A new Interdisciplinary Irradiation Area at SPIRAL2

GANIL, LPC, CRISMAT, IPHC, LPSC, ARRONAX, SUBATECH, CERN, IRFU, CIMAP, DAM, LDM-TEP, CYCERON

Introduction

This contribution proposes an evolution of the current SPIRAL2 Phase 1 facility toward 1) a multiuser facility, 2) a broader scientific scope and 3) an increase of interdisciplinary applications with a potential high societal impact.

SPIRAL2 Phase 1: toward a multiuser facility

Eighty percent of the proposed NFS experiments use the neutron time-of-flight facility. In these kind of experiments, 1% of the beam intensity is driven toward the facility to avoid burst overlap for time-of-flight measurement. This means that 99% of the primary beam is wasted on a beam dump . A first proposal is to evaluate the opportunity to use this wasted beam in parallel to NFS. Today, a beam bunch selector, installed after the RFQ, permanently deviates the beam particles on a beam dump, an electric field restoring only the selected bunches to the LINAC. The largest number the bunch selector is able to send to the LINAC is 1/100 (a lower number is possible). There are several difficulties to install a bunch selector at higher energy and in particular, 1) the voltage rise time required for high-energy particles (after the LINAC) and 2) the space constraints. One idea is to use a medium energy beam bunch selector (after the RFQ as it is the case today) followed by a high-energy kicker installed after the LINAC to alternatively send the beam to NFS and to a new area where it can be fully exploited. In such a situation, it would be possible to select one bunch for NFS and M bunches for another purpose, the number M depending on how fast the voltage can be raised to properly kick the unwanted beam in NFS to another area. In this mode, the projectile energy and the peak intensity would be the same for the two rooms. This other area could be a new Interdisciplinary Irradiation Area (I2A), where a very broad physics program could be pursued (independently of the new bunching mode), enlarging very significantly the potential of GANIL in the long-term future. This possible new area is proposed in the following paragraph.

A new interdisciplinary area at SPIRAL2

The SPIRAL2 facility will deliver beams with unprecedented intensities (p, d, heavy ions with A/q=3). These beams in the milliampere range could be exploited in several domains providing a new area is designed on purpose. We propose here to build a new area, named I2A, capable of hosting instruments that will benefit from the full beam power. Neutron science, high power targetry development for the next generation neutron source, R&D for the production of innovative radioisotopes, and demonstration of an Accelerator Based-Neutron Capture Therapy setup will have access to unprecedented beams.

A compact neutron source at SPIRAL2

Neutron scattering is an essential technique in the chemistry and physics of condensed matter ([1,2]). The electrical neutrality of the neutron makes it insensitive to the internal electric fields of matter. It therefore deeply penetrates in matter and serves as a probe for the atomic structure and dynamics of the crystal lattice when having a wavelength of the size of the investigated structure (En<25 meV). In addition, the neutron interacts with the magnetic medium it is passing through, revealing the hidden order of spins or more complex magnetic structures. Neutron is also one of the best probe to study a broader range of sciences: fundamental physics, materials science, biology, medicine and environmental sciences. Beyond the scattering techniques, non-diffractive methods like imaging techniques are used more and more often.

There are currently many projects around the world to design compact neutron sources. This is mainly driven by the very important request from the neutron scattering community. In Europe and more specifically in France, the shutdown of Orphée (2019) and the ILL (planned in 2030, ESFRI optimistic scenario [3]) reactors will impact dramatically the users and it is estimated that, with ESS, the number of days.spectrometers will be reduced by 94% for the French community [4]. To anticipate this dramatic reduction of neutron beam time, the Fédération Française de Diffusion Neutronique (2FDN) published its roadmap ([5]), which recommends in particular the construction of a new compact neutron source. Several projects are currently under study like SONATE for instance [6-8]. In this contribution, we propose to install in a new interdisciplinary area, a complementary Compact Accelerator driven Neutron Source (CANS). This neutron source would be based on the existing SPIRAL2 Phase 1 facility and would use to start with, the already tested 50 kW Carbon converter. This latter was initially designed for the Phase 2 of SPIRAL2 and has been tested with an electron beam for 40 days at 50 kW and 70 hours up to 70 kW with success. For the definition of an optimal CANS, the design of the target and moderator is of paramount importance: this ensemble must ensure a maximal neutron flux at the location of each instrument and for the required energy. A new neutron production target, more compact than the C converter, should be designed to improve the performances. Other possibilities like using a Be or a liquid D_2O converter which produce significantly more neutrons than C in the same conditions, can be advantageously envisaged. A multi-purpose moderator/reflector assembly could be placed around the target to provide neutrons with different wavelength in order to be sent to multiple dedicated scattering instruments, nuclear physics experimental lines, and neutron irradiation sites. Another option could be to design multiple moderators which could be placed at the target location depending on the user needs. The neutron energy (wavelength) could be tuned in choosing proper moderators. To reduce the neutron energy down to an average of 25meV, a moderator using e.g. polyethylene or D_2O could be combined. The moderator could also use e.g. liquid H_2 at 20K to reduce the energy even further down to 3 meV. The I2A will offer a unique opportunity to test and validate the target and moderator design, the beam delivery system. Detector developments are also crucial for any R&D work associated with the use of neutrons. Several teams are working in this field. For instance, the DeSIs team at IPHC is involved in the development of neutron detectors for hadrontherapy or for photonuclear activation. The MIMAC team at LPSC has developed a directional neutron spectrometer covering a wide range of energy based on the 3D nuclear recoil track reconstruction opening the possibility to perform active phantom measurements. The I2A thus offers a unique experimental facility to optimize the main parameters for CANS.

The neutron flux generated by deuterons impinging various converter materials is shown in Fig. 1 together with the energy spectrum. With a 1 mA beam current, the neutron flux is of the order of 10^{14} n/s/sr at 0° (10^{12}/n/cm^2/s 10 cm downstream of the converter). This source would provide high-energy neutrons, which can be moderated if thermal or low-energy neutrons are required. The neutrons energies could also be adjusted from 40 MeV down to 1.45 MeV by reducing the deuteron beam energy as it would be the case for the AB-NCT (see below).

Such a neutron source fulfils the requirements of a large scientific community and nicely complement the existing time of flight facility at NFS, as far as nuclear sciences and in particular, fundamental data measurements are concerned. Beyond time-of-flight measurements, the physics cases, which would be covered by the proposed CANS are: Material irradiation (fusion, fission), neutron diffraction, thermal neutron radiography, nuclear astrophysics; nuclear structure: preparation of radioactive targets; activation; radioelements for nuclear medicine; etc. I2A could be a first step toward a complementary and fully dedicated facility where specific cases could be implemented on a shorter term.

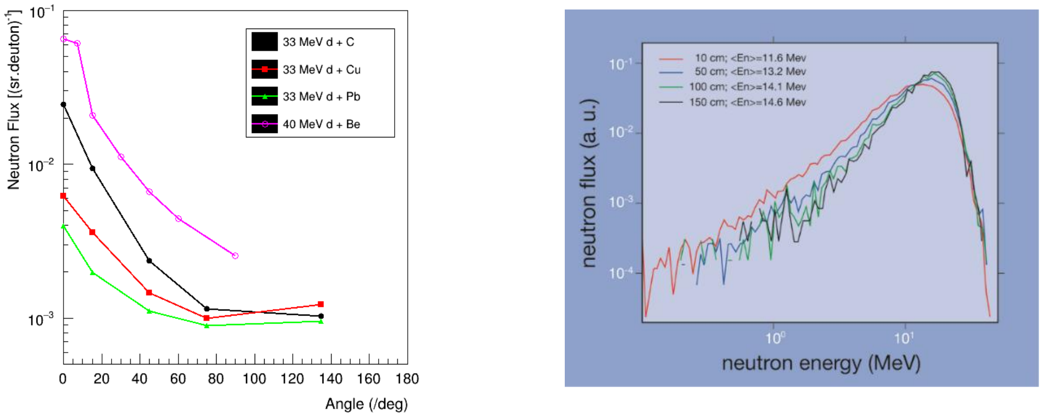

Fig 1: (Left) Neutron flux generated by deuteron projectiles on several converter material as a function of the scattering angle. (Right) Neutron energy spectrum after a carbon converter (from "The Scientific Objectives of the SPIRAL2 Project")

Even if the relevant scale for such a facility is national, the local support is crucially important to build and attract a user community. Beyond GANIL, already involved in neutron science, R&D on innovative radioelements, nuclear physics and astrophysics, several laboratories around it are already very active in scientific areas covered by the proposed CANS. In material science, the CRISMAT (laboratoire de CRIStallographie et de sciences des MATériaux) is a laboratory working on the synthesis and study of new materials with complex atomic structures and/or associated with functional properties (superconductivity, thermoelectricity, multiferroicity, magnetism…). Neutron scattering is an irreplaceable tool to understand not only the atomic but also the magnetic structure of materials, the vibrational modes of the crystal lattice at a microscopic scale, and their link with macroscopic physical properties. Particular states of quantum matter, such as superconducting vortex lattices or magnetic skyrmions, are also studied by neutron scattering. The proposed alternative of an accelerator driven compact neutron source, is a very interesting prospect, which would allow the production of a sufficient neutron flux to carry out most of the experiments essential to CRISMAT with, in addition, a strengthening of the local context and enriched collaboration possibilities with GANIL.

More specifically, Small Angle Neutron Scattering (SANS) is a technique, which makes it possible to determine the size and shape of nano-objects (aggregates, latent traces) in materials. It is a simple technique, very useful in many fields. The required spectrometer (12-15 m long) is one of the most productive machines with the largest number of users and potentially the CIMAP at the local level.

The qualification of electronic components to be used in radiation environment, an important activity for the CEA DAM, requires dedicated test facilities. Very few are able to deliver large neutron flux and the characteristics of the I2A facility meet the requirements for microelectronics. This facility would allow performing the required irradiation in France and within a reasonable timeframe, as opposed to existing facilities that currently require very long irradiation time to reach the requested neutron fluence.

Ultra cold neutrons (UCN) are a very good tool to probe fundamental physics and to look for physics beyond the standard model. For instance, the neutron Electric Dipole Moment (nEDM) [9] is a way to search for new CP violation sources and maybe explain the matter anti matter asymmetry in the universe; the solution to the neutron lifetime (τ_n) puzzle [10] might be a hint to dark matter; neutron beta decay studies [11] provide many limits and constraints on fundamental parameters; gravity has been tested at the microscopic level with UCN [12]. These experiments can also probe new dimensions existence. A new neutron source would give the community an opportunity to test new methods of producing UCN and dedicated experimental setups. Locally the LPC Caen has been involved in nEDM and τ_n and would provide a strong support to this project.

Nuclear science would also strongly benefit from this new area. There is indeed a great interest using thermal neutrons for nuclear physics experiments linked to the fission process. Some are interested in the process itself (Lohengrin, VAMOS,…) while others are interested in the structure of fission fragments (EXILL, LICORNE, FIPPS…). An area would also be very useful for nuclear data measurements by the activation method (yield measurements for instance). The neutron spectrum in the area should be characterized in order to perform integral measurements, which are crucial for nuclear data evaluations.

R&D production of radioisotopes

The new I2A would also host high-power target stations able to sustain up to several kW of beam power to perform R&D work on the production of innovative radioelements for medical applications using beams of light charge particles. This activity has started at GANIL in 2016 and will be first implemented in the converter room of the NFS area. As a starting point, a focus is made on alpha emitters and more specifically on ^{211}At. This research activity is currently developing through a collaboration with INP Rez (Czech rep.) and an approved ANR grant (REPARE) in collaboration with ARRONAX, SUBATECH, LDM-TEP and CERN. This project involves important perspectives in the exploitation and valorization of the newly produced radioisotopes for the development of radiopharmaceuticals useful in oncology. LDM-TEP and CYCERON are local partners with high skills and technical facilities in the radiochemistry field. These two units have developed since many years a strong experience in radiopharmaceutical development for pre-clinical researches and clinical studies, especially for multi-modal imaging and animal models that efficiently contribute to the evaluation of the therapy benefit. However to fulfill the design specifications for time of flight measurements and to avoid a useless complication on the design of the converter, the NFS area has significant limitations in terms of radioprotection (the maximum allowed number of neutrons in NFS is the one produced by 50 μA of deuteron beam at 40 MeV impinging a thick beryllium target). Therefore, the optimal use of the full available beam intensity of SPIRAL2 can only be made in the new I2A we propose here. We also stress that such an activity on innovative radioelements would also be performed using high neutron flux irradiation at the proposed CANS.

Accelerator Based-Neutron Capture Therapy

Boron Neutron Capture Therapy (BNCT) is a technique proposed to cure cancer by mean of a two-step process consisting in 1) the injection of a Boron loaded agent targeting specific tumor cells and 2) the irradiation with low energy collimated neutrons to induce breakup of the boron nuclei into highly ionizing particles leading to high energy transfer over a short range, limiting the impact on healthy tissues. It requires high fluxes (10^9n/cm^2/s) of epithermal (0.6eV-10keV) neutrons. Therefore, this technique did not really develop one of the most important difficulty being its dependency on nuclear reactors as source of neutrons. Today, with the advent of high intensity sources, very compact RFQ, high power converter and a dedicated moderator, the required neutron flux could be reached making it possible to envisage the design of an Accelerator Based NCT (AB-NCT). France is very well suited for such a project since, first the sources and RFQ of SPIRAL2 are exactly those needed and second the LPSC and CEA-LETI at Grenoble developed the required rotating Be target and the moderator to produce epithermal neutrons. Therefore, it would be possible to design the first AB-NCT demonstrator at GANIL and in view of the compactness, to envisage a possible implementation directly in hospitals. This new opportunity would enlarge the therapeutic arsenal toward a more personalized treatment.

Comparison between BNCT approaches and conventional irradiations (X-ray) as well as ions (p and C) should be developed. Several models (including some that are already used by the LARIA team, CEA/François Jacob institut) have already been successfully tested elsewhere but there is still a lot of research in radiobiology to be done to optimize and democratize BNCT approaches. Furthermore, one can also envisage coupling BNCT with other methods such as radio-enhancer (nano-particles) or radio sensitizer (PARP inhibitors) depending on the tumoral model, its intrinsic radioresistance and mutational status. For this, the future neutron beamline should be compatible with the use of biological samples and equipped with a low-dose dosimetry setup.

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