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

SYLVIE LERAY
CEA/SACLAY, IRFU
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 CO₂ emissions

Electricity

CO₂ emissions

Source: IEA Key world energy statistics 2014
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
### Nuclear Electricity Generation 2014

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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

Source: World Nuclear Association (May 2015)
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 addressed.
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

Differential measurements

Physics understanding

Evaluation

Nuclear reaction models

Library

Transport code

Integral experiments

ENDF/B-VII, JEFF-3, JENDL-4

MCNP5, MCNPX, PHITS, FLUKA...

GNASH, TALYS, INCL, CEM...
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)
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**

**241Am(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

- Very few data with large discrepancies before nTOF measurement

M. Calviani et al., PRC 85, 034616 (2012)
Measurement of cross-sections on isotopes difficultly available as targets

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

\[
\begin{align*}
^{242}\text{Am} + \alpha & = ^{241}\text{Am} + n \\
^{243}\text{Cm} + t & = ^{242}\text{Cm} + n \\
^{244}\text{Cm} + d & = ^{243}\text{Cm} + n
\end{align*}
\]

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

assumes same Jπ 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
• Measurement of capture cross-sections?

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

\[ ^{174}\text{Yb}(^{3}\text{He},\alpha\gamma)^{173}\text{Yb}^* \]

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

→ Difference due to different \( J^\pi \) population in the direct and transfer reactions and \( n/\gamma \) competition

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

Simultaneous measurement of fission and gamma-decay probabilities

→ Precursor experiment at OSLO cyclotron

- 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

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

→ Also important for antineutrino spectra

From Algara et al., PRL 105, 202501 (2010)
Isotopic fission yields from compound nuclei produced in transfer reactions at GANIL

- Access to nuclei above U
- $E^*$ determined assuming no excitation of the light transfer 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

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

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

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

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

J.F. Martin, PhD thesis

From A. Chatillon et al., CHANDA Meeting April 2015
HIGH-ENERGY DATA
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

3He DDXS in p+\(^{56}\)Fe, at 175 MeV
Bevilacqua et al., PRC (2015)

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

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).
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.

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 cm³
• Fuel element: U₃Si₂Al, 20% ²³⁵U
• Refueling: 1/7ᵗʰ 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. Catania, June 21-26, 2015
• 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

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