Neutrons for Science (NFS) at SPIRAL-2

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I. Introduction

The accelerator and experimental facilities at GANIL (Caen, France) will be transformed over the next 5-10 years. At the heart of the new project, called SPIRAL-2, will be a new superconducting linear accelerator, which will act as a driver accelerator in order to provide with deuterons of 40 MeV (5mA; 200kW). With this primary beam a huge number of neutrons (~10^{15} n/s) will be produced on a rotating carbon converter in the energy range between 1 keV and 40 MeV. As initially projected, intense high quality beams of neutron-rich nuclei, created in neutron-induced fission of the depleted uranium, will become available at SPIRAL-2. The facility is expected to be operational in 2009.

The main goal of this paper is to examine the possibility of using a linear deuteron accelerator in combination with the rotating target-converter for other purposes, namely,

a) **neutron time-of-flight (nToF) measurements with pulsed neutron beams [1], and**
b) **material activation-irradiation with high-energy high-intensity neutron fluxes [2].**

In this context, Fig. 1 presents the neutron energy spectra (on the left) and neutron beam intensities (on the right) at different distances from the production targets as expected in the case of SPIRAL-2. Use of these neutrons is briefly introduced below.

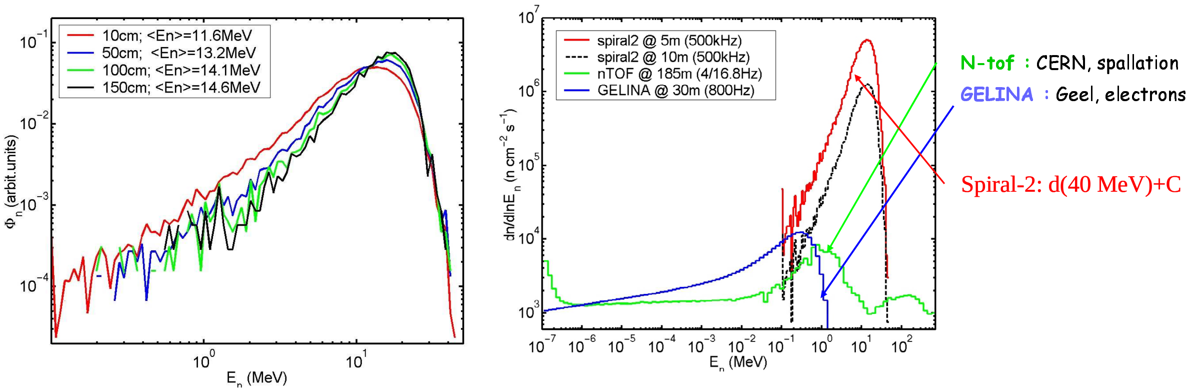

Fig. 1*: Neutron energy spectrum expected at SPIRAL-2 as a function of distance from the production target (on the left); Neutron beam intensities expected at SPIRAL-2 and compared with existing major nToF facilities in Europe (on the right).*

Material testing via irradiation in high energy and high neutron fluxes is of a great interest for very extended community working on nuclear waste transmutation (use of ADS in particular), intensive neutron sources (SNS, ESS, …), RNB production with neutrons (EURISOL, RIA, …), future controlled fusion experiments and reactors (ITER, DEMO, …), space applications (resistance of electronics, shielding, …), etc.

High neutron fluxes with high energy spectra are very attractive to perform integral measurements of the transmutation-incineration of nuclear waste and minor actinides in particular. This type of high energy neutron flux has the advantage of increasing the fission over capture ratio (the capture becoming negligible compared to fission), and thus the direct incineration of the element without the production of heavier elements. For this purpose on-line fission rate measurements could be performed with fission ionization chambers with Np, Am and Cm deposits.

Only very limited data exist for neutron induced reactions above 14 MeV. For many cases both fission and (n,xn) reaction cross sections are unknown. The neutron energy range between 1 and 40 MeV concerns the nuclear waste transmutation in the case of ADS, future fusion applications, etc., where designers need new and good quality data and relevant codes in order to build evaluated data libraries and also to improve theoretical models. The above energy range corresponds also to the opening of new reaction channels like (n,p), (n,α), allowing the pre-equilibrium model studies, i.e. the transition between low (evaporation) and high energy models (intra-nuclear cascade).

The high neutron fluxes would allow performing measurements of small cross-sections and/or with very small targets, which might be rare, expensive, and in some cases radioactive. More fundamental studies can also be achieved, e. g. precise measurements of the neutron-neutron interaction length a_{nn} in terms of the t(n,2n)d reaction are crucial in a few-body physics in order to define without ambiguities the nucleon-nucleon interaction.

High energy neutrons (above ~1 MeV) would also allow producing radioactive elements or isomeric nuclei via (n,xn), (n,p) or (n,α) reactions. Therefore, having very high neutron fluxes one will be able to prepare a number of radioactive or isomeric targets for fundamental physics studies to be performed afterwards with stable or radioactive beams, both available at GANIL.

Below a number of case studies on the physics with SPIRAL-2 neutrons will be presented in more detail (also see Ref. [3]).

II. Neutron Time-of-Flight (ToF) measurements

2.1. Proposed conditions

The Spiral-2 initiative proposes a neutron time-of-flight beam line at zero degrees for which the neutrons are produced by a 40 MeV deuterium beam incident on a thick graphite target. The beam will be pulsed at 500 kHz leaving 2 μs between bursts. The burst width is a few hundred picoseconds. Two flight paths of 5 and 10 m are proposed. Flux estimates were done with MCNPX and amount to $8.8(2.2)\cdot 10^6$ n/(cm^2 s) for 5(10) m. About $6\cdot 10^{12}$ neutrons are produced per second and at this pulse rate the deuteron current is ~28 μA.

2.2. Potential for improvement

It seems possible that from the side of the accelerator and neutron source a gain of maximum ~50 % may be expected by bunching the beam prior to entry into the RFQ and another ~50 % by using Li or Be instead of Graphite as a target-converter. It will be argued below that any gain in intensity enhances the potential for the time of flight measurements. For the time being such potential enhancements will be discarded. Below arguments will be given to establish additional 2.5 and 20 m flight paths.

2.3. General comments

At 6·10^{12} n/s the intensity of Spiral-2 for time-of-flight measurements is less than that for the Gelina facility (3·10^{13} n/s). This first of all precludes competitive moderated spectrum time-of-flight measurements at Spiral-2. This conclusion is further underlined by the fact that for moderated spectrum measurements a maximum frequency of about 10 kHz would be required, lowering the intensity another factor of 50 compared to the above estimate.

For the fast spectrum the situation is altered by the strong forward emission of the neutrons as a consequence of the breakup component of the spectrum. In fact, for E_d = 33 MeV the measurements by Shin et al. show that the yield at zero degrees is 18 times larger than what it would be for isotropic emission. As a consequence, at the same distance from the source the Spiral-2 fast flux at this angle is about twice to three times that of Gelina, where the spectrum is essentially isotropic. An important difference is the hardness of the spectrum. For Spiral-2 the spectrum peaks at14 MeV, whereas for Gelina this is 1-2 MeV. In the neutron energy range 5-35 MeV Spiral-2 competes favourably in terms of intensity with the wide energy time-of-flight source at WNR (LANL), offering similar time resolution and flight path lengths. Another important difference for Spiral-2 is the expected absence of a strong accompanying gamma-flash in the beam. This feature is essential for the effective utilisation of short flight paths for the measurements discussed below. Such short flight paths are prohibited at an electron-accelerator based source like Gelina due to the gamma-flash induced pile-up and detector disturbance.

In brief, the range from 0.3 to 35 MeV for cross section measurements is an energy range that is of particular importance for energy applications, notably accelerator driven systems (ADS) and Gen-IV fast reactors, as well as for fusion related devices.

2.4. Gamma production cross sections for inelastic scattering and (n,xn)

Introduction

Inelastic neutron scattering and (n,xn) cross sections on major construction materials, fuel and inert fuel components, moderators and coolants are among the most needed in nuclear technology applications. This includes accelerator driven systems, GenIV reactors, fusion devices and security installations. The primary importance of these reactions lies in their impact on the energy distribution of the fast spectrum, thereby significantly altering most reaction rates through the so-called indirect effect. Significant uncertainties in estimated k_{eff} values for fast systems result as a consequence of the large uncertainties associated with these cross sections. Even precision estimates of k_{eff} in light water reactors are affected. Other issues where inelastic scattering and (n,xn) reactions play an important role concern radiation shielding and, as a consequence, damage to containment structures, as well as radiation heating. In the latter case the gamma-production cross sections themselves are of main importance. Naturally, (n,xn) reactions additionally play an important role in neutron multiplication, e.g. for ADS and for fusion.

It should be noted that measurements of inelastic and certainly of (n,xn) cross sections in the energy range of importance - threshold to 20 (30) MeV - are considerably more sparse than total, fission and capture cross section measurements. At the origin of this sparseness and the often considerable scattering of the available data lie technical difficulties associated with direct measurements on the basis of neutron detection and the availability of neutron sources with suitable conditions. For reactions on actinides, the data bases rely mostly on models. A typical example is the ^{233}U(n,2n) reaction competing with the fission of ^{233}U in the thorium based fuel cycle with fast neutron flux. As illustrated in Fig. 2 (on the left) the three main data bases disagree strongly in this particular case. Equally, the (n,2n) reaction cross sections are poorly known for ^{241}Am (see Fig. 2 on the right), being one of the most important minor actinides to be incinerated.

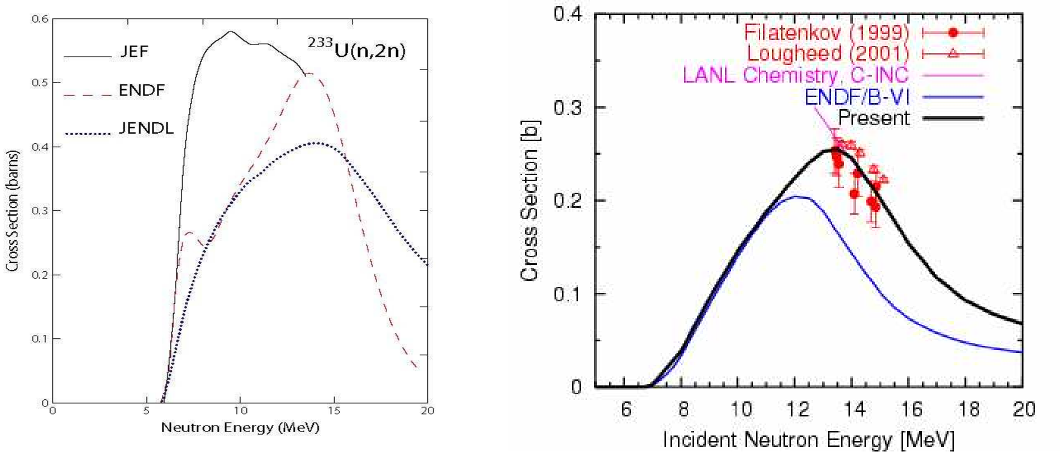

Fig. 2: *The present data status of the ^{233}U(n,2n) (on the left) and Am(n,2n) (on the right) reaction cross sections and different evaluations.*

Other examples are the (n,n') and (n,2n) reactions on ^{208}Pb as presented in Fig. 3. It has been estimated that the errors on the (n,n') cross sections on lead, being the essential material in the design of ADS, would imply an uncertainty of ~2 % on the criticality calculations of such a system!

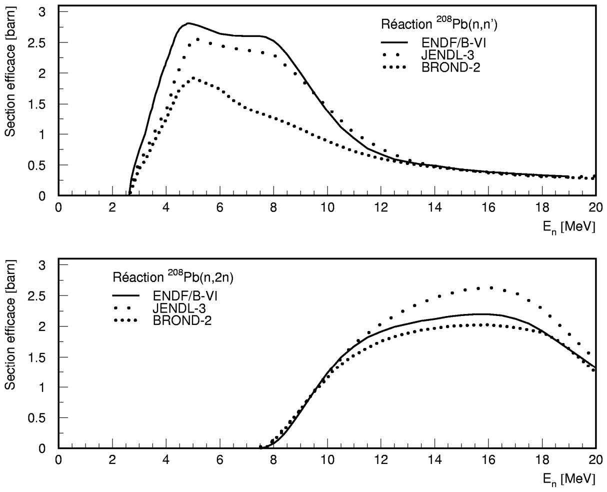

Fig. 3: The ^{208}Pb(n,n') (upper part) and ^{208}Pb(n,2n) (lower part) cross sections as compiled in different data files.

It was shown recently that gamma production cross sections for photons associated with inelastic scattering and (n,xn) reactions can be reliably measured with good resolution over a wide energy range at time-of-flight facilities. These cross sections can be used to construct estimates of the inelastic and level inelastic cross sections and the (n,xn) cross sections. More importantly these cross sections are of importance to benchmark nuclear model calculations that in turn will provide the best estimates for the desired cross sections and the neutron emission spectra. These gamma production cross sections can serve to address issues in level density modelling, gamma-strength functions, neutron optical models and pre-equilibrium treatments.

Recently, at the Gelina ToF facility a setup for high resolution measurements with two large volume HPGe detectors using the fast spectrum at 200 m flight path length was developed. It was applied to ^{52}Cr, ^{58}Ni, ^{209}Bi, ^{207}Pb and will shortly be employed for ^{206}Pb and ^{208}Pb. An example of the good energy resolution that was achieved is presented in Fig. 4 on the left and the full range of the measurements is shown in Fig. 4 on the right. It was also shown for ^{207}Pb that (n,2nγ) measurements can be performed with this setup as well. A significant drawback of this arrangement is the very long measurement time (up to 1000 h) as a result of the low count rate (10 cps), prohibiting a rapid survey over the mass table. Required sample masses are large making studies of enriched isotopes expensive, whereas these are essential for clean spectra, disentanglement of inelastic and (n,xn) channels and studies of isotope chains.

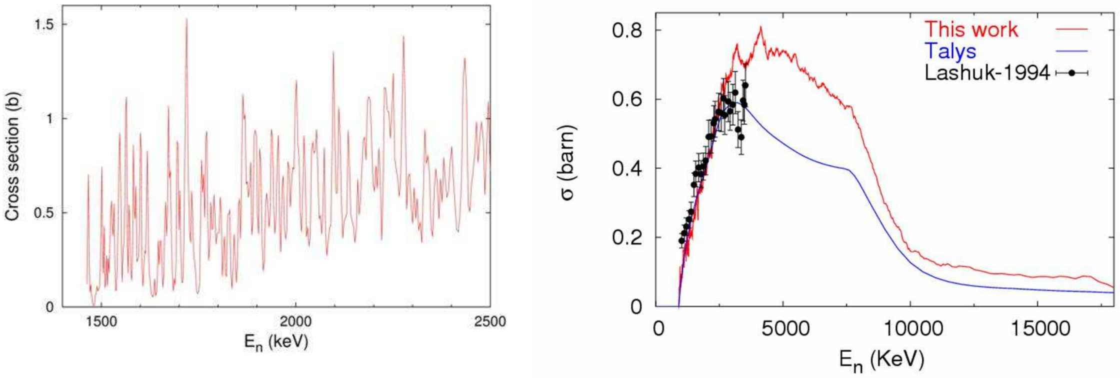

Fig. 4: *Detail of the excitation function for the* 2^+_1 *to ground state transition for* ^{52}*Cr (on the left); full excitation curve for the 896 keV transition of* ^{209}*Bi (on the right). Both measured at Gelina.*

It is clear that in many cases the need for very good energy resolution is limited to the first 1 or 2 MeV above the inelastic threshold. At higher energies the instrumental resolution is rapidly broadening and the level density becomes progressively higher. On top of this, resonance widths increase and eventually become larger than the level spacing leading to a rapid washing out of residual structure with increasing energy. In this range an energy resolution of several percent would be adequate.

Obviously, a flight path shorter than 200 m would be sufficient. At Gelina this is prohibited by the very strong gamma-flash. Even at 200 m with a 2 cm ^{nat}U filter in the beam from one in five to one in two bursts result in a prompt gamma scattered by the sample and deposited in the detector. With conventional electronics this implies a dead time of 25 μs, so that for such a burst no neutron-induced event is observed.

In this context, an innovative method of prompt γ spectroscopy, developed by IReS Strasbourg, would be used to measure such reactions. It has been already employed at Gelina, with a flight path of 200 m. It was also shown during these experiments that the effective dead-time can be reduced to 2.5 μs (nearly by one order of magnitude!) using a fast digitizer (65 MSPS) and on board data processing with an FPGA, thus leaving an effective range at 200 m of 20 MeV. Nevertheless, a shorter flight path would severely compromise this range of interest, since there would be a prompt gamma for each burst and the time range would be reduced to exclude measurements above 10 MeV. What is really needed is a neutron source for which a short flight path results in a number of observed prompt gammas per burst and detector of not more than ~10 %.

SPIRAL-2 & other facilities

Prompt γ spectroscopy has also been used at FZK (Karlsruhe), ORELA (ORNL) and WNR (LANL), where in the latter the beam has a frequency of 600 kHz with the flight path of 20 m. Table 1 summarises some of the potential installations where (n,X) measurements are performed.

In general, different neutron beam characteristics at various installations are suited to study the (n,X) reactions. However, none of them are ideal to measure (n,X) reactions on most of the actinides, except the n_TOF facility thanks to its high intensities available. On the other hand, the strong gamma flash present there can only be removed with a beam extraction at the angle of some tens of degrees, the construction of which is not yet decided.

At SPIRAL-2, the beam intensity expected is of the same order as at n_TOF, with however a much higher frequency. A flight path of 20 m would allow covering the energy range of interest for the (n,X) reactions. At this distance the beam intensity would be large enough to allow targets of a few hundreds of mg only and still reasonable energy resolution (below 10 %). Equally, segmented detectors might be helpful in this respect. Indeed, in this case only segments where a γ ray from the flash has been detected are blocked. However, one must be aware that the activity of the target cannot be separated from the reactions, so that in any case the final cross section has to be obtained by subtraction of the long background runs.

Table 1: *Major characteristics of (n,X) cross section measurements at different facilities.*

Beam Distance Period	Δt between Flash and a neutron of 20 MeV	Time resolution for a 1 MeV energy resolution at 20 MeV	Δt between two bursts with wrap-around at 0.5 MeV	Typical mass (a.u.)
200 m n_TOF 2-14 s Gelina 1.25 ms	2.565 μs made possible with digital electronics	84 ns	19.8 ms	~90 g at Gelina ~ 2 g at n_TOF
20 m Los Alamos 20.34 m 1.8 ms	0.257 μs Flash is weak, distributed over more than 100 bursts	8 ns	1.98 μs the activity cannot be separated from the reaction	2.25
3 m Louvain 3.25 m 50-60 ns	0.038 μs Flash cannot be separated from physics	1 ns TOF is impossible, beam must be mono-energetic	0.3 ms beam must be mono-energetic	0.023 high statistics, but γ flash and activity not separated from the reaction

Spiral-2 vs Gelina

To bring out the potential advantages of Spiral-2 for this type of measurements reaction rate estimates were performed for ^{56}Fe(n,n'), ^{56}Fe(n,2n), ^{56}Fe(n,p) and ^{56}Fe(n,α). These estimates are based on the E_d = 33 MeV measurements for the C(d,n) flux by Shin et al. and Fe cross sections from the JEFF-3.0 library, judiciously extended above 20 MeV. The present estimates are for a 10 m flight path. One further assumed a single detector with an absolute peak efficiency of $2\cdot10^{-3}$ corresponding to a 95 % HPGe at about 12 cm from the sample. The sample diameter was 5 cm and the thickness was given by the criterion of 10 % neutron attenuation for a total cross section of 2.5 b (77 g of Fe). Table 2 shows the counts per second that would result in case a single gamma is emitted. In reality the number of emitted gammas will be larger, the average increasing with energy. To remain conservative an average of two will be assumed leading to roughly $5\cdot10^{4}$ cps. For comparison, at Gelina the count rate would be about 10 cps. Evidently, the improvement comprises nearly four orders of magnitude.

Table 2: *Expected count rates at 10 m for 77 g of Fe, one 95% HPGe detector at 12 cm and one gamma emitted per reaction (E_d=33 MeV, I_d=28 μA on graphite target).*

Reaction	Count rate, cps
^{56}Fe(n,n')	18000
^{56}Fe(n,2n)	5800
^{56}Fe(n,p)	1300
^{56}Fe(n,α)	475

To understand how these four orders of magnitude can be used effectively we first need to take a look at three experimental constraints: energy resolution, dead time and the rate of prompt events.

Energy resolution

Fig. 5 shows the relative energy resolution for several conditions. For large volume HPGe detectors, a time resolution of 8 ns fwhm is routinely achieved at Gelina using conventional electronics and was demonstrated to be accessible with a 400 MSPS 12-bit digitizer, as well. Even, under these favourable conditions the energy resolution at 10 m is worse than 10% above 20 MeV, whereas it stays below 7.5 % for the entire energy range at 20 m. Thus, for a physically meaningful measurement a 20 m flight path would be required.

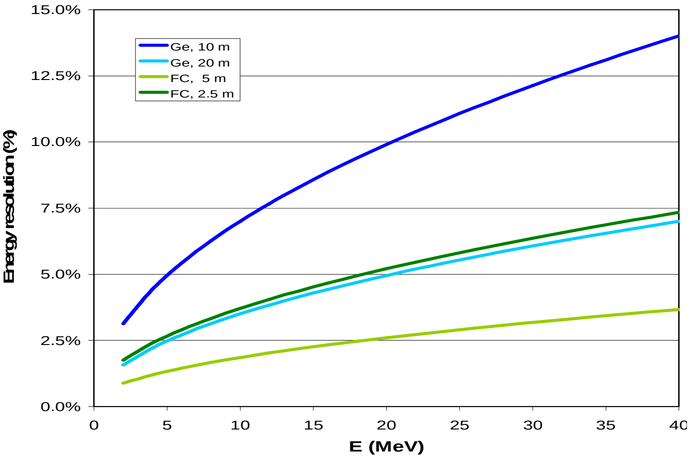

Fig. 5: *Relative energy resolution (fwhm) for different flight path lenghts and detectors. An accelerator burst width of 0.3 ns was assumed. The flight path uncertainty was determined by the source (0.6 cm) and the sample (0.6 cm). The time resolution for Ge was taken as 8 ns, whereas 1 ns was assumed for the fission chamber.*

For a Ge detector, the 8 ns fwhm is achievable with conventional electronics at the expense of a great number of lost events, especially below Eγ = 500 keV, as a result of the use of the slow rise time rejection scheme. Using a 400 MSPS 12 bit digitizer similar timing can be achieved without this set back. This is not the case for the lower sampling rate of 65 MSPS, mentioned above.

Dead time

For precise cross section measurements dead time corrections should be of the order of a few percent. As argued above the dead time for conventional electronics is long (about 25 µs), whereas for fast digitizers it can be as short as 2.5 µs, provided the data transfer rate is negligible. The latter was demonstrated with on board processing by means of an FPGA for the 65 MSPS digitizer of IReS Strasbourg and is expected to be available in the future for the 400 MSPS digitizer under test at Gelina, as well. Thus a ~2.5 µs dead time and a 2 % dead time correction would imply a count rate for a single detector of maximum 8000 cps. This is still a factor of 800 higher than the rate at Gelina, so that the statistics obtained in 1000 h there would be attained in slightly more than one hour at Spiral-2!

Rate of prompt events

Shin et al., measured a prompt photon yield at zero degrees for gammas above 1.5 MeV of $4.2 \cdot 10^{-3}$ γ/sr/d. At 28 µA and 5 cm sample diameter this implies that $1.5 \cdot 10^{7}$ of such gammas are incident on the target. Assuming all are scattered isotropically and taking a 1 % total efficiency this implies $1.5\cdot10^5$ γ/s detected. As such, for one in three bursts the detector sees a scattered photon (10 m flight path). This seems far from the desired few percent, however, it is no problem to come to the wanted value by going to 20 m and reducing sample size by a factor of 200. The present estimate at 10 m merely highlights the reduction of the prompt background compared to that at Gelina, where the same value was attained at 200 m with a thick U filter.

Summary

Spiral-2 offers favourable conditions for the measurement of cross sections for gammas emitted in inelastic and (n,xn) reactions. Adequate energy resolution in the entire accessible range requires a 20 m flight path. At 20 m, a 100 h run on a 200 times smaller sample mass, would result in similar statistics as would be attained in Gelina in a 1000 h run! Thus, systematic studies on isotope chains are readily accessible, since enriched samples on the order of 0.4 g would suffice. Under these conditions the prompt gammas will not disturb the measurements. The small samples have the added advantage of negligible sample size and gamma-attenuation corrections.

A measurement facility of this type can readily be deployed to provide a coherent study of several isotope chains (Si, Fe/Ni, Zr/Mo, W, Pb, Th/U) throughout the mass table to assist nuclear model development and can be focussed at key materials of interest to applications (Si, Cr, Fe, Ge, Pd, …).

The potential for the use of advanced HPGe detectors/arrays in these measurements is evidently large. Increase in efficiency (detector number) allows reducing further sample masses, enabling the study of more exotic samples. Any decrease of Compton background would potentially enable the technique for the study of weaker cross sections, such as those associated with (n,xp) and (n,xα) reactions. Increased detector numbers and segmentation open the route to measurements on more highly radio-active targets than the ‘stable’ actinides. It may be noted that in connection with radiation damage the study of (n,xp) and (n,xα) reactions is of particular importance to support radiation damage studies. A well known problem area for which measurements are particularly scarce is the range from 5 to 35 MeV, which is exactly in the range covered by Spiral-2.

Important experimental constraints not mentioned above are a well collimated beam and a measurement room with negligible background count rate. The latter would require effective shielding between the measurement room and the source, a defining collimator sufficiently upstream to allow the detectors to be shielded from this collimator and a beam dump sufficiently downstream to allow effective shielding towards the detectors. Evacuated flight paths would be needed.

<u>2.5. Fission cross section measurements</u>

For the energy range provided by Spiral-2 fission cross sections on minor actinides are of key importance to studies related to waste management in nuclear reactors. The main isotopes of interest are those of Am and Cm, but contemporary studies include those of U, Th and Pa that are of interest to the Th/U fuel cycle. In addition, such cross section measurements, and in particular an accurate study of their shape, would greatly help nuclear model development (fission barrier systematics, level densities, transition states and fission modes, etc.).

To enable such measurements use can be made of Frisch-gridded ionisation chambers using current amplifiers read out with digitizers. Energy resolution would be excellent even at 5 m (see Fig. 5) and events can be separated up to rates of ~10^6 cps. Using the same data as above and a 5 m flight path about 10 μg of material would be needed to provide $3\cdot10^5$ counts in a run of 100 h, or about 3 % statistical error in 0.1 MeV bins (estimated for ^{243}Am). As the alpha-activity would have to be limited to 1 MBq this implies that measurements are feasible for ^{230,232}Th, ^{231}Pa, ^{233,234,235,236,238}U, ^{236,237}Np, ^{239,240,241,242,244}Pu, ^{243}Am and ^{245,246,247,248}Cm in addition to the beta emitters ^{233}Pa and ^{241}Pu. This excludes several important nuclides that are currently poorly studied: ^{232}U, ^{238}Pu, ^{241,242}Am and ^{243,244}Cm. For these the conditions at Spiral-2 are marginal and another factor of ~10 in flux would be desirable. This may be achieved by a shorter flight path (e.g. 2.5 m) and any gain in neutron source intensity, such as suggested above (C target versus Be or Li target and primary beam bunching).

The main advantages of Spiral-2 over the quasi mono-energetic sources, currently employed to study these reactions, are the continuous energy measurement of the excitation curve with good resolution and a better handle on low energy contaminant neutrons. In fact, the low energy neutron problem at a time-of-flight facility is dominated by room scatter and overlap neutrons. The first is minimised by proper collimation, low mass sample and detector arrangements. The second by avoiding, as much as possible, any components near the neutron source that may scatter neutrons into the flight path or that are efficient moderators. Such considerations are generally of no interest to nuclides with a threshold for fisison, but are of key importance for nuclei with large thermal fission cross sections. The latter are often unwanted contaminants in samples consisting predominantly of the former type of fissile nuclei.

2.6. Double differential (n,chp) cross section measurements

In view of the conditions at Spiral-2 being more favourable than those at WNR (LANL) in the energy range from 5 to 35 MeV, it is evident that a measurement program of double differential charged particle cross sections, with a setup similar to that pioneered at WNR, would also be feasible at Spiral-2. The use of such measurements was argued above in terms of applications (radiation damage). In terms of nuclear physics it is important to note that nuclear modeling of this type of reactions at low energy is considerably more complicated than it is at higher energies. The part of the optical model probed by light-charged particle scattering is different from that probed by the light-charged particle that is emitted in a neutron induced reaction (in particular for the alpha-particle). The dispersive contribution to the optical model is of key importance and the theory of the imaginary part of the potential is not advanced to the point that it is readily used for cross section predictions. More-over the study of complex particle (d,t,^{3}He) emission in equilibrium and pre-equilibrium reactions would greatly benefit from a systematic set of new results. It would be of interest to encourage experimental activity in this area.

III. Quasi mono-energetic neutrons

It was briefly discussed that DC deuterons in the 0.75 to 4(7) MeV range could be used to produce quasi mono-energetic neutrons with the (d,D) and (d,T) reactions making full use of the 5 mA current available from the source. For comparison, this would provide an intensity gain of 100 to 1000 over most available VdG facilities where such reactions are currently employed. The main point that was not addressed so far and which is worth considering is the requirements on target cooling and stability.

Should a target be feasible, then we have for the first time a neutron source in the range below 14 MeV (4-10 MeV) and above 14 MeV (16-20 MeV) comparable in intensity to neutron generators. Thus, sample masses conventionally employed for instance for fission, capture and activation studies could be reduced 100 to 1000 times, or activation studies would result in 100-1000 times larger activities. The range of achievable measurements is then very large. For instance (n,2n) cross sections below and above 14 MeV with the activation technique would be greatly facilitated for important target nuclei such as ^{239}Pu, ^{232}Th, ^{241}Am. All above mentioned fission cross sections would be easily accessible. It would be worthwhile to learn about the feasibility of such a neutron source and the state of the art of high power D and T targets.

IV. Astrophysics with neutrons at SPIRAL-2

The very high neutron flux at SPIRAL-2 offers two unique options for astrophysical applications:

4.1. Preparation of radioactive samples

The neutron capture cross sections of radioactive isotopes are crucial for the interpretation of s-process branching ratios and are of increasing interest for the development of quantitative models of explosive nucleo-synthesis in the r and p process. Presently, it is difficult to produce the samples for such measurements in the required amounts and purities. The high flux of neutrons with energies in the MeV range would allow to obtain suited samples via (n,p), (n,α), and (n,2n) reactions by irradiating selected materials either in parasitic mode or in dedicated runs of about a few weeks. The proper choice of the reaction type will help to separate the product nuclei by physical and chemical methods. A promising example is the production of ^{85}Kr via ^{85}Rb(n,p) or ^{88}Sr(n,α). Other interesting reactions are ^{13}C(n,α)^{10}Be and ^{66}Zr(n,α)^{63}Ni. Typically 10 days irradiation would result in more that ~10^{17} atoms created with 10 g samples.

4.2. Activation

The unstable isotope ^{60}Fe, which was discovered in deep sea sediments, has a half-life of ~1.5 Million years. Therefore, the proto-solar nebula must have been contaminated by substantial amounts of that isotope. Whether it was produced by a nearby supernova or Red Giant star is still an open issue. A reliable answer can be given only if the s-process production can be determined on the basis of experimental (n,γ) cross sections of ^{59}Fe and ^{60}Fe. Likewise, this important information can be obtained by irradiation of a pure ^{58}Fe sample and the subsequent detection of the ^{60}Fe produced. Such double neutron capture studies could be possible in the high flux of SPIRAL-2, provided that the fairly long irradiations can be carried out in parasitic mode in combination with material studies, which are planned anyway.

V. Material irradiation studies

The development of new fusion and fission reactor systems depends strongly on the development and testing of materials that can retain their strength, ductility, and shape, among other characteristics, under intense radiation. Because of its high flux, particular energy spectrum and versatility, SPIRAL2 has a huge potential to conduct these material tests. Detector testing and irradiation of electronic components also could be performed within reasonable time of irradiations thanks to the high neutron fluxes and variable thermal conditions available. Compared to presently available fast neutron generators, the two-order superior intensity of SPIRAL-2 neutron beam would offer the unique possibility to reach the precisely calibrated spectral flux at the position of irradiated samples by combining various model calculations and data from spectral measurements performed by both the multi-foil activation and proton-recoil telescope methods.

5.1. Fusion related research

As it is summarised in Table 3 the SPIRAL2 facility would be able to provide rather comparable neutron flux density and irradiation temperature conditions as ITER (controlled fusion demonstration reactor) but for rather limited sample volumes. Typical numbers for SPIRAL-2 are as follows: with the neutron flux higher than ~5x10^{13} n s^{-1} cm^{-2} and material damage rates greater than ~3 dpa/fpy one obtains ~10 cm^3 of a useful irradiation volume. Taking into account realistic beam availability constraints one could expect > 1 dpa per year in ~10 cm^3, i.e. 4 month irradiation per year at full power. It is important to emphasize that a variable temperature environment (between 20°C and 1000°C or higher) for irradiations would be possible at SPIRAL-2.

One notes that, although neutron energy distribution of SPIRAL-2 (average neutron energy ~13-14 MeV, i.e. being nearly identical to “IFMIF – green line” as presented in Fig. 6) is quite different from the fluxes predicted for the first wall of “ITER – blue line”, the ratio of gas production over dpa rates is rather comparable. In the case of SPIRAL-2 we obtain He/dpa = 13, H/dpa = 51, while for ITER one finds He/dpa = 11, H/dpa = 45.

Table 3: *Maximal (on the target back-plate over the beam spot dimensions) neutron flux, displacement rate, gas production and nuclear heating SPIRAL2. The fpy stands for full power year, dpa – displacement per atom, appm – atom parts per million. All values are for* ^{56}*Fe.*

	Neutron flux, (n/(s cm^2))	Damage rate, (dpa/fpy)	Gas prod. (He), (appm/fpy)	Gas prod. (H), (appm/fpy)	Nuclear heating in ^{56}Fe, (W/cm^3)
SPIRAL2	1.1 x 10^{14}	7	95	378	3
ITER	4.0 x 10^{14}	12	140	540	12

*****These are the very maximal expected values.

It seems that SPIRAL-2 with major characteristics summarized above would be able to contribute significantly in testing and qualifying materials under fusion-specific irradiation conditions. In particular, irradiations of miniaturized samples to test their limitations and development qualification of dedicated modelling tools seem to be very attractive. SPIRAL-2 also could be considered as an intermediate step towards new generation dedicated irradiation facilities as IFMIF (d(40 MeV) + Li; I_d = 200 mA) previewed only beyond ~2015.

5.2. Fission related research

Equally, as in the case of fusion related research, SPIRAL-2 could also be used for fission applications, in particular in the case of advanced material development, calibration and validation of data for commercial fission reactors and particle accelerators. In some particular cases, innovative nuclear fuel is μ-structured (in the form of micro-particles), and contains very thin layers of various materials (see Fig. 7). Therefore, even ~10 cm^3 irradiation volumes available at SPIRAL-2 are sufficient to test different materials of such fuel and structure components in terms of burn-up, integrity of structure and barriers, resistance to high energy neutron irradiations at variable temperatures.

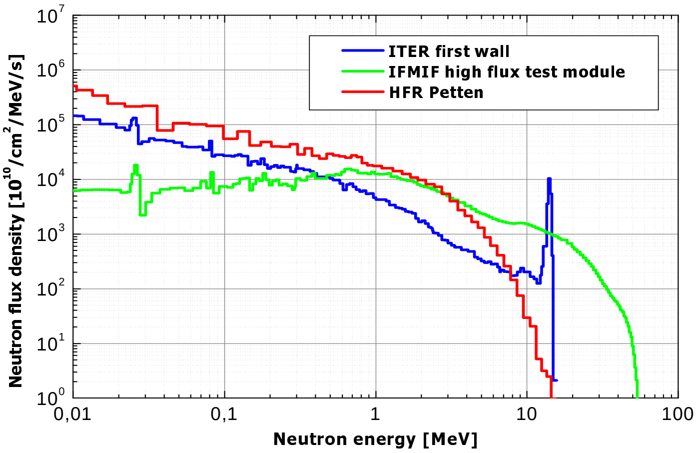

Fig. 6: *Comparison of typical energy spectra of neutrons in the case of nuclear reactor "HFR Petten", "IFMIF" or "SPIRAL-2" and "ITER first wall".*

Thanks to the advances in the numerical simulations and new measurement tools, even a few dpa in a few mm^3 become of great interest, if the results are available in a short time for interpretation and progress in model development. It seems that present numerical simulations have a huge potential to bridge the gap between "small scale" experiments towards "real scale" tests in terms of validation, transposition and extrapolation, in this way building a shorter path from basic science to application oriented design tools.

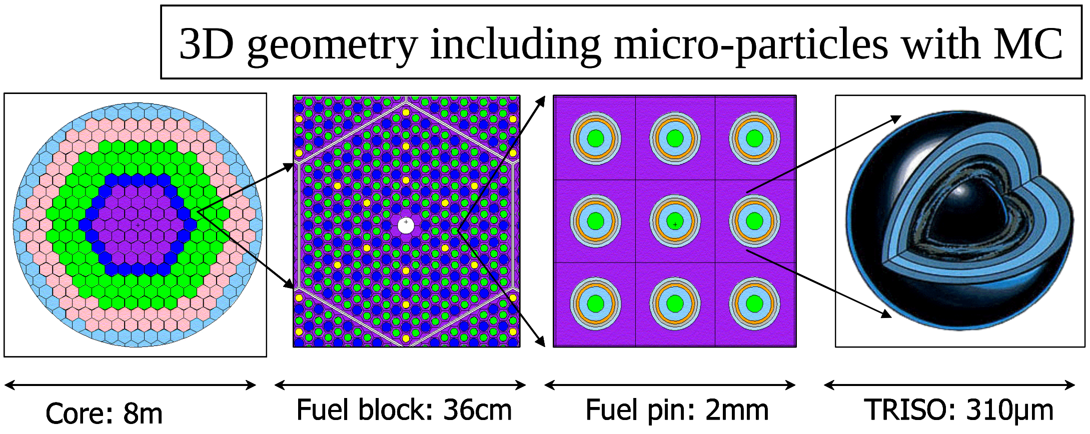

Fig. 7: *Simplified picture of different structure elements of the innovative high temperature reactor GT-MHR: from reactor core (~8 m) to microscopic fuel particles (~300 µm).*

Finally, it is important to note that one could also profit the access to heavy ions of present GANIL accelerators. Some irradiations could be done with ions and later on with neutrons at the same installation.

5.3. Testing of neutron detectors

Use of intense high energy neutrons from SPIRAL-2 would be ideal for characterization of so called CVD Diamond Detectors, calibration of which is urgently needed in the neutron energy range from 14 MeV to 20 MeV. In this context, contribution of competing inelastic reactions as (n,α), (n,p), (n,d), etc. should be known with much better precision as it is available today. In particular, compilation of data of the reaction ^{12}C(n,α)^{9}Be (see Fig. 8) and also neutron induced reactions on ^{13}C is urgently needed.

Irradiations of such detectors with SPIRAL-2 neutrons (desired fluence rates could be obtained in less than 1 hour (!) at full beam power) would permit to explore radiation damage mechanisms, define sensitivity and life-time of such and other detectors, optimize their geometry, materials, signal to noise rations, etc. in “hard” irradiation conditions with high energy neutrons.

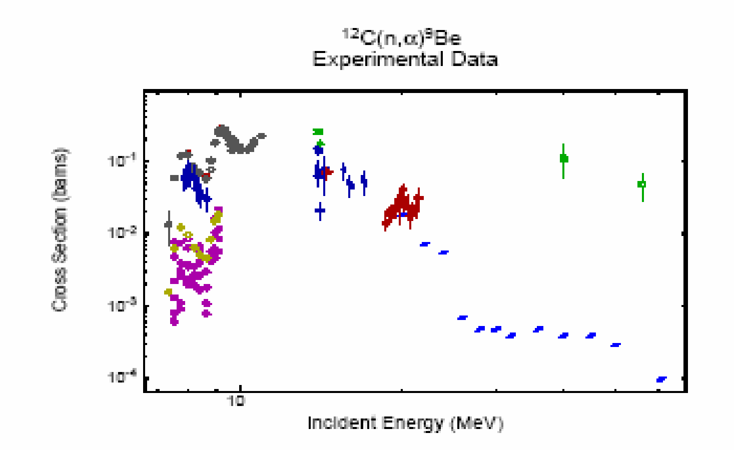

Fig. 8: *Status of the available data on the* $^{12}C(n,\alpha)^{9}Be$ *reaction channel (note the log-log scale).*

VI. Conclusions

Both cross section measurements and various applications could be realised successfully using the high energy neutrons produced at SPIRAL-2. Two particular cases were examined in more detail, namely: (a) neutron time-of-flight (nToF) measurements with pulsed neutron beams, and (b) material activation-irradiation with high-energy high-intensity neutron fluxes.

Thanks to the high energy and high intensity neutron flux available, SPIRAL-2 offers a unique opportunity for material irradiations both for fission and fusion related research, tests of various detection systems and of resistance of electronics components to irradiations, etc. SPIRAL-2 also could be considered as an intermediate step towards new generation dedicated irradiation facilities as IFMIF previewed only beyond ~2015.

Equally, the interval from 0.1 MeV to 40 MeV for neutron cross section measurements is an energy range that is of particular importance for energy applications, notably accelerator driven systems (ADS) and Gen-IV fast reactors, as well as for fusion related devices. It is also the region where pre-equilibrium approaches are often used to link the low (evaporation) and high energy (intra-nuclear cascade) reaction models. With very intense neutron beams of SPIRAL-2 measurements of very low mass (often radioactive) targets and small cross sections become feasible in short experimental campaigns. Production of radioactive targets for dedicated physics experiments is also an attractive feature of SPIRAL-2.

In brief, it was shown that SPIRAL-2 has got a remarkable potential for neutron based research both for fundamental physics and various applications. In addition, in the neutron energy range from a few MeV to, say, 35 MeV this research would have a leading position for the next 10-15 years if compared to other neutron facilities in operation or under construction worldwide.

References

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[3] International Workshop on Neutrons for Science (NFS) at SPIRAL-2, GANIL, Caen, France; 13-14 December 2004; presentations available at http://www.ganil.fr/spiral2ws2/.