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The sciences and applications of the Electron LINAC-driven neutron source in Argentina*

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Abstract. The Neutron Physics group at Centro Atómico Bariloche (CNEA, Argentina) has evolved for more than forty five years around a small 25 MeV linear electron accelerator. It constitutes our compact accelerator-driven neutron source (CANS), which is dedicated to the use and development of neutronic methods to tackle problems of basic sciences and technological applications. Its historical first commitment has been the determination of the total cross sections of materials as a function of neutron energy by means of transmission experiments for thermal and sub-thermal neutrons. This also allowed testing theoretical models for the generation of scattering kernels and cross sections. Through the years, our interests moved from classic pulsed neutron diffraction, which included the development of high-precision methods for the determination of very low hydrogen content in metals, towards deep inelastic neutron scattering (DINS), a powerful tool for the determination of atomic momentum distribution in condensed matter. More recently non-intrusive techniques aimed at the scanning of large cargo containers have started to be developed with our CANS, testing the capacity and limitations to detect special nuclear material and dangerous substances. Also, the ever-present "bremsstrahlung" radiation has been recognized and tested as a useful complement to instrumental neutron activation, as it permits to detect other nuclear species through high-energy photon activation. The facility is also used for graduate and undergraduate students' experimental work within the frame of Instituto Balseiro Physics and Nuclear Engineering courses of study, and also MSc and PhD theses work.

1 Introduction

The determination of the total cross section of a material as a function of neutron energy by means of transmission experiments is a classic application of a pulsed neutron source. With relatively simple spectrometer and associated instrumentation, it allows obtaining sound statistical data even using a compact accelerator-based neutron source (CANS).

Our group in Bariloche (Argentina) has focused, since the early 70s, on the determination and analysis of the total cross section for thermal and sub-thermal neutrons, a quantity that is sensitive to the geometric arrangement and movement of the atoms in condensed matter, over distances ranging from the "first-neighbor scale" up to the microstructural level or "grain scale". In addition, high-statistics measurements over the thermal and epithermal energy regions were performed on a number of elemental and isotopically enriched samples, to determine their absorption and scattering cross sections values, or even some fundamental properties of the neutron itself.

The availability of such capacity also brought about a powerful tool to test the cross sections and scattering kernels generated in our group, based on a successful bound-atom synthetic scattering model.

After some initial years of pulsed neutron diffraction, when we built and used a time-focused, large-Q instrument to study the stability of some phases in Zr-based alloys, interest moved towards deep inelastic neutron scattering (DINS).

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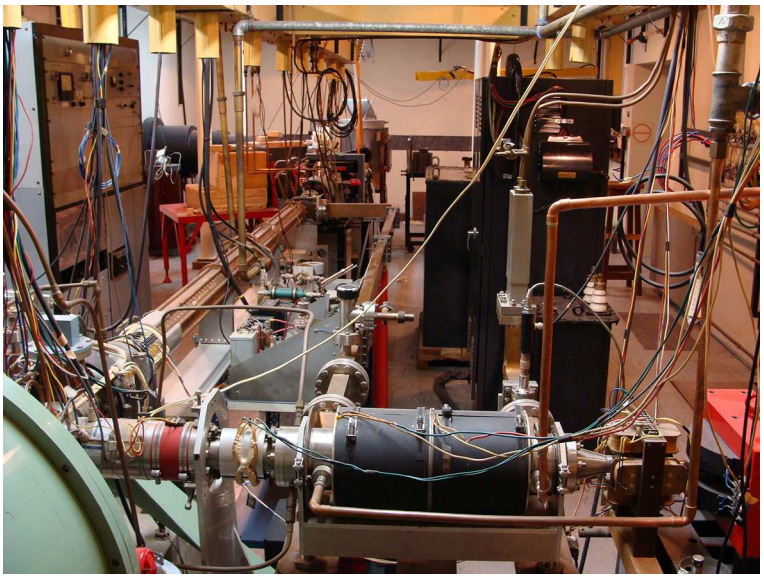

Fig. 1. View of the acceleration section of the Bariloche LINAC, with the injector and a "buncher" in the foreground and the TMR system at the end.

This technique has proven to be a powerful tool for the determination of atomic momentum distribution in condensed matter, and is also employed in non-destructive mass spectroscopy. A DINS spectrometer has been implemented, characterized and employed with different samples.

Also, by exploiting the large downscattering probability in the interaction of epithermal neutrons with hydrogen, we developed and tested a new method based on a filtering and time-of-flight technique, to determine very small concentrations of hydrogen in metals.

In recent years non-intrusive techniques aimed at the scanning of large cargo containers have started to be developed with this CANS, testing the capacity and limitations to detect special nuclear material and dangerous substances in thick cargo arrangements.

More recently, the use of the ever present bremsstrahlung has been recognized as a useful complement to instrumental neutron activation, as it permits to detect other nuclear species through high-energy photon activation.

Last but not least, our facility has been used for decades by the graduate and postgraduate Physics and Nuclear Engineering students at Instituto Balseiro, to perform experimental work related to Nuclear and Neutron Physics courses.

2 Neutron source and experimental set-up

An Electron LINAC begun operations in 1969, as the central piece of the experimental infrastructure of the by then newly created Neutron and Reactor Physics Division at Centro Atómico Bariloche. Since then, our small accelerator based pulsed neutron source was employed to perform a range of activities, including subthermal, thermal and epithermal neutron measurements, development and testing of new ideas, methods and devices, and of course for educational purposes (fig. 1).

Electron pulses (1.4 μs width) are accelerated up to 25 MeV, before hitting a water-cooled lead target, where bremsstrahlung radiation is produced and the induced (γ, n) reactions give rise to a fast neutron pulse. Typical repetition rates are 12.5, 25, 50, and 100 pulses per second, with an average current corresponding to the latter frequency of 25 μA at the target. Different types of moderator systems have been used depending on the specific requirements of a given experiment, optimized for production of subthermal, thermal, or epithermal neutrons, as well as in terms of the pulse-width that controls the time-of-flight (TOF) resolution. To accomplish that goal we have used throughout the years paraffin at liquid nitrogen temperature, light water, polyethylene and polypropylene as moderation materials, in the form of thin and thick slabs, without any decoupler or with 2-D (sandwich-type) or 3-D (grids-type) inhomogeneous poisoning. A cold neutron source based on solid mesitylene operating at liquid nitrogen temperature was designed and built, and it is the moderator system in use nowadays.

In our transmission facility (fig. 2) we have two detector stations, located at 8 m and 17.9 m from the neutron source, where the detection bank, consisting of seven ^{3}He proportional counters (10 atm filling pressure, 6″ active length, 1″ diameter) can be placed. The sample changers intersect the evacuated flight path at 4 m and 8 m from the neutron

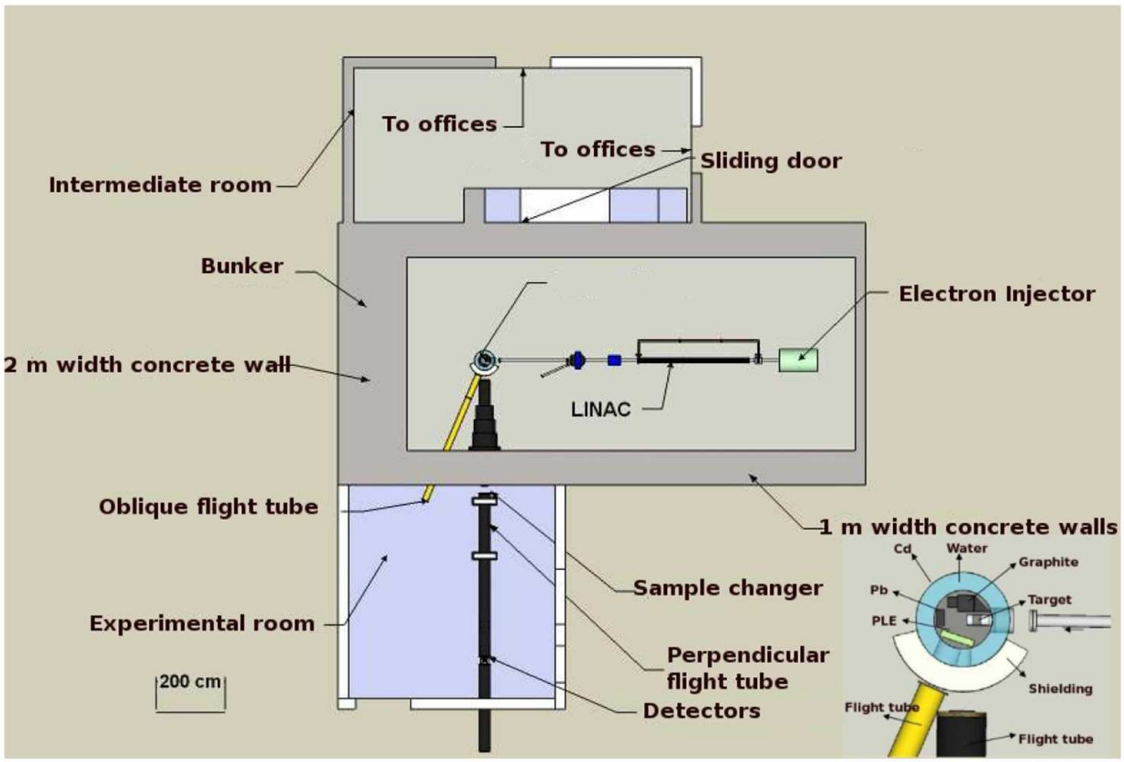

Fig. 2. Lay-out of the e-LINAC, its bunker, and the neutron extraction tubes.

source, respectively. The sample-in/sample-out method is normally employed to minimize the effect of beam power fluctuations, and the raw data are corrected for dead time, mean emission time of the neutron source, and background.

In the next sections we present typical examples of the different activities our group was involved in, mostly of experimental nature using our pulsed neutron source, but also those prompted by the availability of means to prove or validate theoretical developments. We will also mention others experiments performed by us to illustrate the range of possibilities that techniques based on CANS are able to support.

3 Total neutron cross section

Neutron transmission is a very simple technique that measures the reduction in intensity in a neutron beam after traversing a sample. The reduction in intensity depends on the energy of the incident neutron, on the nuclear cross section and microstructure and dynamics of the material composing the sample. So, analysis of the transmitted neutron spectra provides information about the microscopic properties of an object.

More than forty years ago the total cross section of D_2O was not known with the required accuracy, and that problem was tackled in our lab as one of the first applications of the then recently built facility. A moderator consisting of a paraffin block cooled down to liquid nitrogen temperature was used, in combination with a low repetition rate, to achieve statistically significant data below one millielectronvolt. Mixtures of light and heavy water were also measured, in order to obtain the total cross section of the molecular species HDO, to subtract its contribution to the real heavy water transmission and eventually determine the total cross section of pure D_2O at room temperature [1].

Through the years, we performed transmission experiments on a large number of molecular systems, with particular emphasis on materials of interest as neutron moderators at different temperatures. As an example, fig. 3 displays the total cross sections of Plexiglas and Mesitylene.

After the development of a synthetic scattering model to describe the interaction of slow neutrons with molecular systems [2], we used total scattering cross section measurements to refine some of its parameters before generating the scattering kernel for a material. That is exemplified by the solid lines in the same fig. 3 for Plexiglas at room temperature [3], and for Mesitylene at 32 K [4], in this latter case using the code NJOY.

The energy dependence of the total cross section of a crystalline sample for thermal neutrons is dictated by the structure and dynamics of the atoms composing the material. The effect of the *microscopic* ordering on the total cross section results in the appearance of discontinuities called Bragg edges. The position and height of the Bragg edges of polycrystalline materials can be measured to high accuracy with the TOF technique.

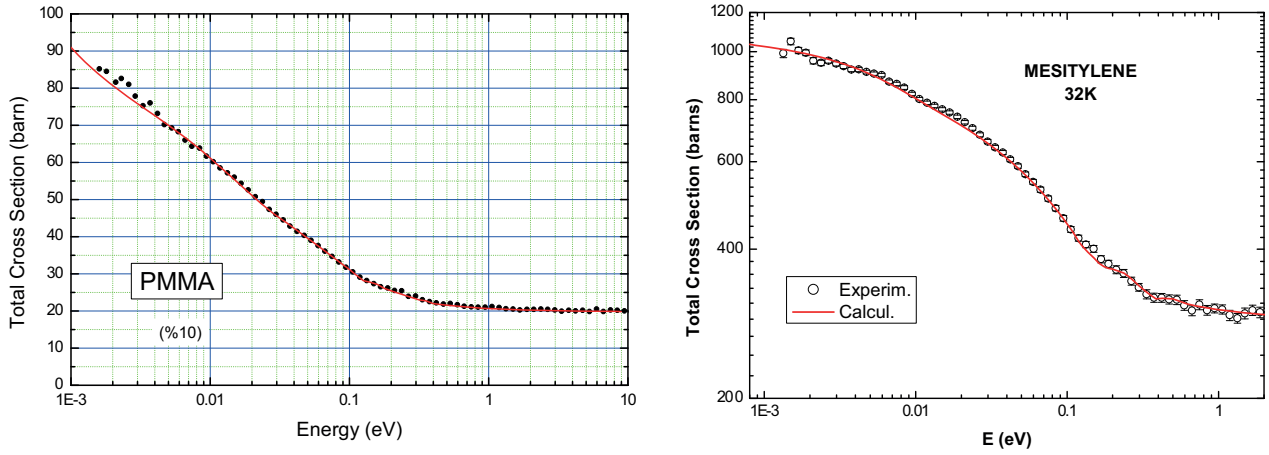

Fig. 3. Our measured total cross sections of Plexiglas at room temperature, and Mesitylene at 32 K.

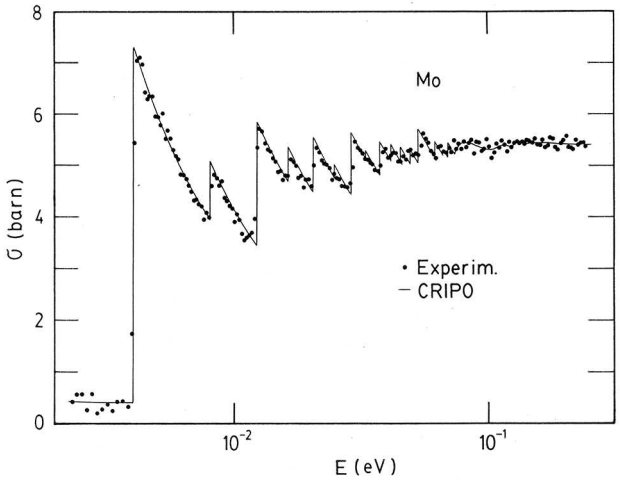

Fig. 4. The total cross section of polycrystalline molybdenum over the termal neutron range. The solid line represents the evaluated data according to CRIPO.

In the mid 70s there was a lack of precise information on several metallic elements considered of importance as structural materials in reactor design. In many cases, the values of the nuclear constants σ_c, σ_i, σ_{bound}, quoted in the literature showed some inconsistencies between them. We performed experiments in order to get consistent sets of parameters for scattering and absorption through measurements of total cross sections. As an example, the experimental curve for polycrystalline molybdenum [5] is shown in fig. 4, with its theoretical fit over the whole energy range using our code CRIPO [6].

As already shown in fig. 4, the structure of a polycrystalline material is clearly reflected through the Bragg edges, and from that pattern the lattice structure and unit cell parameters can be obtained. Although the latter will in general be not as accurate as those obtained from a conventional diffraction measurement, there are many circumstances in which either the sample size, or the extreme conditions required, or the need to follow some rapid evolution across the phase diagram, may demand the use of more intense incident and outgoing neutron fluxes.

As the position and height of the edges depend on the same laws as the position and intensity of conventional diffraction peaks, information about the stress state [7], texture [8] or the phases present in the sample [9] is readily available from an analysis of the transmission pattern. For multiphase materials, the total cross section displays Bragg edges from all crystallographic phases. Hence, the volume fractions of the constituent phases can be determined from an analysis of the height of the edges. Under certain circumstances, these measurements provides some advantages over conventional neutron diffraction: for relatively thick samples transmission patterns can be collected faster, as the transmitted count rate is high compared to the intensity diffracted into a certain solid angle.

On the other hand, the effect of the *mesoscopic* structure (between 0.1 and 100 μm) on the total cross section has received little attention. We are currently investigating the effect of such microstructural features in the total cross section, with the aim of using neutron transmission for non-destructive characterization of nuclear materials (fig. 5).

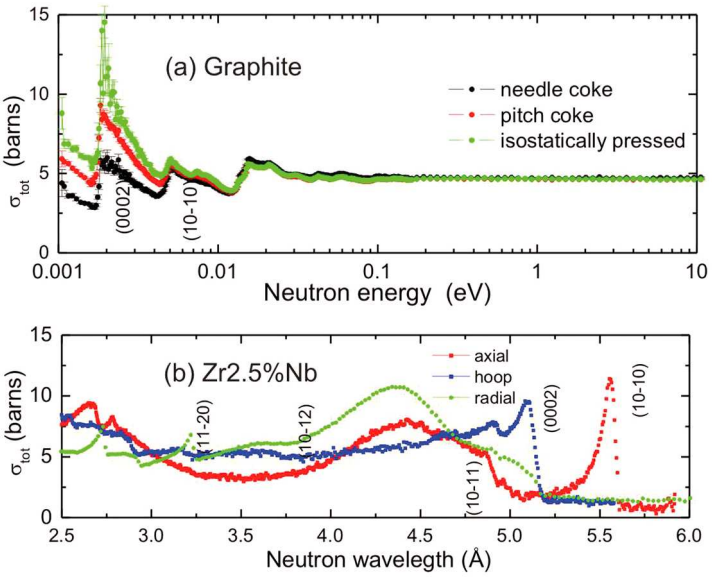

Fig. 5. Top: total cross section measured at our laboratory for nuclear-grade graphite produced by different manufacturing processes. Differences seen at neutron energies below 0.004 eV are due to different porosities. Bottom: total cross section of a Zr2.5%Nb pressure tube from a CANDU power plant along the three principal directions. Large differences between directions are due to crystallographic texture in the material.

Even though the total scattering cross section is an integral magnitude, related to the Van Hove scattering function $S(Q,\omega)$ [10] by

$$\sigma(E) = \frac{\sigma_b}{4\pi} \int \frac{k'}{k} S(Q,\omega)\, \mathrm{d}\Omega\, \mathrm{d}E',$$

where $\hbar Q$ and $\hbar\omega$ represent the momentum and energy transfer, respectively, some broad dynamical features can be extracted from the sample's transmission. A simple example is the determination of the Debye temperature θ_D of a polycrystalline material from the variation of the Bragg jumps caused by the Debye-Waller factor, under the hypothesis of a Debye model to describe the lattice dynamics. An usually more efficient method to obtain θ_D, not limited to polycrystals, is related to the behavior of the inelastic contribution to $\sigma_s(E)$ which is dominated at low neutron energies by one-phonon processes [11].

At the other end of the thermal energy region, the behavior of the total scattering cross section for epithermal neutrons tends to the free-atom value, corresponding to the sum of the cross sections of the constituent atomic species. More precisely, the approach to that limit corresponds to the behavior of an ideal gas, formed by particles with the atomic mass and animated by an effective temperature related to the complete excitation spectrum of the system [10,11].

In another class of systems, we have shown that more detailed dynamic information can be obtained from total cross-section measurements, and a method was introduced to obtain the density of states (DOS) from the incoherent part of the inelastic total cross section [12]. For the application of this method, the elastic and multiphonon contributions must be known beforehand, to subtract them from the experimental data. This can be achieved by the approximation of the density of states through some simple model, such as a combination of a Debye spectrum to describe the acoustic modes plus Gaussian functions to account for the optic ones. We have applied this method in the case of three metal hydrides (based on zircalloy, magnesium and niobium), whose total cross sections, were measured in our laboratory. Those DOS results, shown in fig. 6, are in fair agreement with the inelastic scattering experiments performed at high-flux sources over the range from 40 to 250 meV.

The measurement of neutron total cross section for heavy elements over an energy range from zero up to several keV, permits a determination of the neutron-electron scattering length and the neutron electrical polarizability [13, 14]. We have used our facility and that of the KURRI Linac (Kyoto University, Japan) pulsed neutron source to perform transmission experiment on Pb and Bi, over epithermal neutron energies, together with a full calculation of the different electromagnetic interactions and their corresponding contributions to the scattering length [15]. From the high-precision total cross section values (uncertainties varying from 0.2% to 0.3%), we were able to extract a value for the neutron's electric polarizability quite consistent with the best values obtained at that time.

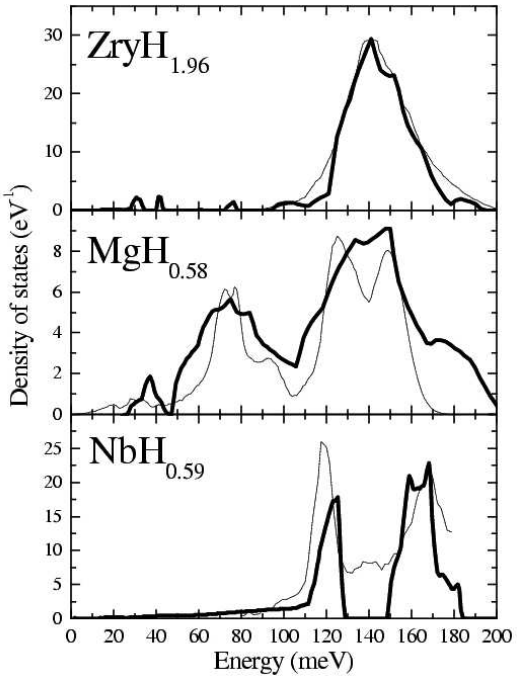

Fig. 6. Density of states of a few hydrides, obtained from our measured total cross sections (black lines) and from high-precision inelastic measurements (grey lines) [12].

4 Neutron diffraction

The use of small pulsed neutron sources has proved to be a valuable tool in neutron diffraction studies of condensed matter. It has been pointed out that one of the more prominent features of an accelerator based pulsed source lies in its ability to produce a significant flux of epithermal neutrons, thus allowing powder diffraction measurements to be extended into the range of high values of the scattering vector ($Q \sim 25\,\text{Å}^{-1}$), which in turn renders possible a greater accuracy in the determination of thermal and structural parameters.

The introduction of the time focusing concept permits an increase of the counting rate while maintaining the same resolution as in a single detector by adequately placing a set of detectors connected electronically in parallel. If the detectors are placed on a surface Qt = const., where Q is the momentum exchange, then all the elastic coherent scattered neutrons (for a powder sample and a fixed distance between the crystallographic planes) reach the detector bank at the same time, regardless of the scattering angle. Better resolution is achieved for back-scattering designed detector banks. A diffractometer based on those concepts was built by the mid 80s [16]. It is worth mentioning that even with low intensity and resolution, this diffractometer has been useful for the study of meta-stable phase structures in inter-metallic alloys [17,18].

5 Low hydrogen (and deuterium) content

In our laboratory we have applied several TOF-based neutronic methods in order to determine H content in Zr alloys non-destructively [19]. For this, we have used the TOF diffractometer presented in the previous section, as shown in fig. 7(a) for a sample of Zircaloy-4 turnings containing deuterium, with a content equivalent to 270 wt ppm of H. Provided the deuterium solubility is extremely low at room temperature (< 1 wt ppm) the deuterium appears as second phase precipitates, as the δ-zirconium deuteride phase of composition $\sim \text{ZrD}_{1.66}$. In the figure we have indexed the hcp a-Zr peaks in black at the bottom, and the fcc d-Zr deuteride in red at middle height. The solid red line in the figure shows a Rietveld-type least-squares fit to the data including both phases, from which the phase volume of the deuteride phase, and hence the deuterium was obtained.

For H determination we have applied energy-resolved transmission measurements, exploiting the fact that in the sub-thermal range the total cross section of H is about two orders of magnitude that of Zr, whilst in the epithermal range both cross sections are comparable. Figure 7(b) shows in open symbols the measurements performed in our laboratory on a Zircaloy-4 specimen containing 35 wt ppm of H. The dashed red line is the values expected for a Zircaloy-4 specimen, which describes well the asymptotic values at epithermal energies, but failed to reproduce the points measured at low energies. The point-to-point differences seen in the thermal range are mainly due to crystallographic

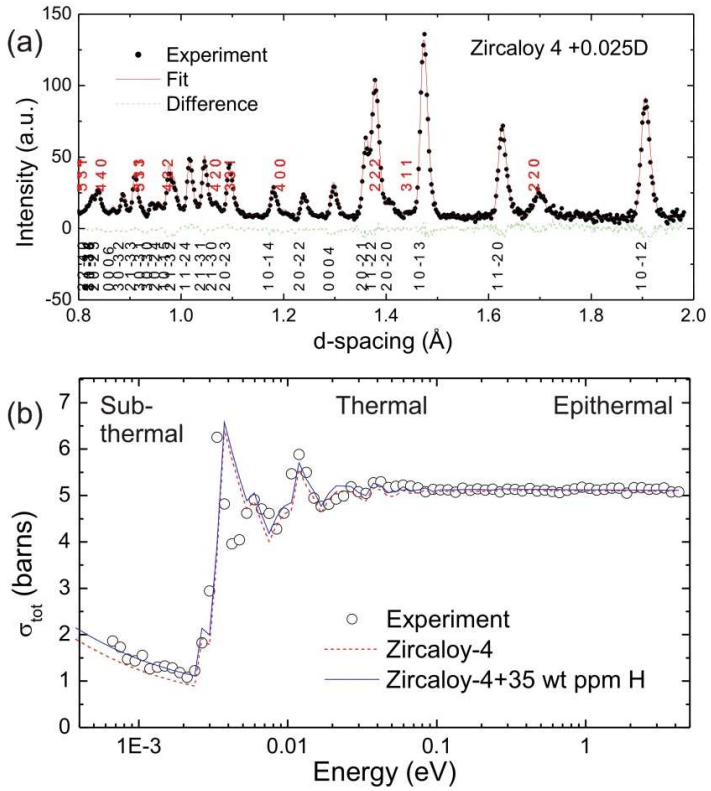

Fig. 7. (a) Deuterium determination by diffraction. (b) Hydrogen determination by transmission.

texture as described in sect. 3, and exemplified in fig. 5. On the other hand, the overall difference below the first Bragg edge is due to the presence of zirconium hydride. The solid blue line shows a least-squares fit performed on the data including the two phases, using only the l data recorded in the epithermal and sub-thermal ranges.

Moreover, we have also developed an original method for H determination and built a dedicated spectrometer in order to implement it in our laboratory [20]. The principle of the method lies on the great difference in the inelasticity involved in the neutron scattering by hydrogen and by heavy atoms, using a combinationof a notch filter and ToF techniquesto resolve that difference with appropriate sensitivity. Figure 8(a) shows how a white spectrum marked by an Indium filter is modified after scattering with Zr or with H atoms. Whilst the Zr spectrum essentially coincides with the incident one, the spectrum resulting after scattering with H is heavily distorted, populating with neutrons the original region notched by the filter. Hence, by using the TOF technique to record the neutrons appearing in a specific TOF window it is possible to detect H contents with ~ 2 wt ppm resolution. Figure 8(b) shows a detail of the spectrometer built in our laboratory.

6 Deep inelastic neutron scattering (DINS)

The deep inelastic neutron scattering (DINS) technique (also known as neutron Compton scattering) was originally devised by Hohenberg and Platzmann in the 60s to investigate the Bose-Einstein condensation in superfluid ^{4}He. Due to its ability to investigate momentum distributions in Condensed Matter, it was later established as a usual research tool. In a DINS experiment scattered neutrons detected at a given angle, pass through a mobile filter (with a neutron absorption resonance at a few eV energy), and alternative "filter-out" and "filter-in" spectra measurements (as a function of time of flight) are performed. The difference between these spectra is the basic magnitude determined in DINS experiments.

The DINS technique was firstly developed at Rutherford Appleton Laboratory, where the instrument VESUVIO is still operative. Later, in our laboratory in Bariloche a DINS instrument was designed, optimized and built, and a number of samples were studied with it [21,22]. Our interest was especially focused on the development of correction procedures to the experimental data due to multiple scattering, attenuation and detector efficiency effects. The methodology allowed us to determine the intensity of the recorded spectra on an absolute basis, which gives the opportunity to determine cross sections (in barns) of the atoms that compose the sample, and/or the sample composition.This, in turn, enables the technique to be employed as a non-destructive mass spectrometer, that recently arose the interest of a specialized forum [23].

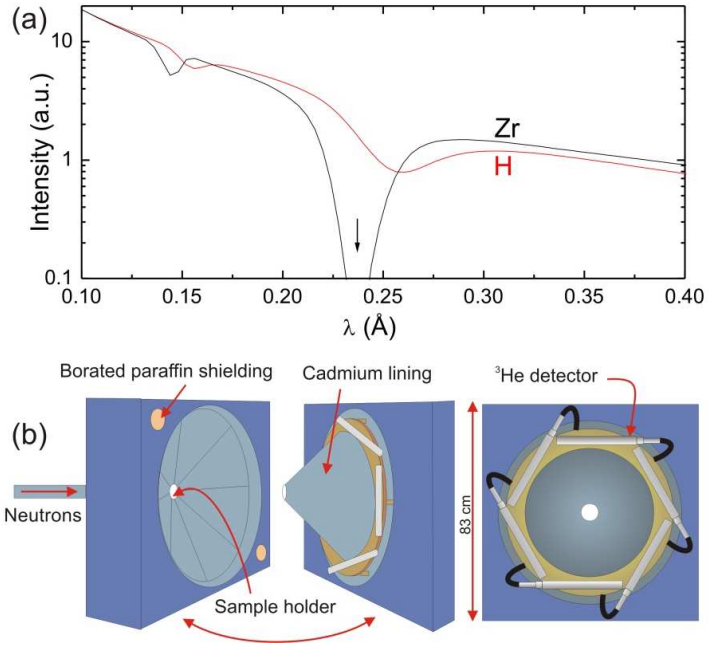

Fig. 8. (a) Principle of the H detection method. (b) Details of the dedicated spectrometer.

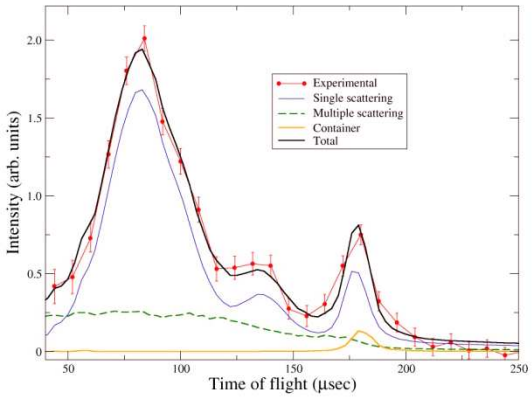

Fig. 9. Measured neutron Compton profile for the light-water/heavy-water mixture, together with results of Monte Carlo simulations showing single, multiple and total scattering contributions to the observed spectra.

A remarkable result in the methodological aspect, was the determination of the Compton Profiles' absolute intensities in light-water/heavy-water mixtures, depicted in fig. 9 [24], which showed no anomalies in the cross section of hydrogen at epithermal energies, which was the subject of a long scientific debate [25,26].

At present we have two ^{3}He detector banks, which allow the simultaneous measurement at selectable angles. This combination aims at the study of the profiles of hydrogen and light atoms. A combination of forward and backward scattering angles, allow the separate study of the profiles of light and heavy atoms.

7 Complementary techniques for cargo scanning

The use of slow neutrons for the purpose of investigating thick cargo arrays is viewed here as complementary to the widely tested fast neutron approach. Slow neutrons tend to diffuse into samples, with loss of time-of-flight (TOF) information, but inducing absorption reactions through higher interaction cross sections.

Detector set-ups were used to probe into realistic 2 m thick cargo arrays with 3 mm steel plates in the incoming and outgoing sides of the simulated container. To mimic a lower intensity neutron source, the experimental set-up is positioned at least five meters away from the target of the 25 MeV linear electron accelerator. The low intensity falling on the sample is in the order of 200 thermal n/cm^{2}sec and 90 near epithermal n/cm^{2}sec (above cadmium cut-off energy).

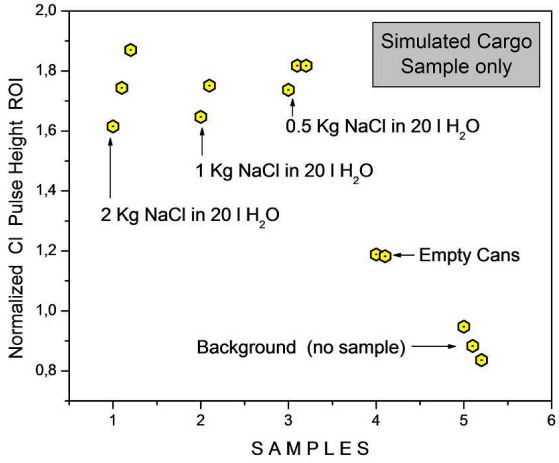

Fig. 10. Simulated empty container. Later loaded with different NaCl solutions, 2, 1 and 0.5 kg in 20 l of water. 5 minutes recording time determinations. Appropriate regions of interest (ROI) of each gamma spectrum most representative of the substance, were normalized to a region of the spectrum not influenced by that substance.

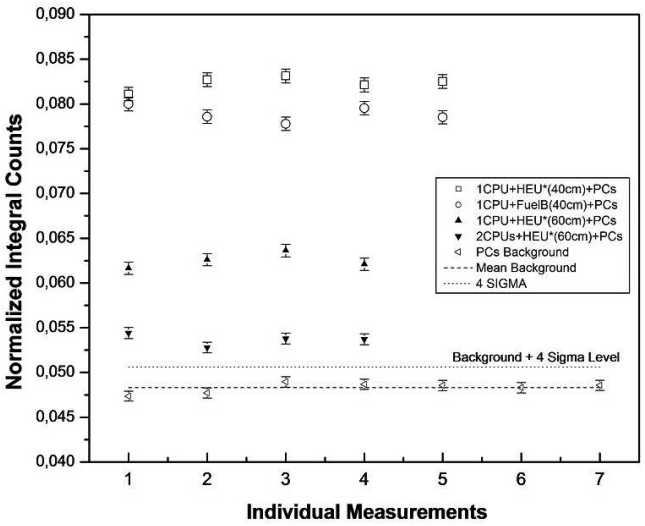

Fig. 11. Integral fast neutron counts for each 5 min recording time determinations with HEU and FB, hidden behind different number of PCs and 3 mm steel plate. The mean background 4 sigma level is indicated for comparison.

One detector array built consists of four commercial $2'' \times 2''$ NaI(Tl) scintillators with PMTs and *ad hoc* voltage dividers coupled to only one preamplifier, designed to reduce the initial dead time after each accelerator burst. Shielding made it possible to sort-out the gamma response to neutron interactions in the presence of a combined intense pulsed high energy X-ray and neutron field. Substances of interest tested for their gamma response are Cl, N, S, Ag, As, Cr, Cd, and Hg.

Most attention was dedicated to chlorine, for which the only real case of interest is that of a container almost full of unwanted chlorinated contaminants. Figure 10 shows the result of plotting several 5 minutes irradiations, where the signals from solutions of different concentrations are not distinguishable, but clearly separated from the Cl in the empty container composition, and far from the background of the non-chlorinated cargo array.

Fast neutron detection from uranium-induced fission after each accelerator burst [27,28] was carried out through $70 \times 100\,\mathrm{cm}^2$ active area detectors incorporating 10 He^3 tubes (2.5 cm diameter and 55 cm active length, 4 atm gas pressure) inside Cd wrapped moderator. Uranium in simulated cargo arrays was materialized through an enriched uranium sample (HEU, U-235 mass = 27.5 g in Al) or a natural uranium fuel bundle (FB, U-235 mass = 38.38 g in 13 fuel pins), fig. 11.

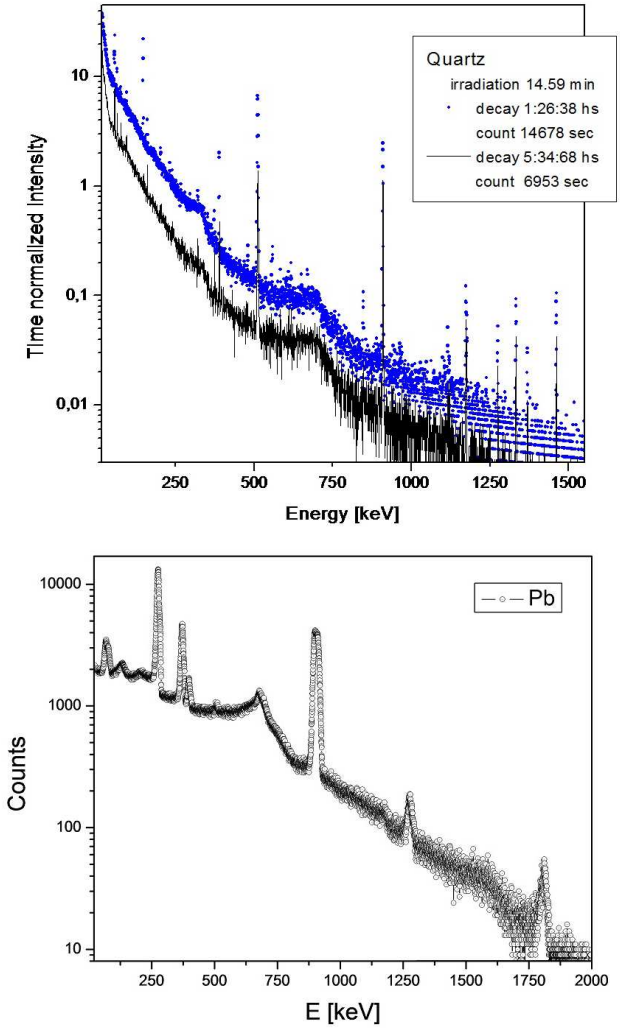

Fig. 12. Gamma response from samples activated through photonuclear reactions. Top: gamma spectra from quartz sample after two initial decay times. Bottom: pure lead sample.

8 High-energy photon activation

The exploitation of the high-energy bremsstrahlung (high-energy photons emitted by fast, relativistic, electrons being stopped by interaction with a heavy atomic nucleus) for photonuclear activation (PNA) has recently been explored. Several samples were activated and analysed. Figure 12 depicts two examples of initial interest. The upper graph is related to the need to find out if the pure quartz containers usually employed for neutron activation analysis would be apt for PNA. The result is that they are clearly not convenient for the considerable number of gamma "peaks" that quartz produces and, consequently, if some existing samples were to be analysed with the new technique, they would have to be removed from the quartz capsules. The lower graph shows the result of activating a pure lead sample to test if lead could be easily detected and if impurities would be distinguished from it, because lead is not detectable through conventional instumental neutron activation analysis.

9 Prompt gamma emissions at absorption resonance in ^{115}In

The prompt gamma neutron activation analysis technique (PGNAA) is the spectra analysis of the prompt gamma emission produced after neutron absorption. Very complete data tables have been published listing the prompt gamma emissions intensities of all known isotopes when the absorbed neutrons are thermal. However, many isotopes have absorption resonances for epithermal neutrons, and therefore the emitted prompt gamma spectra are strongly dependent on the absorbed neutron energy. The LINAC facility in Bariloche has been employed as pulsed source for PGNAA selecting the neutron energy by the time-of-flight method. The procedure was used to find new prompt gamma emissions of the reaction ^{115}In (n,γ) ^{116}In, when the neutrons have an energy around 1.45 eV, one of the resonances of ^{115}In [29].

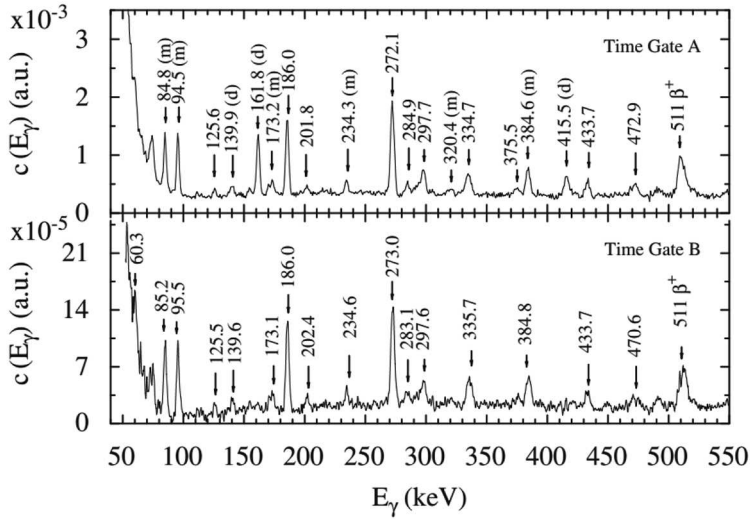

Fig. 13. Top: PHA spectrum of prompt gamma emissions measures during a time gate that spans the absorption of thermal neutrons (Gate A). Bottom: PHA spectrum of prompt gamma emissions during time gate B, which takes into account those gammas generated by the absorption of epithermal neutrons around the 1.45 eV nuclear resonance. The lines indicated with (d) correspond to beta β^-, while the indicated with (m), are from unresolved multiplets.

For the experiment, a gamma semiconductor Ge(Li) detector was employed to acquire high-resolution prompt gamma spectrum, extending the known energy of gamma emissions for the 1.45 eV resonance of ^{115}In, below 273 keV, the previous lowest tabulated value. Only the epithermal neutrons from the pulsed source were allowed to reach the sample, a thin very pure indium foil, by means of a cadmium sheet just after the neutron 4 cm thickness polyethylene moderator.

With the TOF technique it is possible to acquire the gamma spectrum only if the pulses from gamma detector arrive to the multichannel analyzer in a time after the neutron pulse, between the beginning and the end of a time gate (Gate B) that corresponds to the energy of the neutrons of the 1.45 eV ^{115}In resonance. It is possible to set another gate for thermal neutrons (Gate A). Figure 13 shows the prompt gamma spectra for gates A and B.

For absorbed neutrons around 1.45 eV, nine prompt gamma lines were observed below 273 keV and their relative intensities were determined. Three of these peaks (60.3, 95.5 and 186 keV) were reported before [30] using a lower resolution gamma detector, while the other six gamma lines (at 85.2, 125.5, 139.6, 173.1, 202.4 and 234.6 keV) were not found in the reviewed literature for epithermal neutrons until the moment of the experiment.

10 Education

Students of Nuclear Engineering and some students pursuing Master or Doctoral degrees, perform experimental determinations of neutron field profile in moderators by foil activation and measurements of die-away time in moderators, as a function of geometrical buckling and of macroscopic absorption cross section, using miniature fission chamber neutron detectors, taking advantage of the pulsed nature of this versatile neutron source.

LOCA (Loss Of Coolant Accident) simulation experiments are available for students, in which the pulsed neutron field is studied around a natural uranium fuel element in the presence of surrounding moderator, with and without coolant (light water). The fuel pins pitch can also be changed.

Along the years, a number of undergraduate final works, doctoral theses and, recently, master in engineering theses have been carried out through the utilization of our CANS, mostly by means of neutron time-of-flight transmission determinations, neutron diffraction and deep inelastic neutron scattering.

11 Conclusions

The capacity to produce neutrons over a wide range of energies is possible when employing a pulsed neutron source. In our case, relatively simple spectrometers and associated instrumentation employing even a small accelerator based neutron sourceas a 25 MeV electron LINAC, has allowed us obtaining sound statistical data. Bearing in mind the modest neutron flux produced, we built and used instruments appropriate for transmission and scattering measurements, without final energy analysis except the overall change in time of flight caused by inelastic processes. Yet we were able to produce very useful total cross section and diffraction data, as well as some integral variants as DINS and a spectrometer for low hydrogen content determinations.

Also, the possibility to employ the bremsstrahlung high-energy photons has materialized the capacity to carry out elemental analysis. And, although not mentioned here, the direct irradiation with the lower-energy electron beam has been used in other applications such as characterization of electronics for space-satellites use.

In this way, and during more than four decades we have been using our CANS not just to produce good basic information on a number of materials, but also as a workbench for the development of new systems, especially those related to cryogenic moderators for pulsed sources. We very much exploited the flexibility of our installation to devise, explore and test new ideas, in a motivating interplay with related theoretical activity.

Last but not least, our pulsed neutron source served as a central experimental piece for education and training of our graduate and postgraduate Physics and Nuclear Engineering students. They can perform a number of experiments related to Nuclear and Neutron Physics, and in doing so they learn about neutron production, interaction with different materials at different energies, behaviour of a neutron field within a media, neutron detectors and scattering techniques.

It was then possible to attain the major goals a CANS is able to aim at: research, development, and education.

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