Generation IV nuclear energy systems and the need of accurate nuclear data

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Abstract. To satisfy the world’s demand of energy, constantly increasing over the years, a suitable mix of different energy sources has to be envisaged. In this scenario, an important role may be played by nuclear energy, provided that major safety, waste and proliferation issues affecting current nuclear reactors are satisfactorily addressed. In this respect, a large effort is under way since a few years towards the development of advanced nuclear systems that would use more efficiently the uranium resources, and produce a minimal amount of long-lived nuclear waste. The main activity concerns Generation IV reactors, with full or partial waste recycling capability. Their design requires R&D in numerous fields. Among the different needs, it is of fundamental importance to improve the knowledge of basic nuclear data, such as cross-sections for neutron-induced reactions on actinides. The main characteristics and principle of operation of the new generation nuclear systems are here described, together with the related needs of new and accurate nuclear data. Finally, an example of activity currently undergoing in the field is shown, with the recent experimental results obtained at the neutron facility n_TOF at CERN.

1. Introduction
The constant increase in the world population, as well as a global improvement in the life standards, is resulting in a continuously growing demand of energy. Figure 1 shows the world population (left panel) and the primary energy consumption (right panel) over the last 25 years [1]. A comparison with the expectations based on the per-capita consumption of 1980 (green curve) shows that since the beginning of the new millennium, the energy needs are increasing at a faster rate than the world population, mostly due to the economic growth in highly populated areas like Brazil, Russia, India and China. Based on these considerations, the demand of energy is going to continue to raise in the future, and by 2030 it is foreseen to increase by 50 % relative to the current value.

Figure 2 shows the current share of different fuels in the total primary energy supply (TPES), which includes transportation (left panel) and in the electricity production (right panel). At present, a large fraction of the energy needs is supplied by fossil fuels. In fact, oil, coal and natural gas contribute with more than 85 % to the TPES and with 75 % to the electricity production. Among other sources, hydroelectric and nuclear energy significantly contribute to electricity production, while the share of other renewable sources (solar, wind, tide) is around 2 % in electricity production, and almost negligible in the total energy supply. It is clear that the current situation cannot be sustained much longer. The use of fossil fuels, in fact, poses severe environmental problems, due to the large production of CO₂, the main cause of the greenhouse effect and related climatic changes, and of other pollutants. Furthermore, the extraction of fossil
Figure 1. (Color online) Increase of the world’s population (left panel), and of the global energy consumption (right panel), over the last 25 years. The actual energy needs (in British Thermal Units), shown by the blue curve, are compared with the trend estimated on the basis of the world’s population, assuming a constant per-capita value of 1980 (green curve). The effect of the growth of the BRIC countries in the last few years is evident.

fuels is expected to reach a peak in a few years, with a consequent increase in the costs and uncertainties in the availability of this source.

It is therefore becoming urgent to find alternative energy supplies, that are safe, clean and possibly economic. In the short and medium term, a more efficient use of the energy resources may partially counterbalance the continuous growth of the energy demand. Furthermore, the R&D on renewable energy sources, in particular from solar and wind, may lead to an increased contribution from these sources. However, it is generally believed that an important role in the mix of energy sources of the future could be played by nuclear energy. The contribution of this energy supply may in principle become important even in the field of transportation, if large-scale production of hydrogen by nuclear energy is implemented.

As of today, 439 nuclear power plants are operating, mostly in countries members of the Organization for Economic Co-operation and Development (OECD), contributing by approximately 6 % to the total energy consumption and by 15 % to the electricity production alone. Most of the currently operating reactors are Generation II reactors. Generation III reactors, with enhanced safety and efficiency, are already available while a more advanced class (the so-called Generation III+) are expected to become available in a few years. Most of the world’s currently operating nuclear power plants, which started operation in the 70’s and were originally certified for a 40-year operation, are expected to apply for a 20-year license extension. As a consequence, by 2030 many of them will be at or near the end of their life and will need to be replaced. Research is therefore now being carried out with the objective of developing future-generation nuclear energy systems and making them available for international deployment by 2030. An international cooperation, the Generation IV Forum [2], was set-up a few years ago aiming at defining the technology roadmap towards the development of advanced nuclear
systems that would address safety, waste, economic and proliferation concerns. R&D is required in many areas, such as fuel cycle, fuel preparation and reprocessing, new materials for structural elements and for monitoring systems, risk assessment, etc. Among the request, an important part concerns improvements in the knowledge of basic nuclear data involved in the reactor’s physics. In this talk, the main features of the new generation reactors and the need of accurate nuclear data, mostly on cross-sections for neutron-induced reactions, will be discussed.

2. Current issues in nuclear energy production
The present nuclear reactors are based on the so-called “once-through” process, in which the U fuel, after preparation, goes through the reactor core only once. After the irradiation period, ranging from 8 to 13 months in most reactors, the spent fuel is removed and stored (either in temporary or permanent repositories). The efficiency of the “once-through” cycle, in terms of uranium resources utilization, is quite low. Most importantly, it generates large quantities of nuclear waste for which a suitable repository has to be found.

The main concerns that currently limit a larger use of nuclear energy are related to safety issues in current power plants, to the production of large volumes of radioactive waste to be handled and eventually stored in geological repositories, and to the so-called proliferation issue, that is the possibility to divert part of the fresh or spent fuel for military or terroristic purposes. On a longer time-scale, the issue of the availability of uranium resources may also become a limiting factor in the use of nuclear energy. Estimates of the available resources indicate that, at the current rate, the availability of Uranium may become a problem in 50 to 100 years, but a possible increase in the share of nuclear energy in the near future may lead to availability problems on a shorter time-scale.
Table 1. Main components of the nuclear waste produced in current nuclear reactors, their half-life, and the total amount produced in France.

| Component          | Isotope  | Half-life (years) | Quantity (kg/year) |
|--------------------|----------|-------------------|-------------------|
| Fission Fragments  | $^{135}\text{Cs}$ | $2.3 \times 10^6$ | 400               |
| (39 ton/year)      | $^{99}\text{Tc}$ | $2.1 \times 10^5$ | 1000              |
|                    | $^{93}\text{Zr}$ | $1.5 \times 10^6$ | 900               |
|                    | $^{129}\text{I}$ | $1.0 \times 10^7$ | 200               |
|                    | $^{107}\text{Pd}$ | $6.5 \times 10^6$ | 250               |
| Plutonium          | $^{238}\text{Pu}$ | 88                | 190               |
| (11.4 ton/year)    | $^{239}\text{Pu}$ | $2.4 \times 10^4$ | 6500              |
|                    | $^{240}\text{Pu}$ | $6.5 \times 10^3$ | 2500              |
| Minor Actinides    | $^{237}\text{Np}$ | $2.1 \times 10^6$ | 480               |
| (1.1 ton/year)     | $^{241}\text{Am}$ | 430               | 250               |
|                    | $^{243}\text{Am}$ | $7.4 \times 10^3$ | 140               |
|                    | $^{245}\text{Cm}$ | $8.5 \times 10^{-3}$ | 1                 |

2.1. The problem of nuclear waste

The management of the high-level radioactive waste arising from nuclear power production and from the dismantling of nuclear weapons is one of the major public environmental concern in the use of nuclear energy. Together with fission fragments, several transuranic isotopes are built up in a nuclear reactor, as a result of a chain of neutron captures and successive $\beta$-decays, starting at $^{238}\text{U}$ and, to a lesser extent, at $^{235}\text{U}$. Many of these isotopes are $\alpha$-emitters, characterized by a very long lifetime. They include Pu, Np, Am and Cm isotopes. A list of the yearly production of high-level radioactive nuclear waste in France is reported in table 1. The most important contribution, in terms of long-term radiation hazard, comes from $^{237}\text{Np}$, $^{241,243}\text{Am}$ and $^{245}\text{Cm}$, often referred to as “minor actinides”.

Contrary to fission fragments, which loose most of their radiotoxicity within a few hundred years, actinides remain potentially dangerous for thousands of years, a period too long for the resistance of man-made barriers. Therefore, their disposal requires deep underground geologically stable repositories. The volume of nuclear waste that needs to be stored, however, is so large that currently considered repositories are quickly becoming insufficient, and at the current rate of nuclear power production, new geological sites with large storage capacity would need to be located and prepared every few years.

Typically, the spent fuel of Pressurized Water Reactors (the most common type of current nuclear power plants) is constituted for 96 % by Uranium, 1 % Plutonium and 3 % Minor Actinides and fission products. In some countries, like France, Great Britain and Japan, the spent fuel is reprocessed to extract U and Pu that can be reutilized. The process reduces the final volume of nuclear waste to be stored, but at present is still costly. For this reason, in other countries (in particular the US) the spent fuel unloaded from the reactor core is stored directly.

A possible solution to the problem of nuclear waste could come from transmutation processes in which long-lived radioactive isotopes are transformed into short-lived or stable ones. The most effective nuclear process is neutron-induced reactions. In particular, long-lived fission fragments (LLFF) can be incinerated by means of neutron capture reactions. A typical example is the case of $^{99}\text{Tc}$, a fission fragment with half-life of two hundred thousand years. Following neutron capture, $^{100}\text{Tc}$ is formed, which has the very short half-life of 16 s, decaying in the stable $^{100}\text{Ru}$ isotope. For transuranic elements Np, Pu, Am and Cm, neutron-induced fission is in principle
Figure 3. Fission cross-section as a function of the neutron energy for long-lived minor actinides present in nuclear waste. A recycling of these isotopes in the fuel cycle can only be achieved in advanced nuclear systems with a fast neutron spectrum.

a much more efficient process, since it leads also to energy gain and a surplus of neutrons. However, as shown in the figure 3, the fission cross-section of many actinides is characterized by a threshold, around few hundreds keV, which hinders the possibility to use conventional thermal reactors for their transmutation. The possibility to incinerate the high-radiotoxicity component of the nuclear waste is therefore linked to the availability of a fast neutron spectrum.

Several possibilities are being considered for nuclear waste incineration. One of them is the use of subcritical systems driven by accelerators (the so-called Accelerator Driven Systems). In this scheme, the excess neutrons needed to sustain the chain reaction are produced the spallation of high energy proton beams on heavy material (such as Pb). Another possibility is the use of the so-called fusion-fission transmuters, in which the intense neutron fluxes needed for transmutation are produced in fusion systems. Most of the efforts in the field of advanced nuclear systems are however now being devoted towards the development of Generation IV nuclear reactors.

3. Advanced nuclear reactors
The main challenge in the design of advanced nuclear systems is the possibility to recycle a large fraction of the long-lived actinides produced during operation of the reactor. The use of fuel mixtures that include part of the waste would lead to the double advantage of burning (or transmuting) highly radiotoxic isotopes while producing energy. Contrary to once-through process, therefore, recycling would allow on the one hand to reduce the volume of nuclear waste to be permanently stored in geological sites, and on the other hand to better exploit the uranium resources, thus ensuring a long-term sustainability of the nuclear energy option. In the following, the basic principles of Generation IV nuclear reactors are described.
Table 2. A list of the six types of Generation IV nuclear reactors currently being considered for development. The main features of the reactors are also indicated.

| Reactor type                  | Acronym | Neutron spectrum | Main use         | Size            |
|-------------------------------|---------|------------------|------------------|-----------------|
| Gas-cooled Fast Reactor       | GFR     | Fast             | Electricity & Hydrogen | Medium          |
| Lead-cooled Fast Reactor      | LFR     | Fast             | Electricity & Hydrogen | Large or small |
| Sodium-cooled Fast Reactor    | SFR     | Fast             | Electricity      | Large or medium |
| Molten Salt reactor           | MSR     | Thermal          | Electricity & Hydrogen | Large          |
| Supercritical-Water-Cooled Reactor | SWCR | Thermal          | Electricity      | Large          |
| Very-High-Temperature Reactor | VHTR    | Thermal          | Hydrogen         | Medium          |

3.1. Generation IV reactors

The perspectives of a larger use of nuclear energy to fulfil the energy needs of the futures rely on the design of new systems that would solve the issues of safety, economics, waste management and proliferation resistance affecting current generation reactors. Schematically, Generation IV reactors should present the following characteristics: (i) Sustainability: the new nuclear energy systems should be characterized by efficient fuel utilization, so to ensure long-term availability of the U resources; (ii) Safety: the new systems should have a very low probability of incident and core damage, by relying as much as possible on passive safety systems; furthermore, solution maximizing the physical protection against acts of terrorism should be adopted in their design; (iii) Environmental impact: the new systems should minimize the production of nuclear waste and related long-term impact on the environment; (iv) Economics: Generation IV nuclear systems should have costs and financial risks comparable to other energy sources; (v) Non-proliferation: with the new systems it should become very difficult the diversion or theft of material for military use or for terrorist purposes.

It should be emphasized that the use of Generation IV nuclear systems for energy production would make easier to meet clean-air objectives since, as in current reactors, the emission of CO$_2$, either in the direct or indirect processes related to fuel extraction and preparation, is much smaller than for other energy sources.

At present, six types of reactors are being considered. They are listed in table 2. Three of them are fast reactors, which are able to burn minor actinides, and that could be eventually loaded with the nuclear waste produced by thermal reactors (including the present ones). The other three types are thermal reactors, characterized by a much improved burn-up and thermal efficiency. An important aspect regards the possibility to build the new reactors in various sizes. While large, monolithic reactors in principle are more convenient due to the scale economy, recent studies have shown that small and medium size reactors could represent a more desirable solution in several cases, for example for countries with small electric grids (< 10 GW), or with a limited investment capacity. Small reactors may also be a solution for producing electricity in remote locations, such as the Poles or islands, or in places far from the electric grid. Finally, small or medium size reactors may allow to minimize the investment risks typically associated with the large capitals needed for the construction of large nuclear power plants.

The main challenge in the development of the Generation IV reactors is to ensure a minimal production of long-lived nuclear wastes and a very efficient utilization of the uranium resources.
For this reason, the basic requirement in the design of some reactors is the possibility of reprocessing and recycling the fuel, which could include together with uranium and plutonium, all other actinides as well. It is important to stress that the new systems would allow the transmutation of the long-lived minor actinides Np, Am and Cm, with a consequent reduction of their inventory. In fact, the main objective of the three fast reactor is electricity production and waste management. Another objective of some Generation IV reactors is the possibility to produce hydrogen by exploiting high temperature processes. In particular, one of the Generation IV reactors chosen for R&D, the Very High Temperature Reactor, is expected to operate with a coolant outlet temperature of 1000°C, which would enable high efficiency thermochemical water-splitting without carbon emission.

Considering the different goals of future generation reactors, it is unlikely that they can be met by one or two of the designs now being considered for development. More realistic, the objectives of the Generation IV systems will be achieved by employing a combination of the different reactors types. In particular, while all six types of Generation IV reactors are characterized by a higher thermal and burnup efficiency, relative to current systems, efficient transmutation of long-lived waste can only be performed with the three fast reactor (LFR, GFR and SFR), whose operation should therefore allow to reduce inventory of minor-actinides produced by the thermal reactors based on the once-through process. An appropriate mixing of the different Generation IV reactors may therefore be needed to meet in a sustainable way the future nuclear energy demand.

The time-scale towards the development of Generation IV reactors, as envisaged by the Generation IV Forum, will proceed in three phases. The next few years will be devoted to the so-called “viability phase”, i.e. to the feasibility study and to the proof-of-principle of the new reactor concepts. This phase is expected to be completed for all six types of new reactors by 2015, although for some reactors (like the Sodium-Cooled Fast Reactor), this first phase may be completed in a shorter time-scale, due to sufficient experience already gained in the past. The second phase regards the study of the performance of the new systems. In this phase, the various parts of the new systems, including fuel recycling, will be developed and optimized. This phase will end up when it can be shown that the performance of the various systems is good enough, so to allow implementation on an industrial scale. Presumably, this phase may be completed by 2020. At that point the third and final phase, of the demonstration, will take place, with the aim to proof the capability of the new and innovative technology to be exploited on the large scale for energy production and/or for other predicted uses. If the demonstration phase is successful, the new systems may be ready for commercialization by industries. As already mentioned, it is desirable that this would occur by 2030, when a large fraction of the current reactors will be about to be shut down.

3.2. Accelerator Driven Systems

Another innovative systems currently being considered, mainly for nuclear waste incineration (via transmutation reactions) are the so-called Accelerator Driven Systems. They refer to a device obtained by combining a sub-critical nuclear reactor with a proton or deuteron accelerator that provides, through the spallation process on a heavy material, the neutron excess necessary to sustain the chain reaction. The main advantage of such a device resides in the fact that it is intrinsically safe, since the chain reaction cannot by itself run out of control (being the neutrons that sustain it produced with an external source that can be easily switched off). Furthermore, the use of high energy primary beams could be advantageous in tailoring the neutron energy spectrum so to match the fission cross-section of minor actinides, thus maximizing their transmutation rate.

Most of the proposed designs of Accelerator Driven Systems assume continuous-wave proton beams with energy ~1 GeV, and rely on Pb as spallation target and, in some cases, as reactor
coolant at the same time. The main objectives of these systems could be to burn transuranium and minor actinides produced by conventional thermal reactors, although part of the energy released in the waste burnup could be used to produce electricity for powering the accelerator.

Several technological issues have to be solved towards the development of Accelerator Driven Systems. In particular, the accelerator should be able to deliver high beam currents, steadily and with only minor interruptions. At present, the accelerator technology is still far from reaching the required performances, although progresses are being made in this respect.

3.3. The Th/U fuel cycle
A final remark regards the possibility to develop new reactors based on innovative fuel cycles. In particular, a topic of great interest is the use of the Th/U fuel cycle in either critical or subcritical systems. This cycle is based on the fertile $^{232}$Th isotope, which breeds the fissile $^{233}$U by neutron capture and subsequent $\beta$-decay of $^{233}$Th and $^{233}$Pa, according to the following scheme:

$$ ^{232}\text{Th}(n, \gamma)^{233}\text{Th} \rightarrow ^{233}\text{Pa} \rightarrow ^{233}\text{U} , $$

where the first steps has a half-life of 22.3 minutes, and the second one of 27 days. An interesting advantage in using this cycle, as compared to the conventional uranium/plutonium cycle currently used in all operating power plants, is related to the low production of high-mass actinides, due to the absence of $^{238}$U which is the seed for the production of most actinides in conventional reactors. As a consequence of the much lower buildup of heavy transuranium isotopes, the radiotoxicity of the spent fuel in reactors based on the Th/U fuel cycle is significantly reduced. Another advantage of this cycle is the large availability of the fuel. In fact, thorium is 3 to 4 times more abundant than uranium in the earth crust, and is widely distributed in nature as an easy mining resource in many geographical areas. Finally, natural thorium is entirely constituted by the fertile $^{232}$Th isotope, so that there is no need for isotopic separation in the preparation of the fertile component of the fuel.

4. The need of nuclear data for advanced nuclear systems
In order to reduce uncertainties in the design and operation of new generation reactors, high precision data on the cross-section for neutron-induced reactions on a variety of isotopes are required, from thermal energy to several tens of MeV. In particular, a pressing need exists for new measurements on capture and fission reactions for the main isotopes involved in the Th/U fuel cycle, as well as for long-lived Pu, Np, Am and Cm isotopes. Finally, data are required also for long-lived fission fragments involved in transmutation projects, and for structural material. A list of the requests is contained in the “Nuclear Data High Priority Request List” [3], from the Nuclear Energy Agency, constantly updated with new requests coming from different fields, such as current and advanced reactor systems, various industrial applications, nuclear medicine, radioprotection, space applications, etc..

Neutron cross-sections are available by means of compilations of experimental data [4] or through evaluated nuclear data libraries [5], such as ENDF (mostly compiled in the United States), JEFF (the European library maintained by the NEA), JENDL (the Japanese database) and BROND (the Russian one). Together with the evaluated cross-section, these libraries include information on the reliability of the data, which is mostly linked to the accuracy of the available experimental results. Evaluated data and related uncertainties are the result of a large effort in which experimental data are combined with nuclear model calculations, often based on sophisticated reaction theories.

The present knowledge of the neutron cross-section results largely inadequate for the new applications in the field of emerging nuclear technologies, and they need to be updated with new experimental or theoretical information. Sensitivity studies performed by means of Monte
Table 3. Current and needed accuracy (in %) on neutron cross-sections required for the design of Generation IV fast reactors [6].

| Isotopo | Reaction | Energy range  | Current accuracy | Needed accuracy |
|---------|----------|---------------|-----------------|----------------|
| $^{238}$Pu | fiss | 0.2–1.4 MeV | 17 | 3–5 |
| $^{239}$Pu | capt | 2–500 keV | 7–15 | 4–7 |
| $^{241}$Pu | fiss | 450 eV–1.4 MeV | 8–20 | 2–5 |
| $^{242}$Pu | fiss | 0.5–2.2 MeV | 19–21 | 3–5 |
| $^{241}$Am | fiss | 2.2–6 MeV | 9 | 2 |
| $^{243}$Am | fiss | 0.5–6 MeV | 12 | 3 |
| $^{244}$Cm | fiss | 0.5–1.4 MeV | 50 | 5 |
| $^{245}$Cm | fiss | 67–183 keV | 47 | 7 |

Carlo simulations indicate that for most long-lived fission fragments and minor actinides, the present uncertainties are much larger than needed for the reliable design and safe operation of new generation reactors. Table 3 lists the current and needed accuracy on the cross-section of various reactions involved in the design of advanced nuclear systems. The table applies to different types of Generation IV fast reactors, as well as for ADS, and has been obtained for different core design. The need of improving the current knowledge of nuclear data is evident. A striking example is the case of the neutron-induced fission cross-section of $^{243}$Am.

In figure 4 the results of the most important measurements performed up to date on this reaction are shown (coloured symbols). The available data cluster in two groups, with a discrepancy between them of around 15%. The current evaluations follow the lower cluster. However, a large uncertainty still persists, with the most recent experimental results (collected in 2004) indicating a cross-section higher than all previous results. New and accurate measurements are therefore needed to settle this question.

Following the sensitivity analysis performed for Generation IV fast reactors, as well as for ADS and other projects of nuclear waste incineration [7], a long list of needed data can be made. Capture and fission cross-sections are needed for fertile and fissile isotopes involved in the Th-cycle, in particular $^{232}$Th, $^{231}$Pa, $^{233}$U, $^{234}$U, and $^{236}$U. Similarly, reliable experimental data on capture, fission and inelastic cross-sections, in a wide energy range are required for transuranic isotopes, in particular $^{237}$Np, $^{238}$, $^{240}$, $^{241}$Pu, $^{241}$, $^{243}$Am, and $^{244}$, $^{245}$Cm. Furthermore, the incineration scheme of long lived fission products requires accurate capture cross-sections for $^{79}$Se, $^{99}$Tc, $^{129}$I, $^{135}$Cs, $^{151}$Sm, etc. Finally, data on structural material being considered as neutron-production target or as coolant, are still far from being accurately known, especially at high neutron energy. New measurements on stable isotopes are thus called for.

5. The n_TOF contribution

The study of neutron-induced reactions has always been of great importance for a large variety of fields, from Nuclear Astrophysics, where neutron capture processes are at the bases of Stellar Nucleosynthesis of heavy elements, to fundamental Nuclear Physics for studies on, for example, neutron-induced symmetry breaking and nuclear level densities. Finally, neutron cross-section data are fundamental for applications to nuclear technology. In recent years, studies performed towards the development of advanced nuclear systems have shown that for many nuclides, current nuclear data are characterized by an insufficient accuracy [7]. The necessary update of the neutron cross-section libraries rely on the availability of new and accurate measurements that can only be performed at advanced neutron sources.
Figure 4. The neutron-induced fission cross-section of $^{243}\text{Am}$.

Data from the most recent measurements tend to cluster in two groups, with a discrepancy of 15%.

With the aim of fulfilling some of the requests of nuclear data for advanced reactor systems, as well as for collecting fresh new data of interest for Nuclear Astrophysics, an innovative neutron facility was built at CERN: n_TOF [8]. Proposed by Rubbia, n_TOF is a time-of-flight installation based on a spallation neutron source. The neutron beam is produced by 20 GeV/c protons from the CERN Proton Synchrotron accelerator, impinging onto a large Pb block, surrounded by a water layer acting both as coolant and moderator of the neutron spectrum. A scheme of the facility is shown in figure 5. The main features of the neutron beam are the very high instantaneous neutron flux and the wide energy spectrum, covering over 9 orders of magnitude, from thermal to approximately 1 GeV neutron energy, as shown in figure 6. Another advantage over existing neutron facilities is the high resolution in neutron energy (reconstructed from the time-of-flight), thanks to the 200 m long flight path used. Several detection systems have been set up at n_TOF. Among them, a $4\pi$ Total Absorption Calorimeter made of 40 BaF$_2$ crystals was built for measuring capture reactions, while fission measurements are carried out with a Fast Ionization Chamber and a stack of Parallel Plate Avalanche Counter. Finally, an innovative Data Acquisition System, based on fast Flash ADC, has been adopted for the first time at a neutron facility, in order to handle the very high count-rate produced at n_TOF as a consequence of the intense neutron beam and of the natural radioactivity of the samples.

5.1. Recent results

Together with the innovative features of the n_TOF facility, the high-performance experimental setups and state-of-the-art acquisition system allow to collect, in some cases for the first time, accurate neutron cross-section data even on highly radioactive samples or on isotopes available in small quantity. In the first experimental campaign, data have been collected on several reactions of interest for the Th/U fuel cycle, for Generation IV fast reactors, and for Accelerator Driven Systems aimed mostly at nuclear waste transmutation. A list of the cross-sections measured at n_TOF can be found in [9]. In most cases, the accuracy of 3 to 5%, required for the
Figure 5. A schematic map of the n_TOF facility at CERN. The proton beam from the PS accelerator complex impinges onto a massive Lead block, located in the TT2 tunnel. A water layer acts surrounding the block acts both as coolant and moderator. Neutrons produced in the spallation process propagate in a vacuum tube. Several collimators, shielding walls and a magnet are position along the flight path. At the end of the 200 m line, the experimental area hosts different experimental apparatus.

Figure 6. Simulated and measured neutron fluence per proton pulse, available for measurements in the experimental area of the n_TOF facility at CERN.

applications to emerging nuclear technologies, has been reached in the n_TOF data. Accurate capture cross-sections have been obtained in particular for the $^{232}$Th(n,γ) [10], as shown in
Figure 7. Simulated and measured neutron fluence per proton pulse, available for measurements in the experimental area of the n_TOF facility at CERN.

Figure 7, and $^{233}\text{U}(n,f)$ [11], the two most important reactions involved in the Th/U fuel. For the same application, the fission cross-section of $^{232}\text{Th}$ and $^{234}\text{U}$ have been also measured and are now in the process of being released.

Similarly, high accuracy data have been collected on the capture cross-sections for some of the most important transuranic isotopes involved in transmutation processes, in particular $^{237}\text{Np}$, $^{240}\text{Pu}$ and $^{243}\text{Am}$ [12]. Finally, accurate neutron-induced fission cross-section measurements have been performed for the minor actinides $^{241}\text{Am}$, $^{243}\text{Am}$ and $^{245}\text{Cm}$ [13, 14]. As shown earlier in this publication, the current accuracy on these isotopes is much poorer than requested for the reliable design of Generation IV nuclear energy systems. The n_TOF results, now in the process of being published, have shown severe shortcomings in current databases of evaluated neutron cross-section, and have demonstrated their inadequacy for the new nuclear science applications. In most cases, the n_TOF data, combined with advances in nuclear theories for fission, will provide the basis for new, more reliable evaluation.

Most of the results obtained by the n_TOF Collaboration in the first experimental campaign have been published and uploaded onto the experimental database EXFOR, making them available to the nuclear data community, and for the needs of new applications. A second experimental campaign, with measurements of interest for applied nuclear science as well as for Nuclear Astrophysics and fundamental Nuclear Physics, is now starting and will hopefully produce more interesting results on studies of neutron-induced reactions.

6. The surrogate reaction method

The n_TOF results represent an example of advances in the knowledge of basic nuclear data for applications, that can be obtained by improvements in the neutron facilities, experimental setups and techniques. In particular, the high instantaneous neutron flux of the n_TOF neutron
beam has allowed in the past, and may lead in the future, to measure highly radioactive samples, even with activity of the order of hundreds of MBq. However, some measurements cannot at present be performed neither at n_TOF nor in other existing facilities. This is, for example, the case of neutron-induced reactions on $^{233}$Pa, an isotope of relevance for the Th/U fuel cycle. Due to the relatively short lifetime of 27 days, it is almost impossible to produce and handle samples of this isotope. Furthermore, in the cases of minor actinides, the natural radioactivity of the sample would completely mask the signals coming from the neutron-induced reaction.

A new experimental technique is being employed, since a few years, to collect nuclear data that would otherwise be impossible or very difficult to obtain. The technique allows to determine the cross-section for neutron-induced reactions through an indirect method, also called surrogate method, proposed in the 70's [15]. The method exploits alternative reactions (for example few-nucleon transfer reaction) that lead to a compound nucleus with the same A and Z of the one formed in the neutron-induced reaction. The decay probability of the CN (for example in the fission or radiative de-excitation channel) measured in the surrogate reaction is then combined with the compound nucleus cross-section for the neutron-induced reaction, obtained from optical model calculations. The product of the two represents the cross-section for the desired neutron-induced reactions, provided that the decay widths is dominated by the statistical level density, and the angular momentum of the CN formed in the surrogate reactions is not much larger than the spin-cutoff parameter of the level density distribution.

In the last few years different measurements of surrogate reactions have been performed, allowing to obtain information on neutron cross-sections for difficult cases. In the work of Petit et al [16], the mentioned $^{233}$Pa(n,f) cross-section, very difficult to measure directly or reliably estimate from theoretical calculations, was determined from the surrogate reaction $^{232}$Th($^3$He,p)$^{234}$Pa. Interesting results were also obtained for the fission cross-sections of minor actinides $^{242,243}$Cm and $^{241}$Am [17].

7. Conclusions
The fast growth in the global energy demand, consequence of the increase in the world's population as well as by improvements in the life standards in many previously underdeveloped countries, will pose severe problems in the future. The current situations of energy production, which relies heavily on the use of fossil fuels, cannot be sustained for long, due to the predicted decline in the availability of this energy source and, most importantly, due to the severe environmental impact of fossil fuels, in particular related to the production of CO$_2$ and associated climatic changes. Therefore, safe, clean and cost-effective energy sources have to be developed, in a timely fashion. While energy savings and developments in the use of renewable sources may help reducing the dependence on fossil fuels, in particular in the short and medium term, there is little doubt that an important role will have to be played by the nuclear energy, even in the field of transportation, by large-scale production of hydrogen. The public acceptance of nuclear energy, however, is not very high, at present, mostly due to the safety, proliferation and, especially, waste management issues associated with current reactors. A greater importance of the nuclear energy source requires the development of new generation systems addressing present concerns. In this respect, a new class of reactors, the so-called Generation IV systems, are now being investigated, with the aim of making them available by 2030, when most of current nuclear reactors will have to be replaced. The main concept of the Generation IV reactors is the possibility to recycle a large fraction of the actinides produced during reactor operation, which would allow a much more efficient use of the uranium resources and, more importantly, a large reduction of the volume of long-lived nuclear waste to be stored in geological repositories.

The development of Generation IV reactors requires R&D on several field. Among them, advances in the knowledge of basic nuclear data are fundamentally needed. In particular, the design of fast reactors able to burn Pu isotopes and minor actinides (Np, Am and Cm),
requires accurate neutron capture and fission cross-section data on these isotopes, as well as other information such as fission fragment distribution, neutron multiplicity, delayed neutron emission, etc. A large effort is therefore being devoted, by both the experimental and theoretical Nuclear Physics community, to update the current knowledge of basic nuclear data, and make it more suitable for the application to the field of emerging nuclear technology. In this respect, an important contribution is being provided by the n_TOF Collaboration, which is performing high-accuracy measurements at the innovative neutron beam at CERN. Some measurements with highly-radioactive isotopes will require improvements in the neutron facilities, experimental technique and instrumentation. For some very difficult isotopes, the surrogate method represents a valid alternative to direct measurements, and is now being widely employed in various laboratories around the world. A large effort is also required on the side of theoretician and evaluators, to interpret and combine the large amount of experimental data, so to produce more reliable databases.

In conclusion, in the next few years, it will be necessary, for part of the Nuclear Physics community, to dedicate large efforts to collect nuclear data with high accuracy, needed for the development of new generation energy systems. Although a huge task, it has to be done, as an important contribution to solving one of the main problems of the society, i.e the continuous quest for energy. Recalling the motto of the Generation IV Forum, it will be our contribution in preparing today for tomorrow’s energy needs.

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