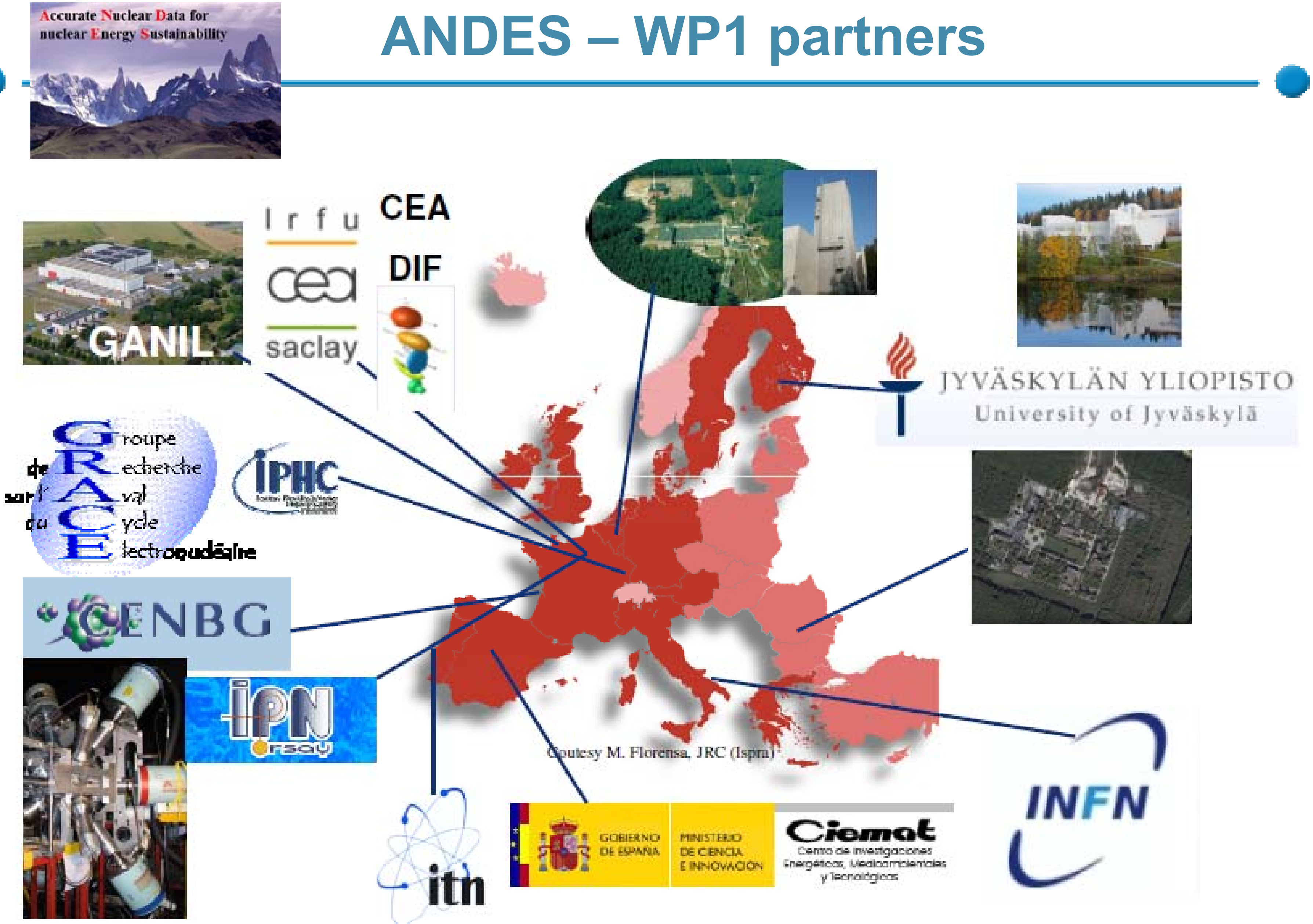
➥ ***Depends on the achievable precision on fission products yields, β-decay***



Nuclear data



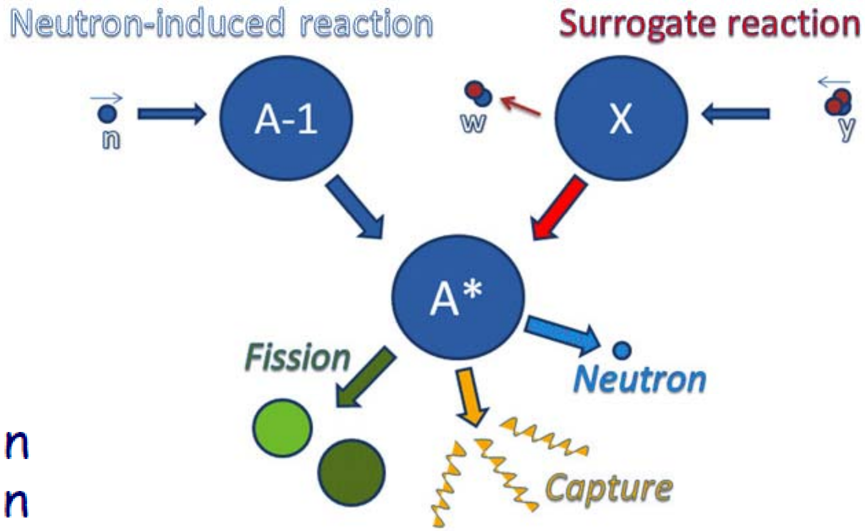
ANDES – WP1 partners



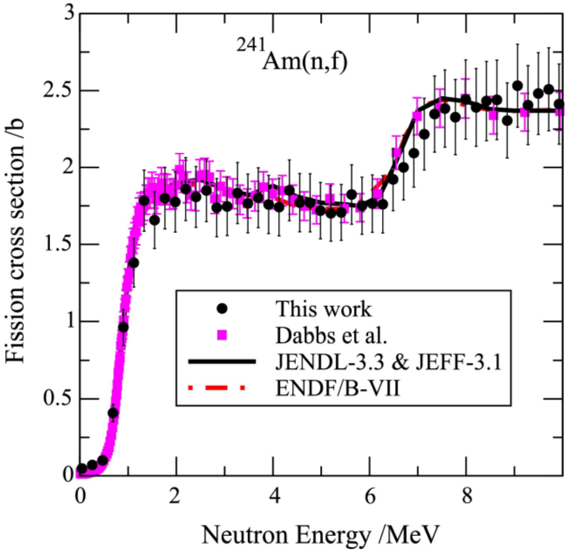
Application to nuclear energy: surrogate reactions

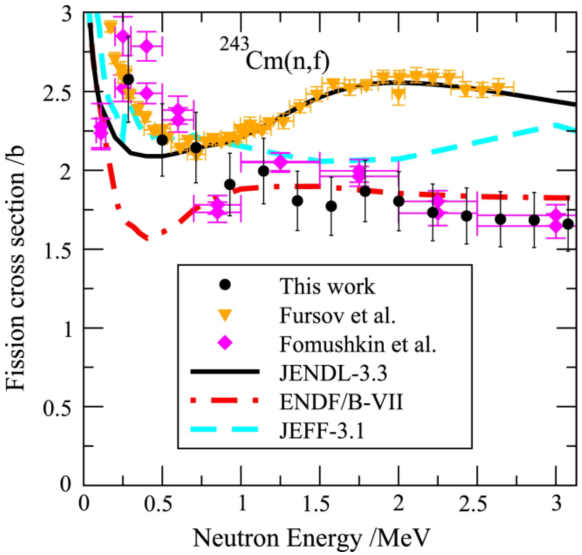
- ***Measurement of cross-sections on isotopes difficultly available as targets***

→ 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

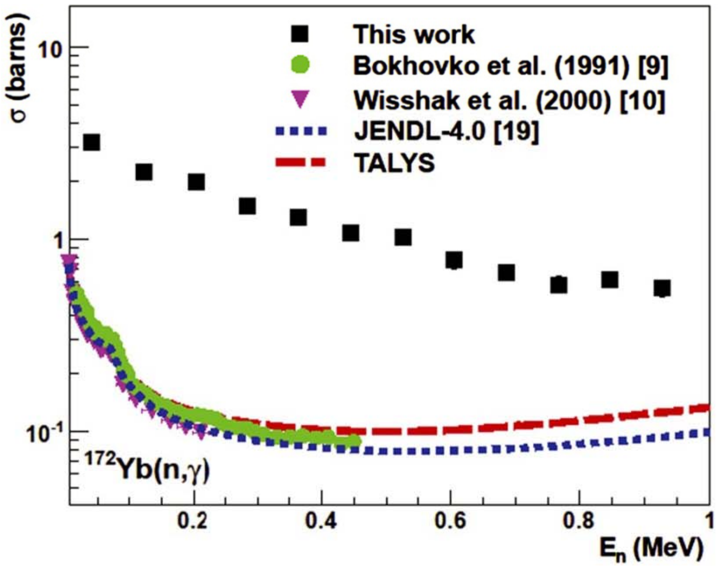
From Kessedjian et al., PL 105, 202501 (2010)

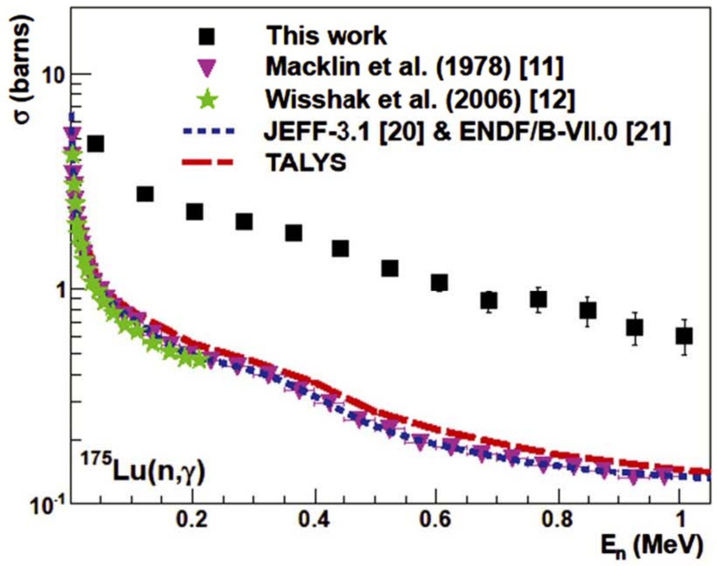
Application to nuclear energy: surrogate reactions

- ***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*

↪ *could however work for actinides for which larger number of states and less sensitivity to J^π population*

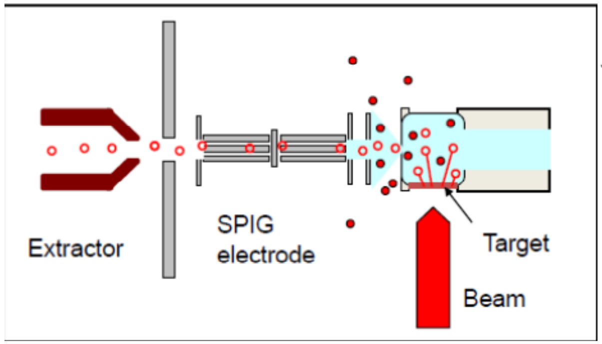
Application to nuclear energy: decay heat calculations

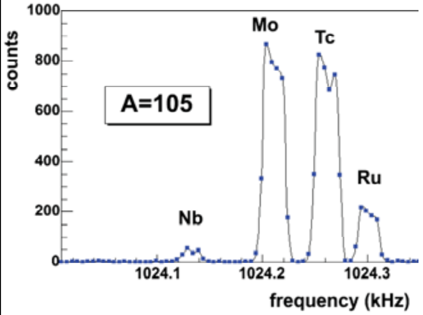
- ***Impact : shorter refueling times, optimized shielding for transfer of spent fuel to reprocessing plants, storage… → target accuracy 10%***

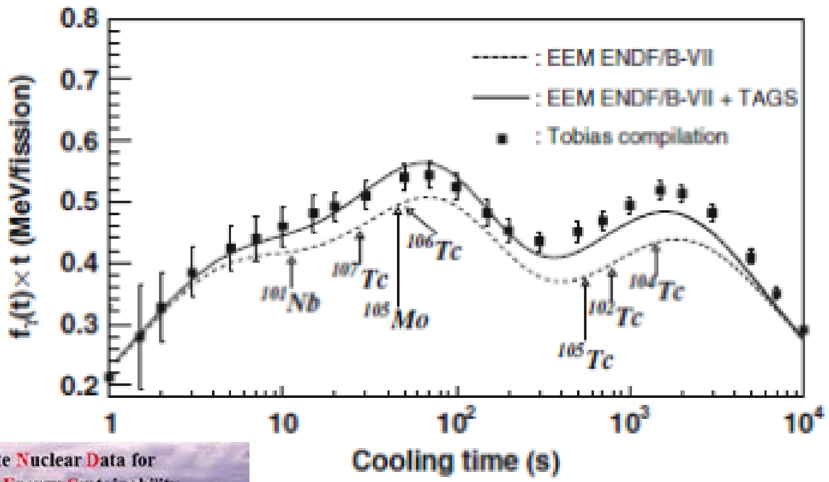
➢ ***need for fission yields, decay data (half-lives, branching ratios, mean β, γ energies***

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

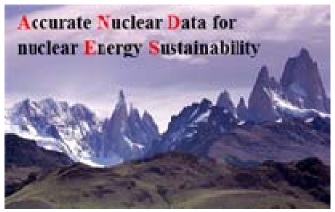
– ***Jyvaskyla IGISOL separator + JYFLTRAP Penning trap for isotopic purification***







↪ ***Also delayed neutron probability measurements with the BELEN-20 detector***



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

irfu
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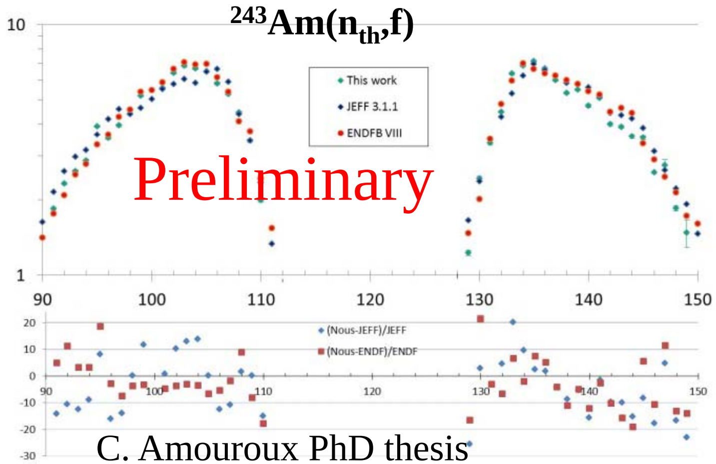
Application to nuclear energy: fission fragment studies

➢ ***Measurements of fission-fragment characteristics***

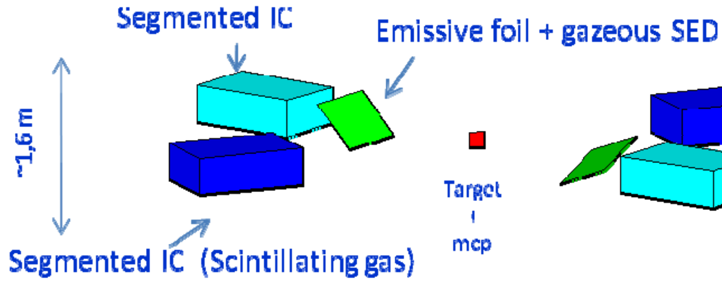
♦ ***with thermal neutrons***

Lohengrin@ILL



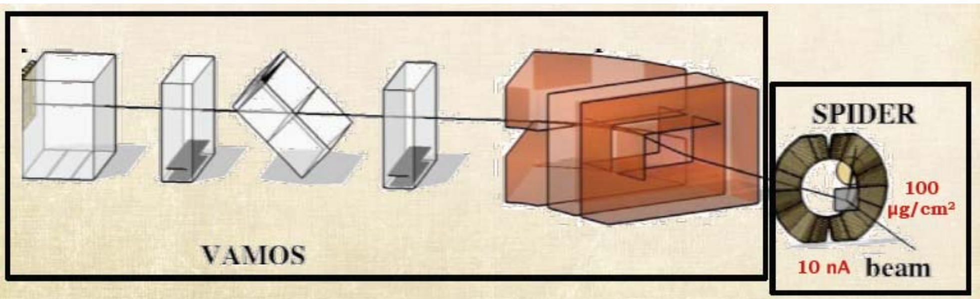
♦ ***with fast neutrons***

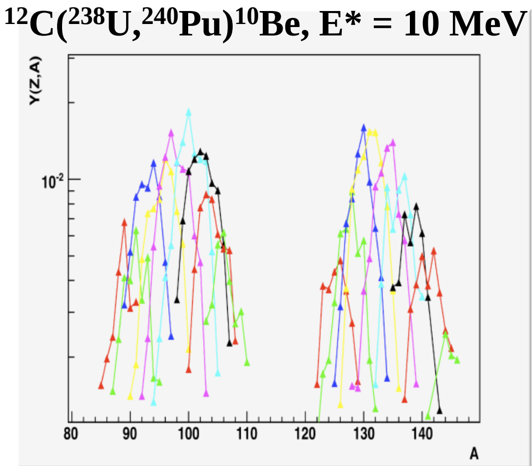
Falstaff@NFS-SPIRAL2



Falstaff 2E-2v spectrometer for NFS

♦ ***through surrogate reactions at GANIL***



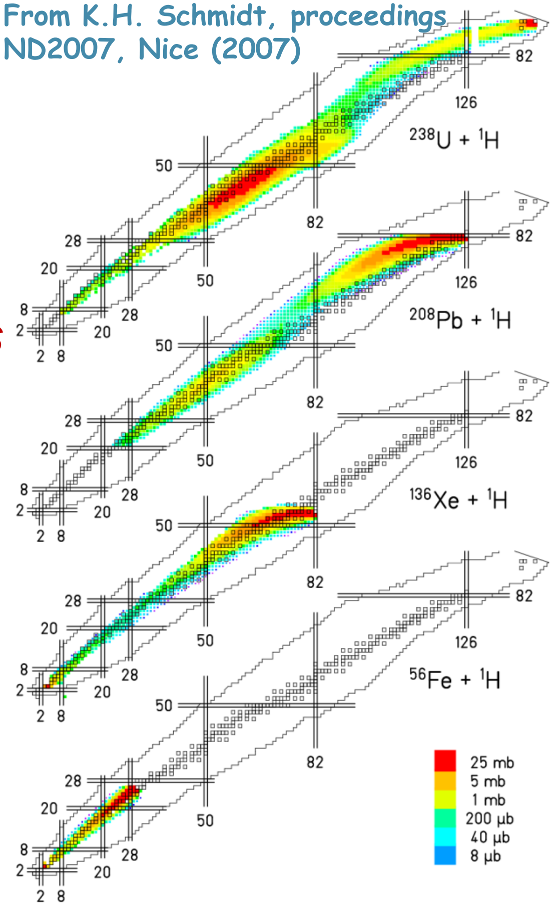


F. Farget, C. Rodríguez-Tajes et al.

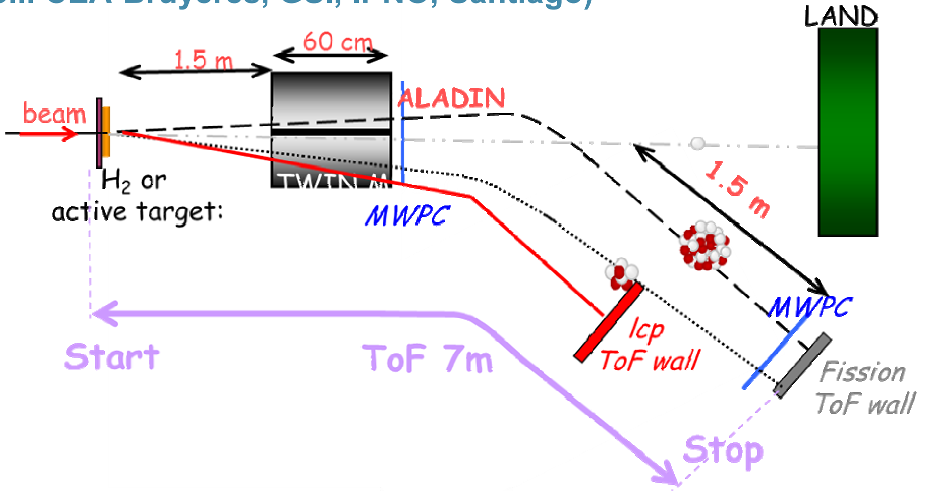
Application to nuclear energy: specific data for ADS

- **Impact :**
  - assessment of radioactivity in the target
  - volatile elements
  - helium and tritium production
  - damages in window and structure materials

From K.H. Schmidt, proceedings ND2007, Nice (2007)



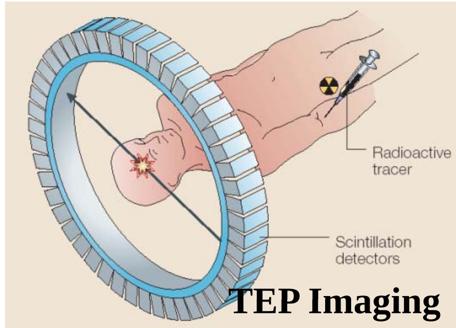
SOFIA@GSI (Coll. CEA-Bruyères, GSI, IPNO, Santiago)

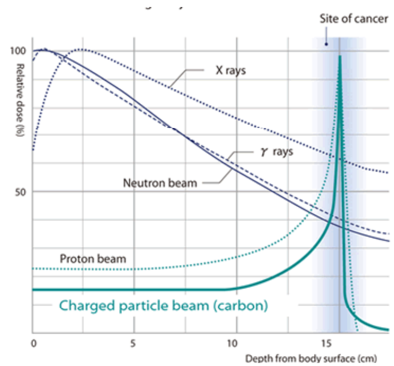


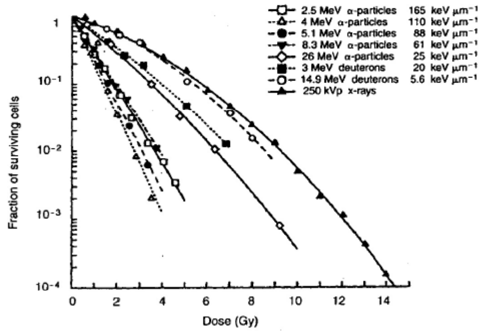
- **further model improvement requires for more constraining experiments**
  - second generation of experiments

Life science

- ***Increasing importance of nuclear tools and methods in the domain of life science***
  - ***Dedicated systems for biomedical imaging :***
    - *New methods for early diagnosis*
    - *Innovating detectors preclinical or clinical imaging*
    - *Control/reduction of radiation doses, moving organs*
  - ***Innovating therapies:***
    - *Development of hadrontherapy*
    - *New radioisotopes for imaging and treatment, vectorized radiotherapy*
  - ***Nuclear tools and methods in radiobiology :***
    - *Study of radiation response*
    - *Effects of low doses*
    - *Development of specific markers*



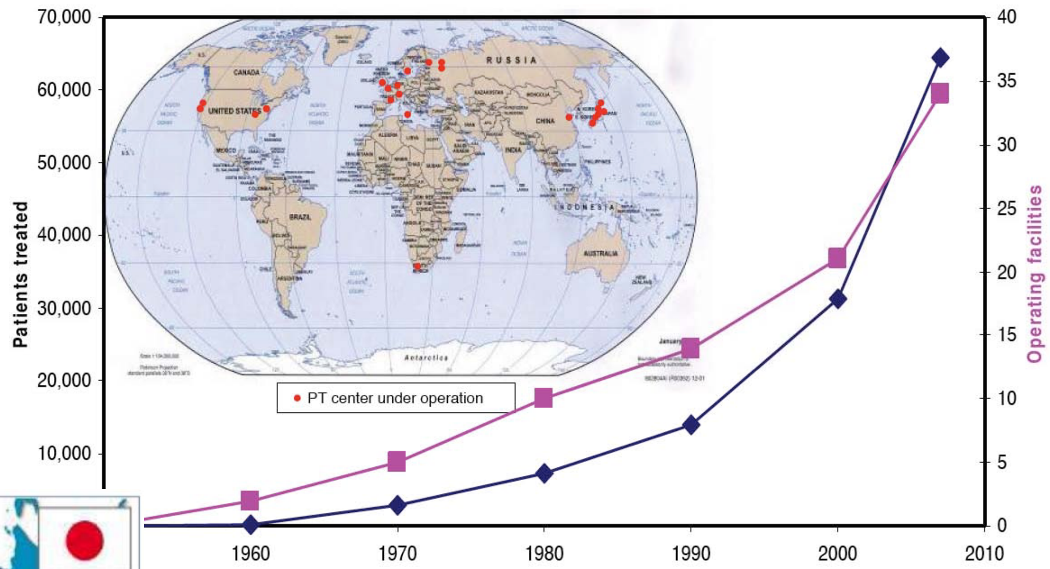


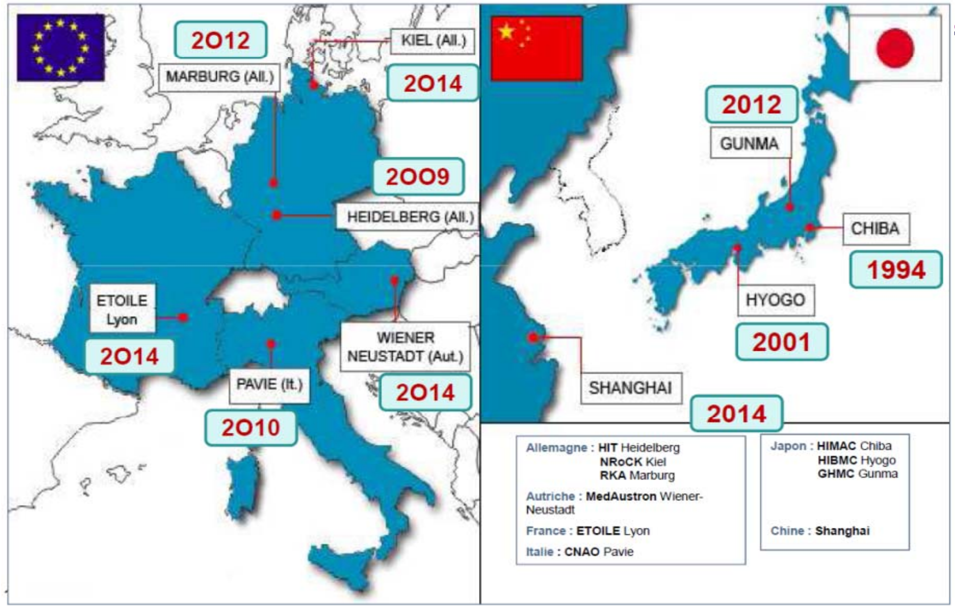


Hadrontherapy

- ***Increasing number of protontherapy centers***

  (70 – 230 MeV)

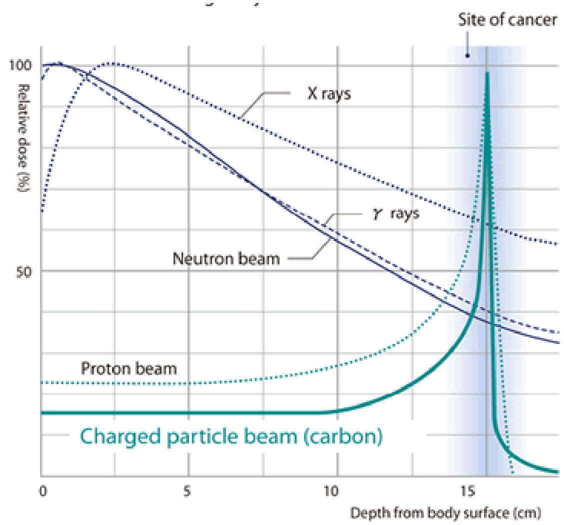




- ***Recent development of carbon therapy (400 MeV/u)***

  European centers (projects):
  HIT, CNAO, MedAustron, Marburg, ETOILE/Archade

Hadrontherapy



➢ Advantages of carbontherapy:

- *balistic*
  - ➥ *high tumor dose, normal tissue sparing*
  - ➥ *mm precision*
- *high relative biological efficiency*
  - ➥ *Effective for radioresistant tumors*
  - ➥ *Effective against hypoxic tumor cells*
- *possibility to use ^{11}C for PET dose control*

➢ Disadvantage

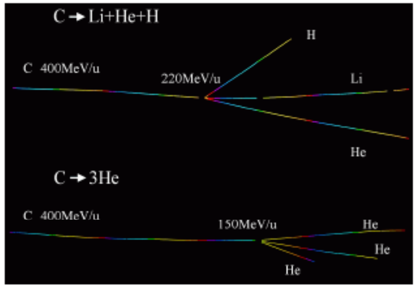
- *fragmentation*
  - ➥ *tail after Bragg peak*
  - ➥ *possible late effects*

➢ other ions (He, Li, O) could be envisaged

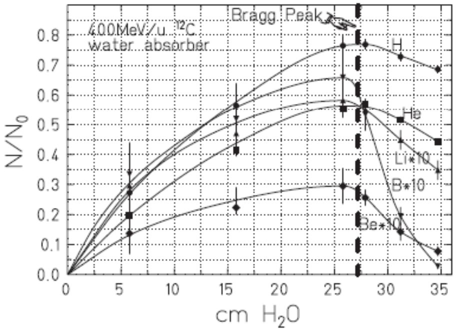
GSI online PET

Medical and space: study of fragmentation

Hadrontherapy: Carbon fragmentation (~50% of the C ions)

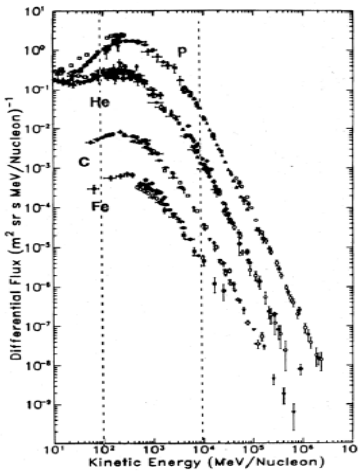


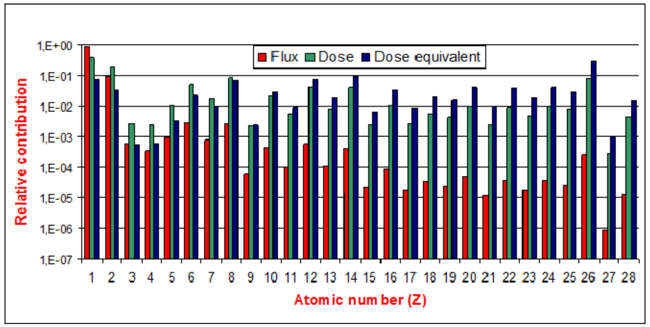
T. Toshito et al., IEEE 2006



E. Haettner et al., (2006)

Space: radiation risk for astronauts, single event upset (SEU) rates for electronics

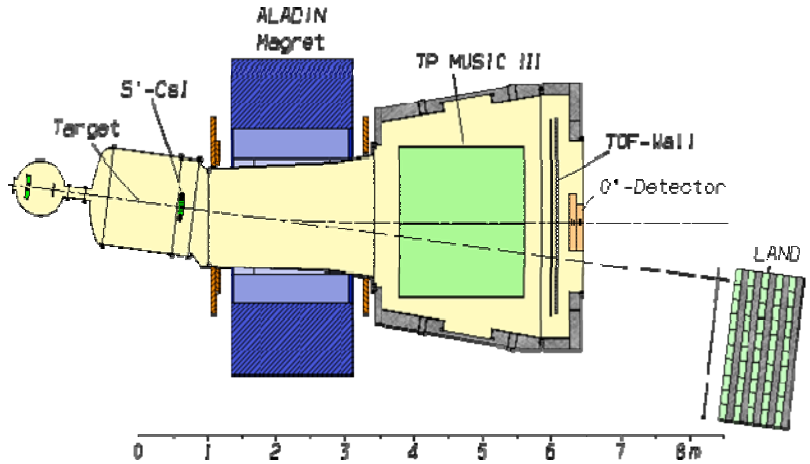




Durante & Cucinotta, Nature Rev. Cancer (2008)

FIRST experiment: Fragmentation of Ions Relevant for Space and Therapy

(INFN - IRFU/SPhN – GSI - ESA)

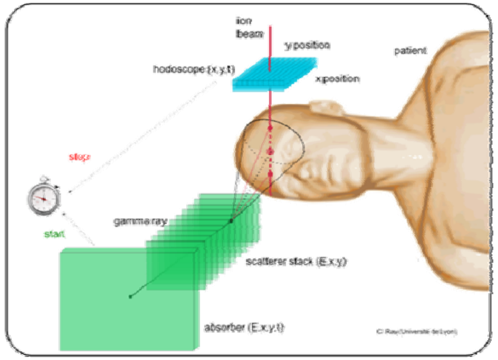


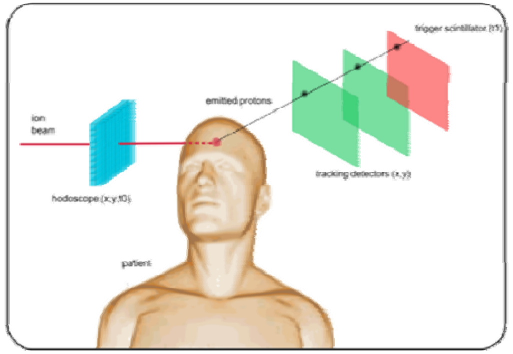
TEP imaging and prompt radiation for on line control

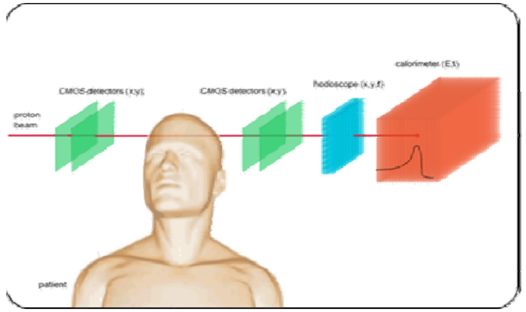
- **TEP using ^{11}C (or ^{15}O) produced in particle therapy**
- **Prompt gammas**
  - Time-of-flight: hodoscope-tagging
  - Compton-camera or collimated gamma-camera
- **Secondary protons**
  - Imaging through vertex reconstruction

(FP7 ENVISION, ITN-ENTERVISION)

- **Proton radiography**
  - In association with proton therapy



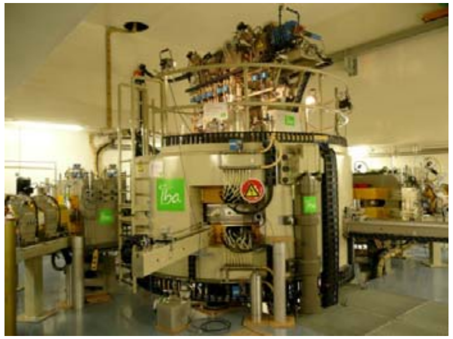




Emerging radio-isotopes

- ***Alternative production modes***

  Production of Mo-99 or Tc99m with accelerators



- ***New needs in nuclear medicine***
  - ***new tracers for fonctional imaging***

    ATSM-Cu-64 for hypoxy measurement, …
  - ***Receptor targeting with radiolabeled peptides***

    Adapting isotope half-life to vector biological period

    Ga-68(68mn), Sc-44(4h), Cu-64 (12.7h), Zr-89(78h)
  - ***Personalized therapy through quantitative imaging***

    couples of isotopes (imaging/therapy):

    Cu-64/Cu-67 ou Sc-44/Sc-47
  - ***best suited isotopes for therapy (alpha / beta)***

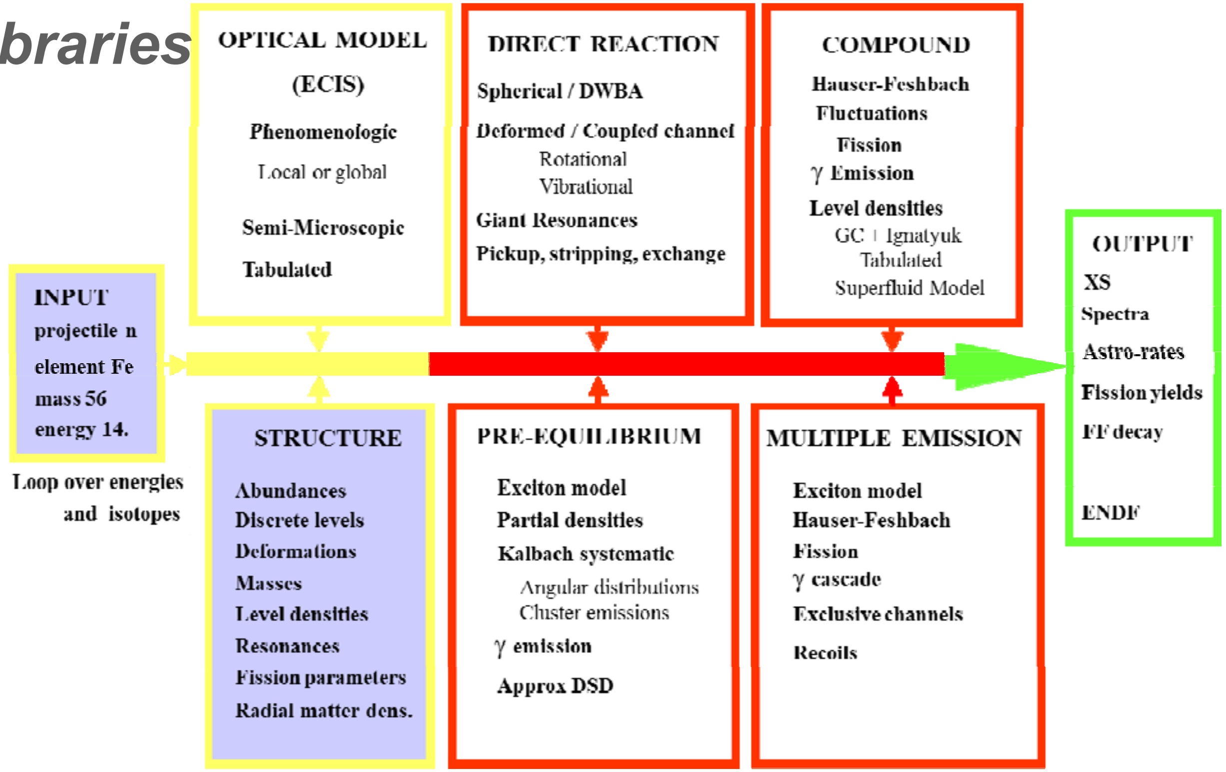
    At-211 alpha emitter

Nuclear reaction models

- ***Low / intermediate energies (up to 150-200 MeV)***

Models generating libraries

ex: TALYS
(A. Koning et al.)



- ***High-energies***

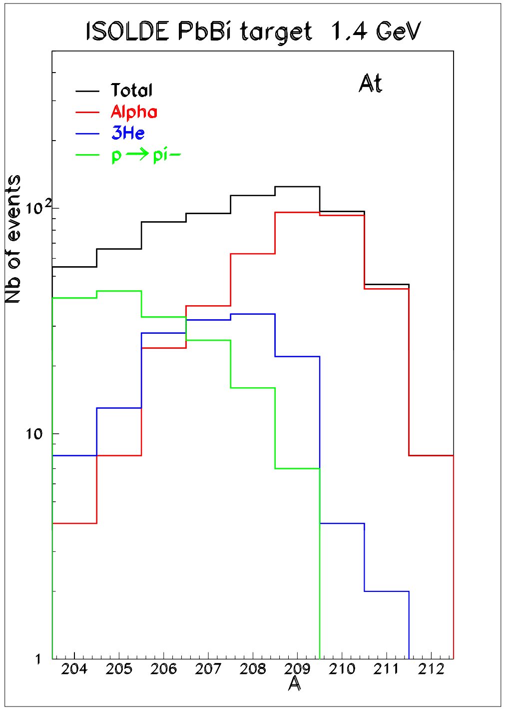
Models implemented into high-energy transport codes (MCNPX, GEANT4, PHITS…)

Intra-Nuclear Cascade + de-excitation (ex: INCL4-ABLA)

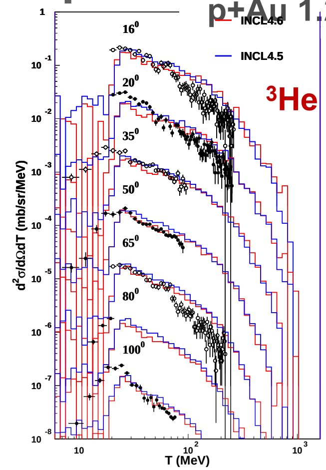
Production of At isotopes in ISOLDE experiment

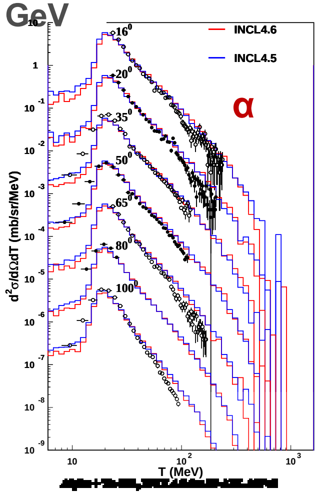
Two production channels:

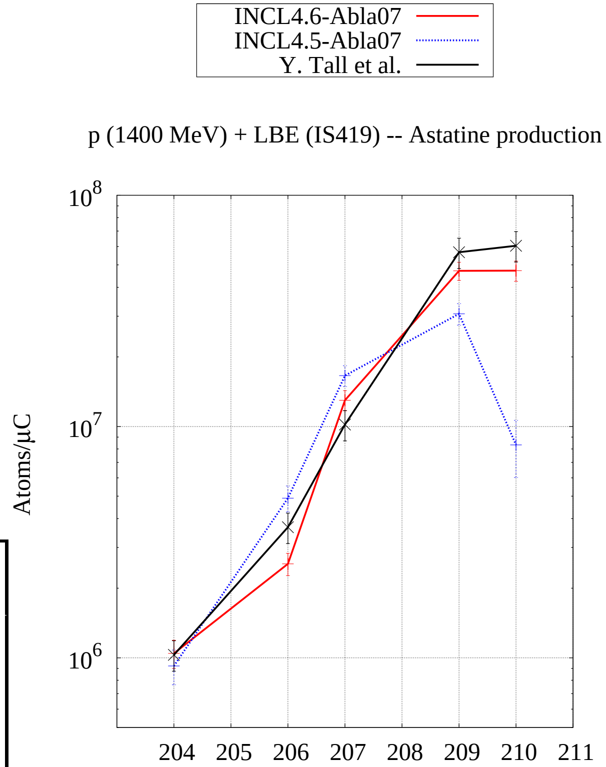
- ➢ **secondary reactions induced by heliums for heavy isotopes**
- ➢ **Bi (p,π⁻) for light isotopes**



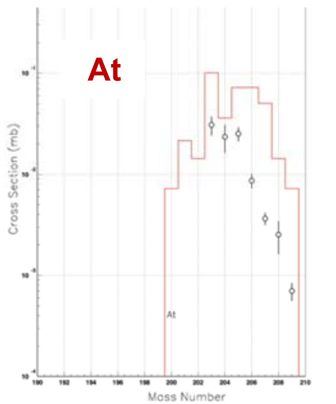
p+Au 1.2 GeV

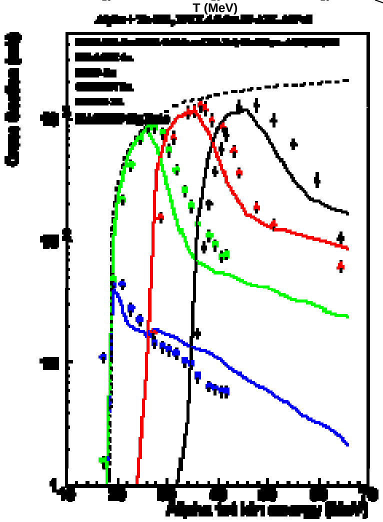






p (480 MeV) +Bi





Data from Y. Tall et al., ND2007

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

Conclusion

- ***Nuclear physicists have an important role in a large number of interdisciplinary fields, and in particularly in energy and medical applications***
  - ➥*Measurements of nuclear data with the most appropriate and innovating techniques*
  - ➥*Fundamental understanding of reaction mechanism in order to develop reliable and predictive nuclear reaction models*
  - ➥ *innovating instrumentation*

- ***Continuity between fundamental research and applications***