Neutrons For Science (NFS) at SPIRAL-2
(Part II: pulsed neutron beam)

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A huge number of high energy neutrons (in the range between 1 and 40 MeV) produced in the carbon converter via C(d,xn) reaction will be present at SPIRAL-2 and in principle could be used for other purposes than RIB production. Mainly two different utilisation methods have been investigated: a) material irradiation very close to the target-converter, and b) time-of-flight (ToF) measurements with a pulsed neutron beam. Below we present only the case of ToF experiments with a pulsed neutron beam, while our companion paper [1] was already dedicated to the 1st application.

Introduction

A huge number of high energy neutrons (~10^{15} n/s; in the range between 1 and 40 MeV), produced in the carbon converter via C(d,xn) reaction, will be present at the SPIRAL-2 project at GANIL (Caen, France) aiming to produce neutron-rich fission fragments [2]. The main goal of this study is to provide quantitative estimates on the possibility of using a 40 MeV (5mA) linear deuteron accelerator in a combination with a carbon target-converter, as projected at SPIRAL-2, for potential time-of-flight experiments with a pulsed neutron beam. It is also aimed to give a direct comparison with two major ToF facilities in Europe, namely n-ToF at CERN (Switzerland) and GELINA at Geel (Belgium).

The neutron energy range accessible by SPIRAL-2 is of great interest for a number of applications [3]. As long as neutron cross sections are concerned, only few 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,alpha), allowing the pre-equilibrium model studies, i.e. the transition between low (evaporation) and high energy models (intra-nuclear cascade). The high neutron flux would allow performing measurements of small cross-sections and/or with very small targets, which might be rare, expensive, and in some cases radioactive. Fundamental studies can also be achieved with the measurement of neutron-neutron interaction length by investigating, for example, the D(n,2n)p reaction.

1 Pulsed neutron beams at SPIRAL-2

1.1 Neutron production

The use of a neutron beam depends on specific characteristics in terms of the available neutron flux, energy resolution and useful energy range. These characteristics give strong technical constraints to the accelerator and experiment hall. The neutrons produced by d+C reaction present a continuous spectrum up to ~40 MeV and are peaked at forward angles (see below). Therefore, the neutron beam should be designed at the very forward angles, presumably at 0°, through a channel in a thick concrete wall out from the room containing the converter (neutron source). A dedicated experimental hall should be built then right behind this wall.

All estimates in this work were done using the MCNPX code system [4] by adjusting the total neutron yield with respect to the experimental data (see Fig. 1). One can clearly see that MCNPX systematically underestimates the experimental data both over 4π and at forward angles in particular. For example, according to the existing experimental data, the d(40MeV) + Li reaction results in 0.07 n/d over 4π, while MCNPX predicts ~2.5 times lower yield. Therefore, the predicted total neutron yield was renormalized according to the experimental values. On the other hand, no corrections for energy and angular distributions were made. Similar absolute neutron yield correction was adopted for the d(40MeV) + C reaction, resulting in 0.025 neutrons per incident deuteron (already corrected). It was shown in [1] that this “correction” approach is justified by testing it in the case of the IFMIF neutron analysis [5].

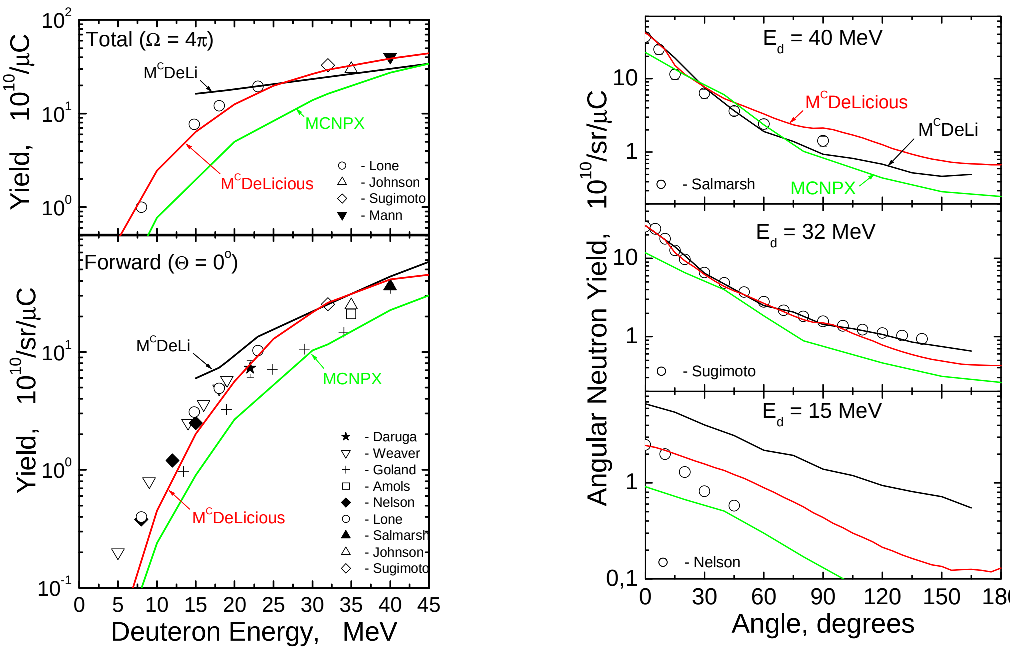

Figure 1: *Neutron yields (total and angular distributions) from the d+Li reactions as a function of deuteron energy. Data points are compared with different code (MCNPX, McDeLi, McDeLicious) predictions as from Ref. [5].*

1.2 Energy resolution

Since the neutrons produced via the d+C reaction are not mono-energetic, a pulsed mode is necessary to determine their energy by time of flight (ToF). The energy resolution (determined by ToF) is given by:

$$\frac{\Delta E}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2},$$

where L is the flight path and ΔL - the associated uncertainty;
t is the ToF difference between a neutron of energy E and a photon for the distance L;
Δt is the time resolution of the accelerator;
γ is a relativity factor.

$\Delta E/E$ at a given energy will depend on the accelerator time resolution and the distance between neutron production and physics targets. The choice of the path length is a compromise between the resolution (increasing with distance) and the available flux (decreasing with distance). Fig. 2 shows the energy resolution as a function of neutron energy with two different time resolutions Δt and two flight paths L. It is clearly seen that energy resolution around 0.5 % could be obtained in the entire energy range for L = 10 m and would be around 1.0 % for L = 5 m when considering the LINAG resolution of Δt = 100 ps. For a detector time resolution of 1 ns the energy resolution is always better than 5 %.

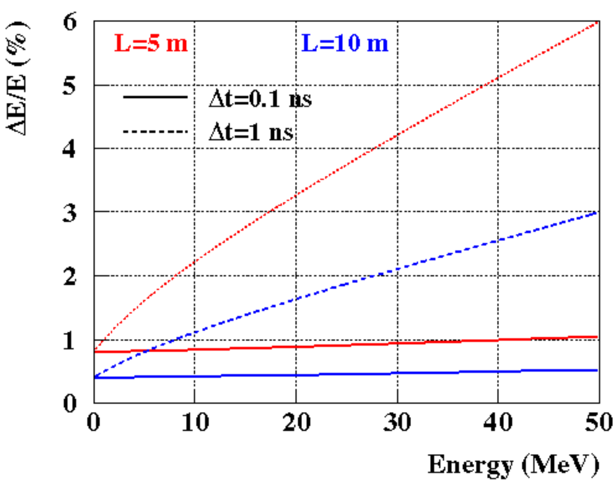

Figure 2: *Neutron energy resolution as a function of their energy for two flight paths (L = 10 m and L = 5 m) and two time resolutions (Δt = 0.1 ns and Δt = 1 ns).*

1.3 Pulsed neutron beam

The primary deuteron beam frequency f is an important characteristic as well. If the frequency is too high, 2 events of time of flight t and $t+T$ ($T = 1/f$) will not be discriminated. Fig. 3 presents the neutron flux as a function of ToF for the distances of 5 and 10 m. It appears that a period of ~2 μs is long enough to limit high (~40 MeV) and low (~1 MeV) energy neutron overlap. Therefore, the beam frequency should be limited to f ~ 500 kHz (or even smaller), what corresponds to a division of nearly by a factor of 200 if compared to a presently planned ~87 MHz repetition rate. Note that the integral neutron intensity is reduced in the same proportion (this is already taken into account in Fig. 3). It is important to note that the beam power deposited on the converter is also decreased proportionally, making its design easier in terms of thermal conditions and damage rates.

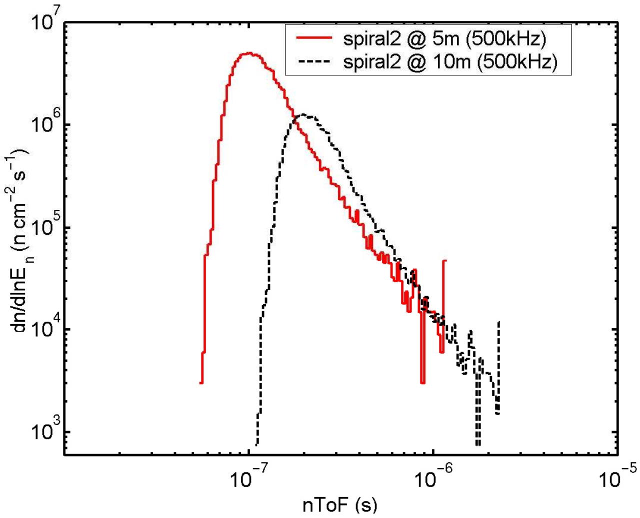

Figure 3: *Neutron flux as a function of time of flight for 5 and 10 m flight paths.*

1.4 Flux and energy spectra of neutrons

The total neutron flux has been calculated using MCNPX. In Fig. 4 the neutron flux as a function of distance from the production target is presented (red points). A carbon disk of 1 cm thick was bombarded by 40 MeV deuteron beam with a 5 cm^2 beam spot distributed homogeneously on the sphere. Due to a particularity of (d,xn) reaction, the neutron source is not isotropic, and the ~$1/L^2$ law is valid only at distances greater than 200 cm (blue line).

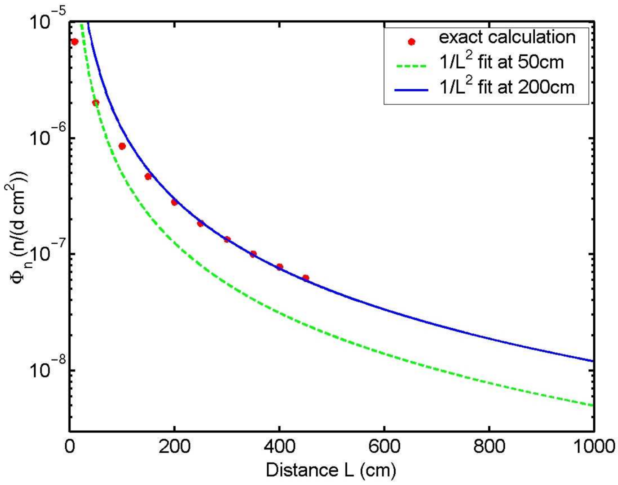

Figure 4: *Neutron flux as a function of the distance, normalised per incident deuteron. Red points are exact MCNPX calculation results. Blue and green lines are ~$1/L^2$ curve normalised to the flux at 200 cm and 50 cm respectively.*

In addition, when the distance increases, the opening angle decreases and the energy spectrum is slightly modified, i.e. it becomes somewhat harder. This observation is illustrated in Fig. 5.

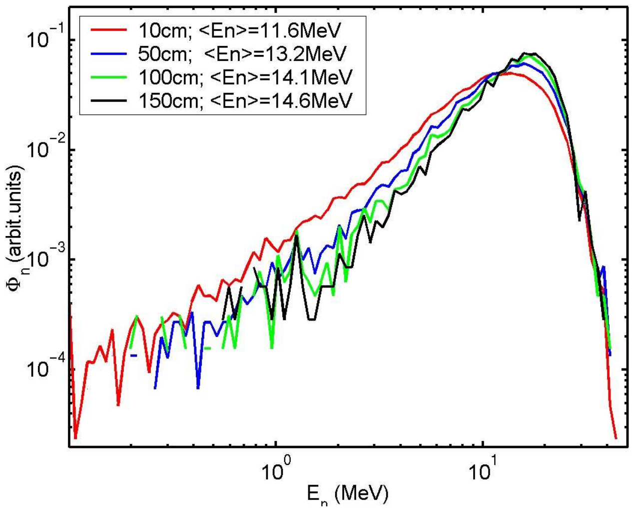

Figure 5: *Energy spectra and average neutron energies as a function of the distance from the neutron source towards the deuteron beam direction.*

1.5 Comparison with other n-beam facilities (fast spectrum)

The absolute neutron flux can now be calculated as a function of the energy and can be compared with two major ToF facilities: n-TOF at CERN (Switzerland) and GELINA at Geel (Belgium) [6]. The following characteristics for SPIRAL-2 have been considered:

- A 500 kHz frequency (a reduction of a factor 200 of the SPIRAL-2 nominal intensity, i.e. 5 mA/200);
- Flight path of 5 and 10 m.

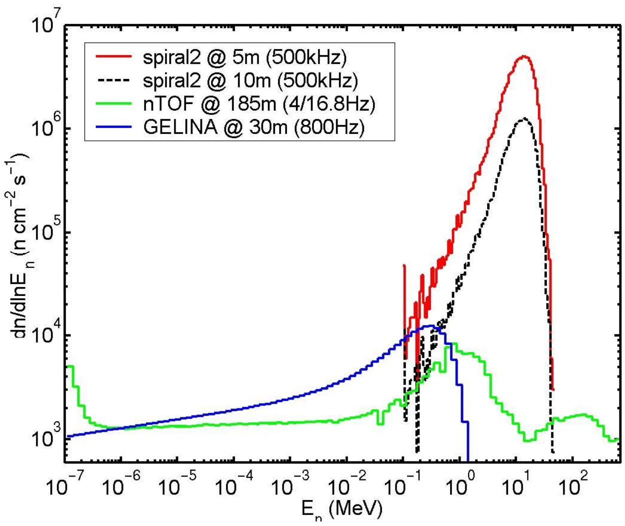

Figure 6: *Comparison of integrated absolute neutron flux available at different ToF facilities. Data for nTOF and GELINA were taken from Ref. [6].*

The results presented in Fig. 6 show that in the range between 5 and 35 MeV the neutron beam produced with the SPIRAL-2 is between 2 and 3 orders of magnitude higher than the flux available at n-TOF (CERN). The relatively smaller flux at the n-TOF facility is explained by a very long flight path (~185 m) and at the same time by a very low frequency (4/16.8 Hz). One should not forget the presence of the neutron background in the experimental room due to thermal neutrons, whose flux is directly related to the averaged integral beam intensity. The low frequency of n-TOF facility leads to low average neutron flux but high signal-to-noise ratio. This ratio will be much lower in the NFS facility at SPIRAL-2 if the entire neutron spectrum is considered, but for fast neutrons (above 0.1 MeV) it should not be a very limiting factor. Further transport calculations have to be performed to evaluate the characteristics of the "neutron environment" in the experimental hall. Equally the background due to the prompt gammas should be evaluated.

1.6 Conceptual design of a dedicated beam line

We saw that a neutron beam facility requires a special deuteron beam frequency and a dedicated hall at zero degrees in respect to the beam line. The low frequency, (~200 times lower than the initial accelerator frequency for the RIB production) presents an important advantage. The design of the plug concept and rotating carbon-converter could be changed since deuteron beam intensity is largely decreased (by a factor of ~200) if compared to the available accelerator power. In addition, in the present design of SPIRAL-2 it seems to be sufficient place for a proposed neutron hall (see Fig. 7).

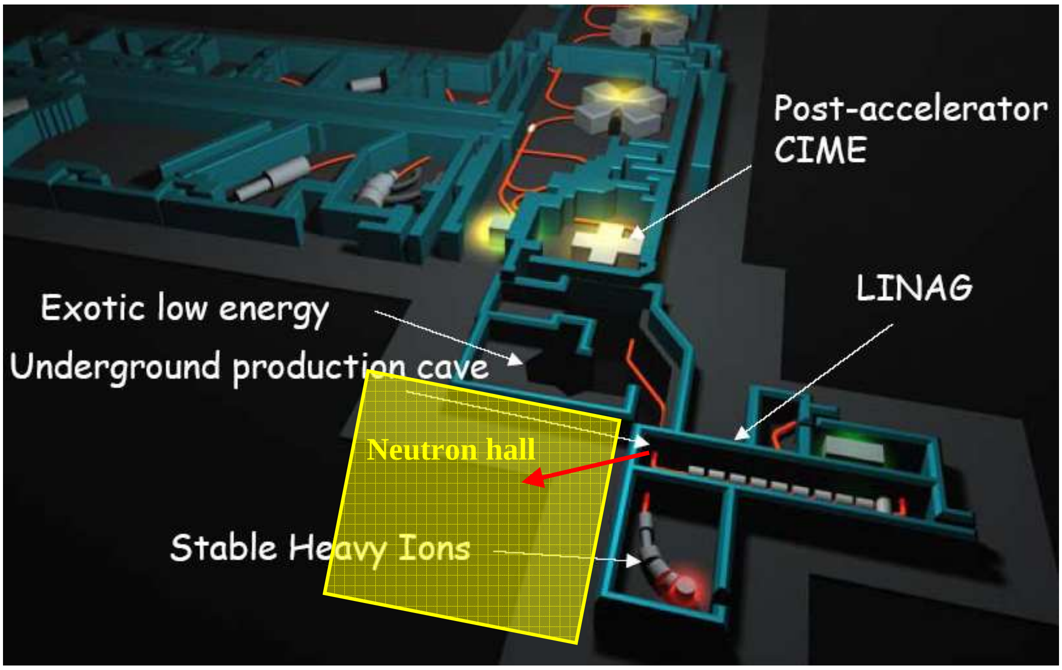

Figure 7: *A schematic view of the proposed experimental neutron hall (in yellow). It could be situated either on the underground level as RIB production cave or on the top level as LINAG accelerator itself. A potential entrance of the deuteron beam into the neutron hall is also indicated (red flash).*

2 Specific neutron beams

2.1 Mono-energetic neutron beam

The SPIRAL-2 property to deliver low deuteron energy beam (as low as 0.75 MeV/A) would allow producing mono-energetic neutron beams. In the low energy range (E_n < 8 MeV) mono-energetic neutrons can be produced by the $^2H(d,n)^3He$ reaction. Solid (deuterium is implemented in titanium) or gaseous target can be used for such purposes. Higher energy neutrons can also be produced in a mono-kinetic way using the $^3H(d,n)^3He$ reaction. In this case only solid target can be used.

For these two applications the possible SPIRAL-2 working mode (low energy of the deuteron) is not nominal but we have to keep in mind that it allows producing mono-energetic neutron beams. The titanium targets (with deuteron or tritium implemented) are of about 1 mg/cm^2 thick. The neutron flux will depend then on the beam power which could be supported by these targets. Further studies along these lines are urgently needed.

2.2 Low energy neutron beams

2.2.1 Energy spectra

Some applications like astrophysical studies require intense neutrons flux in a lower energy range than the typical spectrum as presented in Fig 5. Neutron capture cross-section measurements in the 1 keV –500 keV range are of great interest in the r-process study [7]. In particular, capture on unstable nuclei is very interesting and some radioactive nuclei could be produced by SPIRAL-2 facility in the RIB production target via fission or in dedicated targets by neutron irradiation.

Two types of experiments can be envisaged: irradiation-activation or time of flight measurements. In both cases the neutron flux in region of interest could be increased by slowing down the primary neutrons outgoing from the carbon converter. Fig 8 gives the energy spectra calculated for three examples of moderators composed of 3 cm of beryllium and water. Note that beryllium allows producing an extra number of neutrons by (n,2n) reactions. The D_2O is preferred rather than H_20 because its capture cross section is lower and it produces a lower thermal neutron component, which in any case can be strongly reduced in loading the moderator with ^6Li.

Moderated neutron spectrum could also be used to produce radioactive targets for the follow-up experiments related to astrophysics. Our estimates show that in the energy range from 3 keV to 100 keV available neutron fluxes would be of the order of ~ $4x10^{11}$ n/(s cm^2). Note that in this case a full available primary beam power was used (5 mA; 200 kW), and the irradiation zone was optimized employing the Be-Be type sandwich moderator at zero degrees with respect to the beam axis.

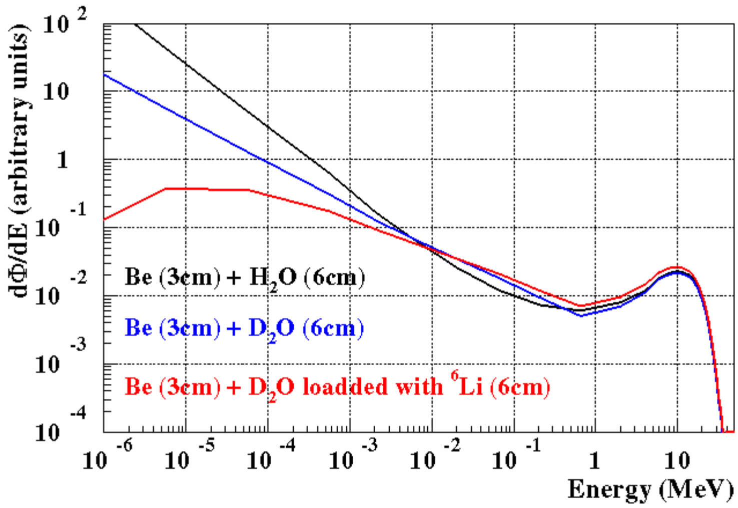

Figure 8: *Moderated neutron energy spectra as a function of different moderators (also see the legend).*

2.2.2 Time of flight and slowing down time

As described above the neutrons of 1 keV have to be separated from the 40 MeV ones. The beam frequency is thus determined by the flight path and the lowest energy to be measured. Table 1 gives the TOF of 1 keV neutrons for 2 flight paths and the associated frequencies.

Flight path	Time of flight	Beam frequency	SPIRAL-2 division
5 m	11,5 μs	87 kHz	1/1000
10 m	2,3 μs	44 kHz	1/2000

Table 1: *Flight path, time of flight, beam frequency, and SPIRAL-2 frequency division for 1 keV neutrons.*

The slowing down time of neutrons in the moderator is of an important parameter because it is directly related to the time resolution and thus to the expected neutron energy resolution. The average slowing down time simulated using MCNPX is given as a function of the energy (at the moderator output) on Fig. 9.

A SPIRAL-2 frequency division of 1/1000 would mean that one has to select one pulse over 1000. In order to increase the neutron flux, long macro pulses containing several micro pulses (100 ps long at a frequency of 87 MHz) could be generated. For example, macro pulses of 50 ns would contain 5 micro pulses and allow multiplying the flux by a factor of 5. The energy resolution taking into account the slowing down time and the macro pulse length is given on Fig. 10. We see that the available neutron flux can be increased by using the macro pulses without degrading energy resolution for low energy neutrons.

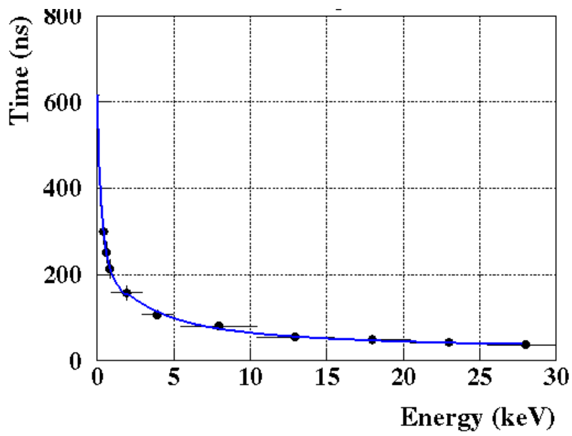

Figure 9: *Average slowing down time of high energy neutrons in a moderator composed of Be (3 cm) and D_2O (3 cm).*

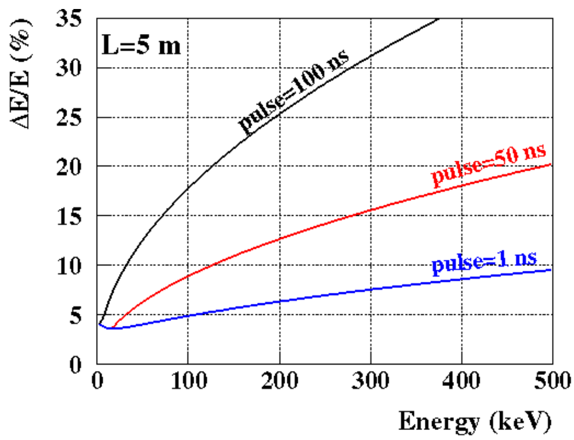

Figure 10: *Calculated energy resolution for low energy neutrons of SPIRAL-2 (the slowing down time in the moderator is taken into account).*

2.3 Comparison with other neutron beam facilities

Fig. 11 presents the moderated neutron flux of NFS in comparison with the n-ToF and Gelina fluxes already shown in Fig. 6. We considered a flight path of 5 m, a SPIRAL-2 frequency division of 1000 (resulting frequency of 80 kHz) and a macro pulse length of 50 ns. Even in this case SPIRAL-2 provides with very high neutron fluxes at E_n > 1 MeV. In the region of the astrophysical interest, NFS neutron flux is of the same order as the other facilities but presents the possibility to produce very low component of thermal neutrons (use of Be instead of CH_2 as moderating materials). Note that the beam rate is higher at SPIRAL-2 (87 kHz) than at n-TOF and GELINA corresponding to more restricting experimental conditions for signal-to-noise ratio or data acquisition.

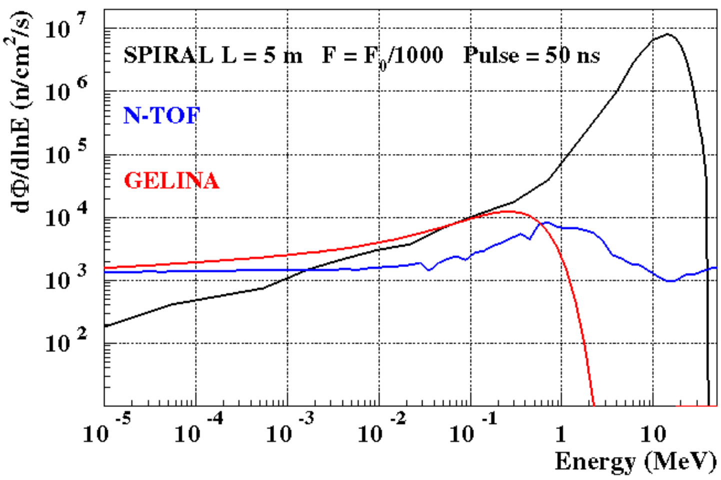

Figure 11: *Comparison of absolute neutron flux and energy spectra available at different ToF facilities. Data for nTOF and GELINA were taken from Ref. [6].*

Summary

Beginning of the construction of SPIRAL-2 is planned in 2005 and should be operational around 2009. It seems that, in addition to the RIB production facility, a pulsed neutron beam installation can be envisaged using the same deuteron beam delivered by SPIRAL-2. In brief, with SPIRAL-2 very high integrated neutron fluxes can be reached (greater by 100 to 1000 times compared to n-TOF at CERN) in the energy range from 5 to 35 MeV, and with the energy resolution of ~1 %. However, at least the following conditions should be fulfilled:

- A design of the experimental room at 0 degrees with respect to the deuteron beam direction;
- An adapted time structure of the deuteron beam with the repetition rate of f ~ 500 kHz corresponding to the use of a single pulse over 200 as initially available. We note that it will reduce by a factor 200 the power deposited on the carbon converter leading to a number of constraints (e.g., temperature of target-converter, radioprotection, absence of the UC_x production target, etc.) much less severe than for the RIB production line;
- It is suggested to preview a beam distributor to optimise the primary beam availability for other users, i.e. the possibility to use the ToF facility in parallel with the RIB production should be investigated;
- Low energy neutron beam can also be produced by moderating neutrons produced in the carbon converter. The production of macro-pulses containing several micro-pulses would increase the average intensity (by a factor of 5 for 50 ns duration macro-pulse), still preserving an acceptable time resolution for low energy neutrons;
- A design of a flight path (distance between the converter, i.e. neutron source and the physics target) of at least 5 m (a 10 m flight path would be penalised by a flux reduction but could allow a better energy resolution).

More detailed analysis on these issues should be addressed in the near future, including preliminary costs of the neutron hall, optimization of collimators, design of additional deuteron beam lines, beam switcher, moderating materials, etc. Full neutron transport calculations (e.g., performed with MCNPX) and corresponding limits in terms of the signal-to-noise ratio including safety radiation are urgently needed to determine the size of the experimental hall, the thickness and composition of the shielding walls, ToF channel geometry and materials, etc.

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