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Compendium of Neutron Beam Facilities for High Precision Nuclear Data Measurements

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COMPENDIUM OF NEUTRON BEAM FACILITIES FOR HIGH PRECISION NUCLEAR DATA MEASUREMENTS

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The recent advances in the development of nuclear science and technology, demonstrating the globally growing economy, require highly accurate, powerful simulations and precise analysis of the experimental results. Confidence in these results is still determined by the accuracy of the atomic and nuclear input data. For studying material response, neutron beams produced from accelerators and research reactors in broad energy spectra are reliable and indispensable tools to obtain high accuracy experimental results for neutron induced reactions. The IAEA supports the accomplishment of high precision nuclear data using nuclear facilities in particular, based on particle accelerators and research reactors around the world. Such data are essential for numerous applications in various industries and research institutions, including the safety and economical operation of nuclear power plants, future fusion reactors, nuclear medicine and non-destructive testing technologies.

The IAEA organized and coordinated the technical meeting Use of Neutron Beams for High Precision Nuclear Data Measurements, in Budapest, Hungary, 10–14 December 2012. The meeting was attended by participants from 25 Member States and three international organizations — the European Organization for Nuclear Research (CERN), the Joint Research Centre (JRC) and the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (OECD/NEA). The objectives of the meeting were to provide a forum to exchange existing know-how and to share the practical experiences of neutron beam facilities and associated instrumentation, with regard to the measurement of high precision nuclear data using both accelerators and research reactors. Furthermore, the present status and future developments of worldwide accelerator and research reactor based neutron beam facilities were discussed.

This publication is a summary of the technical meeting and additional materials supplied by the international experts, together with the individual contributions describing the current status of their respective neutron beam facilities, highlighting major achievements and future developments in this field. This publication describes both the research reactor and accelerator based neutron beam facilities for nuclear data measurements, classifies them according to the type of neutron source (reactor or accelerator based), the neutron energy accessible to individual facilities or the measurement technique employed. In addition, the state of the art of experimental sample and target preparation, instrumentation, data acquisition and new research trends in the field are summarized. Each individual facility reports is available on the CD-ROM accompaning this publication.

The IAEA acknowledges the valuable contributions of the individual participants and the support of the international experts in reviewing this publication. The IAEA officers responsible for this publication were D. Ridikas of the Division of Physical and Chemical Sciences and T. Desai of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

The maintenance of existing and development of new nuclear technologies rely on the availability of molecular, atomic and nuclear data to provide accurate numerical representations of the underlying physical processes. Essential data includes energy dependent cross-sections, the energy and angular distributions of reaction products for many combinations of projectiles and targets, and the atomic and nuclear properties of excited states in addition to their radioactive decay data.

Today modern nuclear facilities and applications have reached a high degree of sophistication in which the safe and economical operation of these complex technologies requires detailed and reliable design calculations. While simulation calculations are becoming more and more economical with rapid advances in computer technology and increased predictive power of physical models, confidence in these calculations is still largely determined by the accuracy of the atomic and nuclear input data. In addition to the field of fission reactor technology, many other nuclear applications such as nuclear fusion, production of radioisotopes, neutron therapy, spallation neutron sources, non-destructive testing and multi-elemental analysis are also of growing economic significance and require substantial data input regarding neutron induced reactions. In this context, use of neutron beams is the most frequently employed technique to provide high quality experimental data for neutron induced reactions in the broad neutron energy range. All of these measurements can be grouped into two main categories:

- Experiments using neutron time-of-flight (TOF) technique in the wide energy spectrum, typically from thermal energies to approximately 200 MeV, e.g., n_TOF at the European Organization for Nuclear Research (CERN), Los Alamos Neutron Science Centre (LANSCE) at Los Alamos National Laboratory (LANL) and Geel Electron Linear Accelerator (GELINA) at the Institute for Reference Materials and Measurements / Joint Research Centre (IRMM/JRC). This powerful method allows for the study of neutron induced capture, fission and secondary particle production reactions. In most cases, the neutron source is driven by a pulsed particle accelerator using protons or electrons, while pulsed research reactors also can be successfully employed for this purpose, e.g., IBR-2 at Joint Institute for Nuclear Research, JINR.

- Guided neutron beams from a steady state research reactor can be employed to determine neutron induced capture cross-sections or gamma emission probabilities, e.g., the Budapest Research Reactor at the Budapest Neutron Centre (BNC). In certain cases neutron beam choppers, various neutron filters or crystal based spectrometers can be applied in order to provide well defined energy selection or produce at least quasi-mono-energetic neutrons, e.g., High flux reactor (HFR) at Institut Laue Langevin (ILL) in Grenoble or Kiev Research Reactor.

All of these facilities have specific characteristics in terms of neutron beam intensities and energy resolutions, associated instrumentation and data acquisition systems, and developed dedicated experimental programmes. A number of new powerful neutron sources and facilities have recently become operational, e.g., Japan Proton Accelerator Research Complex (J-PARC) and Spallation Neutron Source (SNS) in USA, or are in the licensing and planning stage, e.g., China Advanced Research Reactor (CARR) and China spallation neutron source (CSNS) in China, PIK in the Russian Federation, Neutron for science facility (NFS) in

France, the new EAR2 beam line at CERN and European Spallation Source (ESS) in Sweden. Most of them propose very ambitious nuclear data measurement projects either exclusively or as part of their broader utilization programmes and strategies.

The large number of facilities mentioned above and their very particular characteristics, the different experimental programmes carried out at each facility, and the number of new facilities being built/planned in recent years calls for an international effort for reviewing the state-of-the-art in this field. It was thus the purpose of the IAEA to organize a *Technical Meeting on Use of Neutron Beams for High Precision Nuclear Data Measurements* (held in Budapest in December 2012) and to compile in a single document both the research reactor and accelerator based neutron beam facilities for nuclear data measurements presented at that meeting. In addition, the state of the art of samples and targets preparation, instrumentation, data acquisition and new trends in the field is summarized.

1.2. OBJECTIVES OF THE MEETING

The Technical Meeting aimed to provide a forum to exchange good practices as well as lessons learned and practical experiences from use of neutron beam facilities and associated instrumentation, both accelerator and research reactor based, in provision of high precision nuclear data. Present status and future developments of neutron beam facilities worldwide, both accelerator and research reactor based, was also addressed. The meeting concentrated on the following major topics:

- Characteristics of existing and development of new neutron beam facilities for nuclear data measurements;
- Characteristics and development of associated instrumentation and data acquisition systems;
- On-going and future experimental programmes; and
- Good practices and strategies from international collaborations in the use of neutron beam facilities for nuclear data measurements.

1.3. STRUCTURE OF THIS DOCUMENT

The present report consists of eight technical sections, list of references, abbreviations, list of contributors to drafting and review, and list of individual paper contributors. The publication also includes a CD-ROM, in which, through a number of individual technical papers, concrete nuclear data measurement facilities are described either accelerator or research reactor based.

2. RESEARCH REACTOR BASED NEUTRON BEAM FACILITIES

2.1. COLD AND THERMAL NEUTRON BEAMS

2.1.1. Stationary neutron beams

Reactor based thermal neutron beams are used for performing neutron scattering or neutron radiography experiments at many places in the world. The best thermal neutron beams can be constructed utilizing the so called tangential channels of Research Reactors (RR). These channels have no direct view to the reactor core and usually passing through or close to the reflector of the core. Despite of this special geometry, still substantial amount of fast neutron and gamma radiation is coming together with the thermal neutrons though much less than from the radial channels that are looking directly to the reactor core (see Fig. 1). To

suppress the unwanted energetic neutrons and gamma radiation special beam filters are used. Usually polycrystalline materials with low absorption cross sections for the thermal neutrons can be used to scatter out the energetic neutrons from the beam deep inside the reactor shielding. Improving the ratio of the number of thermal neutrons to higher energy neutrons is always a trade-off between the remaining thermal neutron flux and the desired ratio.

Even after filtering, the disadvantage of the thermal neutron beams is the substantial amount of higher energy neutrons and gammas still arriving together with the thermal neutrons. This makes detection of gamma rays arising from the irradiated sample rather difficult.

To avoid this complication, curved neutron mirror guides were developed [1] to reduce the parasitic high energy radiations. Neutron guides transport neutrons by total reflection. The critical angle for total reflection is increasing linearly with the neutron wavelength [2]. Thus, the best result can be achieved by cold (less energetic) neutrons at the expense of a more diverging neutron beam. To have cold neutrons the neutrons are cooled with e.g. liquid H_2 cold source, which is a cooled bottle of liquid hydrogen inserted at the beginning of the guide system close to the reflector of the reactor [3]. The completed "cold plug" connected to 3 neutron guides is shown in Fig. 2 before installation to the Budapest Research Reactor.

Modern cold neutron beams – guided with curved neutron guides – provide virtually background-free radiative neutron capture environment at experimental stations. Curved guides help to reduce the direct beam from the reactor by losing them at the beginning of the guides. The achievable thermal equivalent neutron flux ranges from 10^8- 3×10^{10} $cm^{-2} \cdot s^{-1}$ and will depend on the nominal reactor power. The highest flux is available at the High Flux Reactor in Grenoble, France and at the FRM-II reactor, Munich, Germany using an elliptical focusing guide, both being compact core RRs.

The few laboratories active in neutron capture cross section and nuclear data measurements are the Prompt Gamma Activation Analysis / Neutron-Induced Prompt gamma ray Spectroscopy (PGAA-NIPS) station at the Budapest Research Rector, PGAA facility at the FRM2 reactor of the newly established Heinz Maier-Leibnitz Zentrum, several installations at the High Flux Reactor of the Institute Laue Langevin, the cold beam facility at the High Flux Advanced Neutron Application Reactor (HANARO) in South Korea and neutron beam facilities at the Japan research reactor, JRR-3 reactor in Tokai-mura, Japan.

2.1.2. Pulsed neutron beams

Information given here is taken from the home page of IBR-2 facility [4].

A unique upgraded IBR-2 pulsed fast reactor has been launched in Dubna in 2011, which will make it possible to carry out more than 200 experiments a year with the participation of scientists from more than 30 countries. The modernised IBR-2 generates impulses five times per second. In addition, the reactor is distinguished by its record high average capacity (two megawatts) and the peak neutron flux density. Its main difference from other reactors consists in mechanical reactivity modulation by a movable reflector. The rotors of the main and auxiliary movable reflectors rotate in opposite directions with different velocities. When both reflectors coincide near the reactor core, a power pulse is generated (see Fig. 3 and Table 1). After refurbishment, the IBR-2 facility was back to nominal operation in 2012 [4].

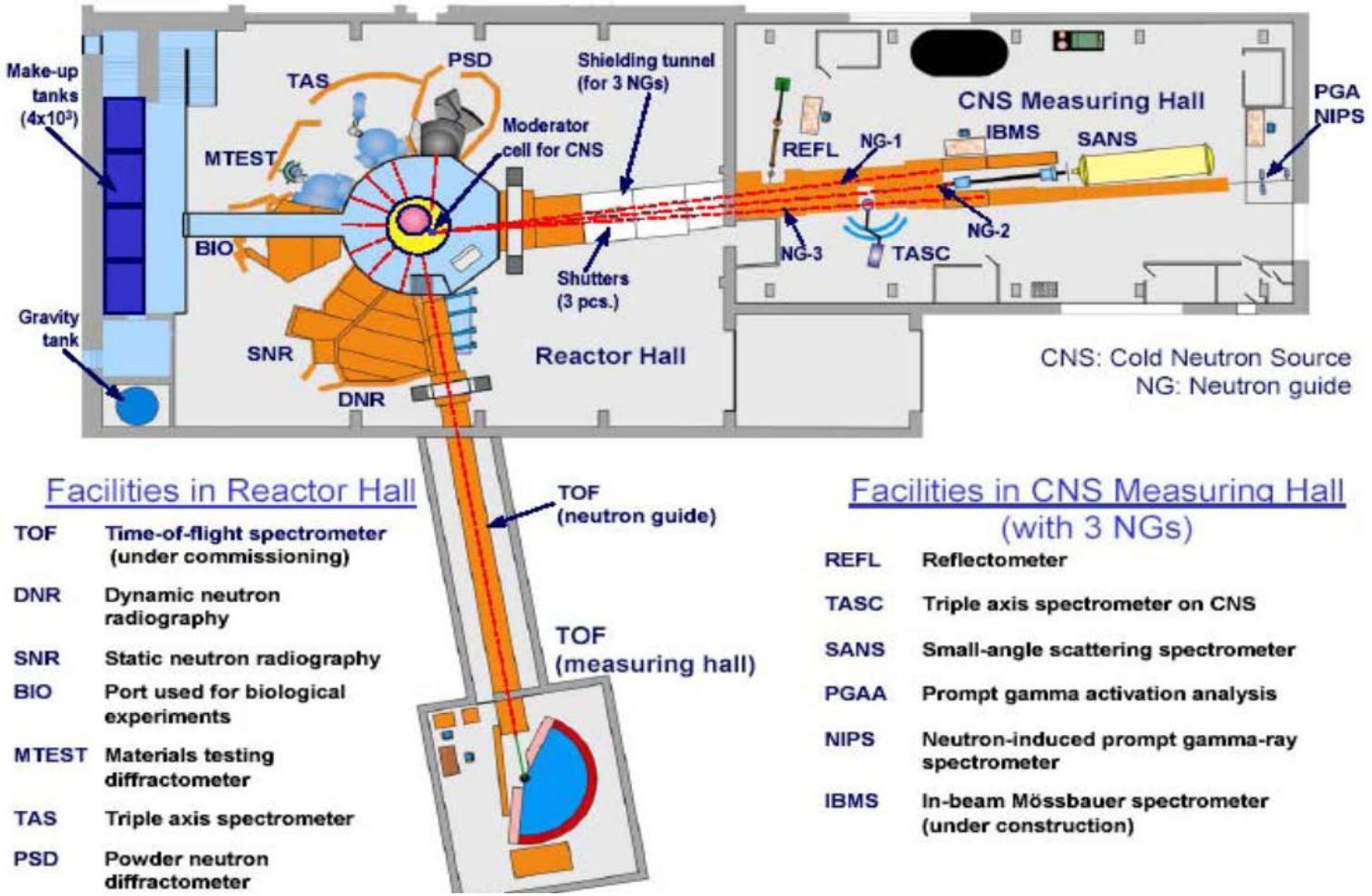


FIG. 1. Schematic drawing of the Budapest Research Reactor Hall; channels noted with PSD and the 3 neutron guides going to the right wall of the reactor hall are connected to tangential beam tubes. All others, drawn with red lines, are radial channels.

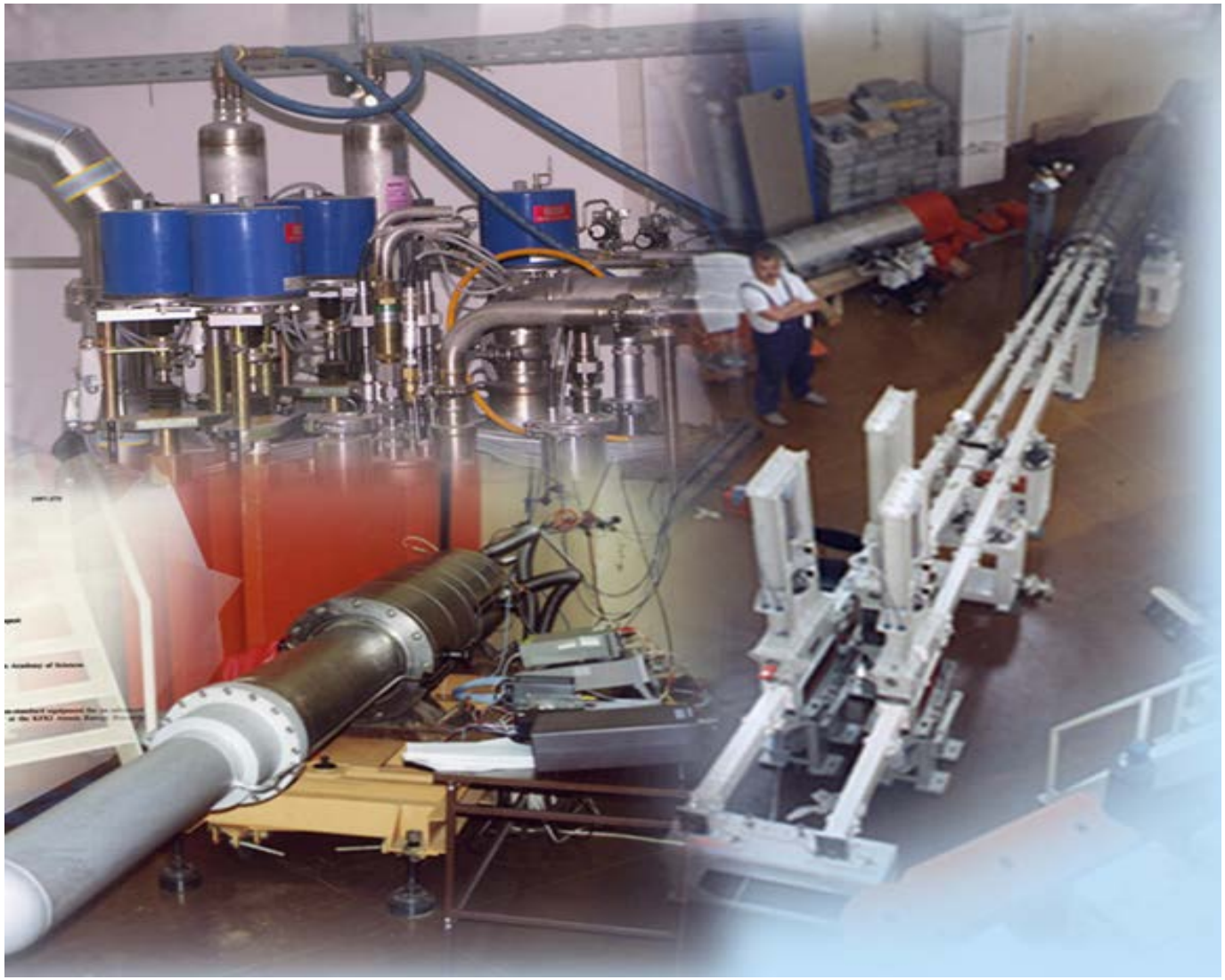


FIG. 2. Composite picture of the "cold plug" (pointing to the lower left corner) and the attached 3 neutron guides (pointing to the upper right corner).

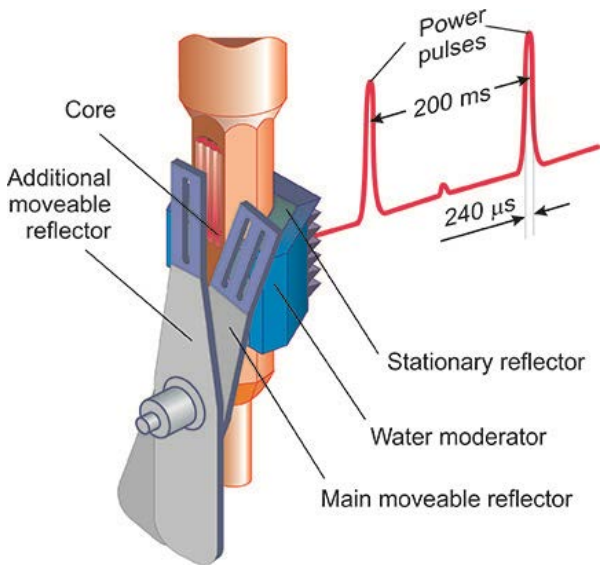


FIG.3. Schematic picture of IBR-2 pulsed reactor [5]

TABLE 1. PARAMETERS OF IBR-2 [5]

Average power, MW	2
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burn-up, %	9
Pulse repetition rate, Hz	5; 10
Pulse half-width, μs: fast neutrons thermal neutrons	 240 340
Rotation rate, turns/min: main reflector auxiliary reflector	 600 300
Materials of main and auxiliary movable reflectors	nickel + steel
Movable reflector service life, hours	55000
Thermal neutron flux density at the surface of the moderator: - time average - burst maximum	 $\sim 10^{13}$ $cm^{-2} \cdot s^{-1}$ $\sim 10^{16}$ $cm^{-2} \cdot s^{-1}$

In 2012 also in Dubna, the instrument development activities on the preparation of experiments at another pulsed resonance neutron source IREN continued [5]. The full-scale scientific research complex IREN will comprise a 200 MeV linear accelerator LUE-200 with a beam power about 10 kW, a subcritical multiplying target, and beam infrastructure with experimental pavilions, as well as technological, control, safety and service systems. The

characteristics of the full-scale complex IREN (integral neutron yield 10^{15} n/s and pulse width 0.6 μs) will allow it to rank among the best neutron sources of such class GELINA (Belgium) and ORELA (USA). The realization of the project is conducted in several stages. The first stage includes the construction of the LUE-200 linear accelerator and non-multiplying target. This will make possible to carry out experiments which require precision neutron spectroscopy in the energy range from fractions of eV to hundreds of eV already at the first stage of IREN. Achieved parameters so far were: pulsed electron beam current – 2.0 A; electron energy – 30 MeV; pulse width – 100 ns; repetition rate – 25 Hz; integral neutron yield up to 5×10^{10} n/s. Recently, the multi-detector system ROMASHKA-1 intended for neutron cross-section measurements were tested on the extracted neutron beams [5].

2.2. FILTERED NEUTRON BEAMS

The goal of the filtered neutron-beams (FNBT) is to extract a quasi-monoenergetic neutron line from a continuous neutron spectrum with high intensity. This extraction is achieved by means of two nuclear physics processes. The first one employs Bragg reflection of neutrons in single crystals. The second one is based on the transmission of neutrons through large quantities of materials, which show deep interference minima in their total neutron cross sections.

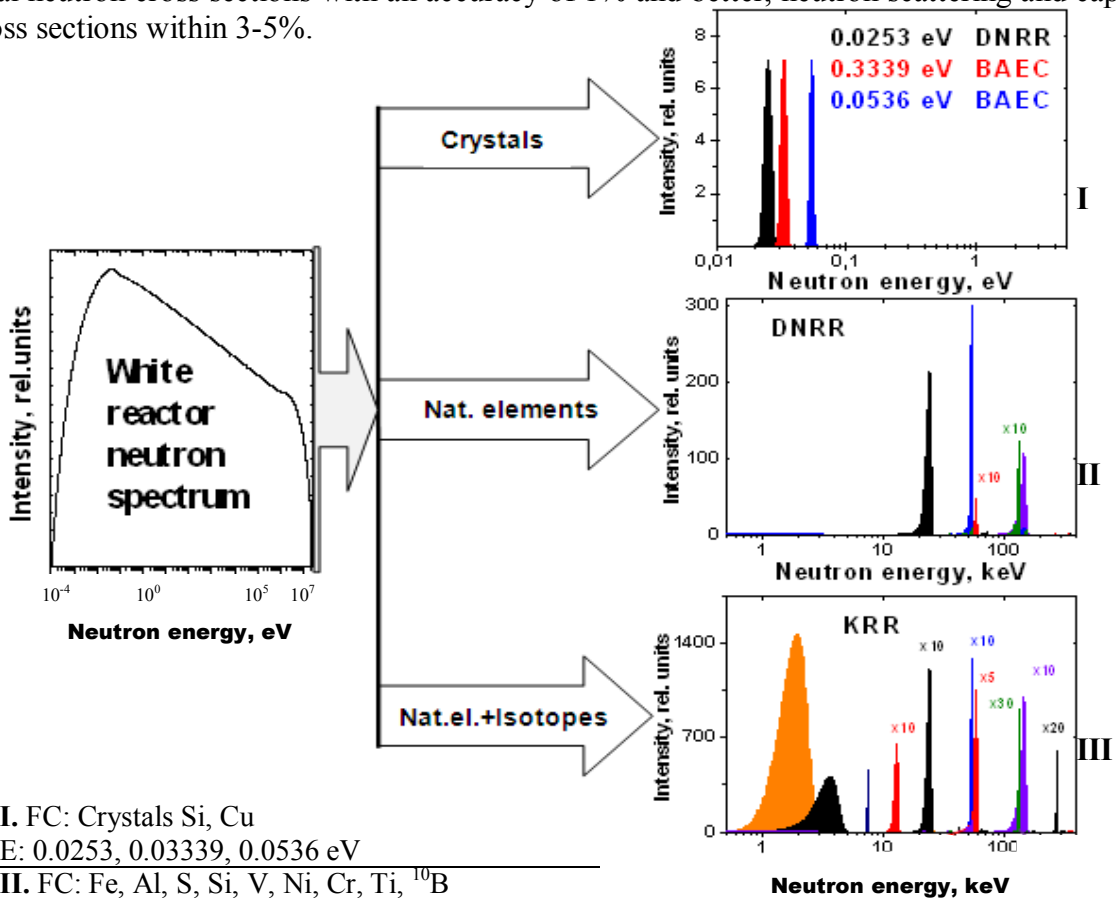
The first type of filters is often called a crystal monochromator. This filter allows selecting neutrons with low energies. The centroid energy of the obtained neutron beam depends on the type of crystal and the angle of the crystal lattice relative to the axis of the incident neutron beam. Using Si single crystals, it is possible to select neutron lines with energies 0.0253 eV (at the Dalat Nuclear Research Reactor (DNRR), Vietnam) or 0.03339 eV (the Bangladesh Atomic Energy Commission TRIGA reactor (BAEC), Bangladesh). Using a Cu single crystal, a neutron beam with energy 0.0536 eV is produced at the BAEC reactor.

The second type of filters is often called a composite interference filter. Usually, these filters are used to produce a single quasi-monoenergetic neutron line with energies in the range from 2 keV to several hundred keV. However, the total neutron cross sections always have several deep interference minima. Therefore, to get only one quasi-monoenergetic neutron line with high intensity these filters must be composed of several different filter materials. The additional materials must have resonance maxima in their total neutron cross sections, which coincide with interference minima of the main filter material, except at the required beam energy. Therefore, these filters are called “composite” filters. Components of these filters may be natural elements as well as highly enriched isotopes. Addition of the highly enriched isotopes improves the filter quality. The purity of the energy spectrum of the required neutron beams may reach almost 100%. Use of the highly enriched isotopes also allows selecting a wide set of energies of the filtered neutron lines.

The composite interference filters consisting of natural elements are used today at the DNRR. Fe, Al, S, Si, V, Ni, Cr, Ti, and B-10 are used and five quasi-monoenergetic neutron lines are available at the DNRR with energies 24, 54, 59, 133, and 148 keV. The intensity of these neutron beams ranges from 5×10^4 $cm^{-2} \cdot s^{-1}$ to 10^6 $cm^{-2} \cdot s^{-1}$. The best purity (intensity ratio of the main neutron line and all filtered neutrons) is obtained for the 24 keV and 148 keV filters (about 96%), the purity for the others smaller than 92%. The designed filtered neutron beams allowed determination of the average value of total neutron cross sections with accuracy of 2% and capture cross sections within 7–8%.

The composite interference filters consisting of natural elements and highly enriched isotopes are used today at the Kiev RR. Use of a wide set of natural elements Mg, Al, Si, S,

Sc, Ti, V, Cr, Mn, Fe, Co, Cu, Rh, Cd, Ce and highly enriched isotopes ^{52}Cr (99.3%), ^{54}Fe (99.92%), ^{56}Fe (99.5%), ^{57}Fe (99.1%), ^{58}Ni (99.3%), ^{60}Ni (92.8% – 99.8%), ^{62}Ni (98.04%), ^{80}Se (99.2%), ^{10}B (85%), ^{7}Li (90%) allow selection of quasi-monoenergetic neutron lines with energies 2, 3.5, 7.5, 13, 24, 54, 59, 133, 148 and 275 keV. Intensity of these neutron beams ranges from 5×10^4 cm$^{-2}\cdot$s^{-1} to 5×10^7 cm$^{-2}\cdot$s^{-1}. The purity may reach 99.5% for some filter arrangements. The designed filtered neutron beams allow determining the average value of total neutron cross sections with an accuracy of 1% and better, neutron scattering and capture cross sections within 3-5%.



I. FC: Crystals Si, Cu
E: 0.0253, 0.03339, 0.0536 eV

II. FC: Fe, Al, S, Si, V, Ni, Cr, Ti, ^{10}B
E: 24, 54, 59, 133, 148 keV
I = 10^4-10^6 cm$^{-2}\cdot$s^{-1}, P = 80-96%
ACS_{tot} = 2-3%, $ACS_{n,\gamma}$ = 6-8%.

III. FC: Fe, Al, S, Si, V, Ni, Cr, Ti, ^{10}B, Mg, Sc, Mn, Co, Cu, Rh, Cd, Ce, ^{52}Cr, $^{54, 56, 57}$Fe, $^{58, 60, 62}$Ni, ^{80}Se, ^{10}B, ^{7}Li
E: 2, 3.5, 7.5, 13, 24, 54; 59*, 133, 148*, 275 keV
I = 10^4-10^8 cm$^{-2}\cdot$s^{-1}, P = 99.0-99.5%
ACS_{tot} = 0.2-1%, $ACS_{n,\gamma}$ = 3-5%.

FC – filter components; E, I, P – energy, intensity, purity of the filtered neutron lines, ACS_{tot}, $ACS_{n,\gamma}$ – the best value of accuracy obtained for the total and capture cross sections.
* – set of the neutron energies.

FIG.4. The principle and current status of the FNBT at research reactors.

Also, two new techniques are being developed at the Kiev RR. One of them is called the modified filtered beams. The primary neutron line, after traditional filtering, is further shaped into narrow lines by adding appropriate filters. Four modifications of the 149 keV filter with V, ^{58}Ni, ^{54}Fe, or all of them are realised, allowing determination of 10 values of the averaged total neutron cross-sections in the energy region 90-160 keV. The

second method is called average energy shift method. The primary neutron line, after traditional filtering, is shifted using the neutron energy dependence on scattering angle. Polyethylene and carbon are used as scattering samples. This method was tested with the 59 keV filter, and 3 values of the averaged total neutron cross sections were measured in the energy region between 48.4 keV and 58.6 keV. The current status of the FNBT at the RRS is illustrated in Fig. 4.

3. ACCELERATOR BASED NEUTRON BEAM FACILITIES

3.1. MONOENERGETIC AND MAXWELL SPECTRUM NEUTRON BEAMS (< 5 MEV)

3.1.1. Accelerators

Monoenergetic and quasi-monoenergetic neutron beams for the precise measurement of nuclear data are usually produced using light-ion beams. Traditionally, electrostatic single-ended or tandem accelerators are employed at many facilities, with terminal voltages ranging up to about 15 MV. In the past the terminal voltages were generated using mechanical charge transport systems (belts or chains). A typical example is the MONNET facility at the Institute for Reference Materials and Measurements (IRMM) in Geel/Belgium [see contributed paper: S. Oberstedt et al.]. Figure 5 shows views of the 7 MV single-ended Van-de-Graaff accelerator which is at the core of this facility. To demonstrate the range of sizes of this kind of accelerators, a compact accelerator with lower maximum terminal voltage is shown as well.

Similar facilities were constructed at many institutes world-wide since the 1960s. Together with white sources they made an enormous contribution to the development of the nuclear data measurements. Older systems with mechanical charge transport are now being replaced by purely electrical high-voltage generation based on the Cockcroft-Walton or Dynamitron principle which yields superior voltage stability and ripple due to operating frequencies in the range of several hundred kHz. Tandem accelerators are now replacing the older single-ended machines because of their smaller footprint for a given beam energy. They also allow producing beams of light ions which can be used to generate neutrons in inverse kinematical configuration [see contributed paper: S. Oberstedt et al.]. Another advantage of tandem machines is the easy access to the ion sources which are located outside the pressure vessel.

The main advantage of electrostatic accelerators for cross section measurements is the excellent energy resolution and stability compared to cyclotrons, as well as simpler operation. Cyclotrons, however, make it possible to achieve higher beam energies for single-charged ions at moderate sizes, while the footprint of electrostatic accelerators rises strongly with terminal voltage. In the neutron energy range below 20 MeV cyclotrons were employed for nuclear data measurements only in special niches. In the energy range above 20 MeV, however, they were the working horses for many years.

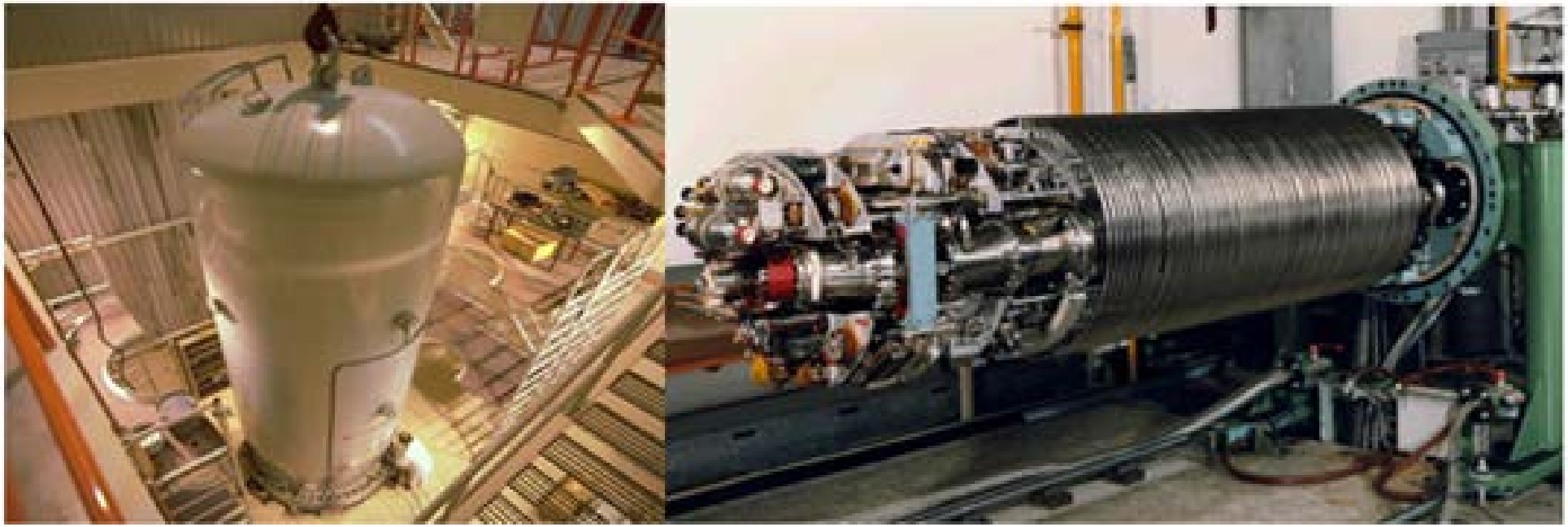


FIG. 5. The left panel shows the 7 MV Van de Graaff accelerator of the MONNET facility at the Institute of Reference Materials and Measurements (IRMM) in Geel (Belgium). To demonstrate the range of sizes, the right-hand panel shows compact 3.7 MV single-ended Van de Graaff accelerator of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig/Germany. Here the pressure tank is removed to show the accelerator structure.

3.1.2. Neutron production

The most important neutron production reactions are ^{7}Li(p,n)^{7}Be, T(p,n)^{3}He, D(d,n)^{3}He and T(d,n)^{4}He [6, 7]. With these reactions the energy range from about 30 keV to 8 MeV and from 14 MeV to 23 MeV can be covered with monoenergetic neutron beams. In the so-called gap region between 8 MeV and 14 MeV, the D(d,n)^{3}He reaction provides a neutron spectrum with a monoenergetic peak and a break-up continuum ranging up to about 6 MeV below the monoenergetic peak. Since the target thickness is limited by the requirement for low energy spread, the neutron yield can only be increased by using high beam currents which requires the use of targets capable to withstand high heat loads. This is particularly challenging for solid Ti(T) targets when air cooling has to be used to avoid the excessive target scattering by massive targets set-up.

Figure 6 shows the forward neutron yield per unit beam charge of the standard neutron production reactions for a target thickness effecting a relative width $\Delta E_n/E_n$ = 1% at 0°. In addition to the standard neutron production reactions mentioned above, also other (p,n) and (α,n) reactions are occasionally used to extend the neutron energy range accessible at a particular accelerator, if the smaller neutron yield can be tolerated. Examples of such reactions are ^{9}Be(α,n), ^{13}C(α,n) or ^{15}N(p,n). The latter reaction can also be used with a gas target.

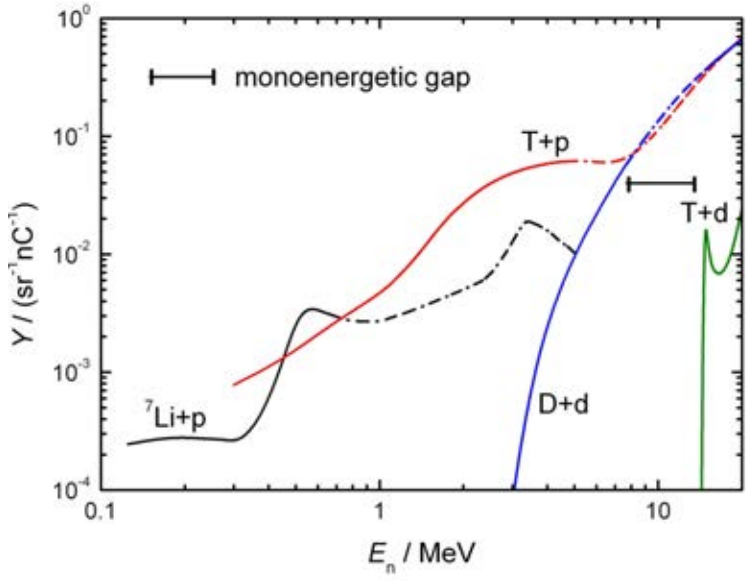


FIG. 6. Neutron emission yield Y at 0° for the four most important neutron-production reactions as a function of the neutron energy E_n. The dashed line indicates the energy range where the reactions are not monoenergetic. The yields were calculated for a relative neutron energy spread $\Delta E_n/E_n$ of 1% due to energy loss of the projectile in a target consisting of the reacting isotope only.

High-intensity 2.5 MeV and 14.8 MeV neutron beams are produced using low-energy high-current deuteron beams from so-called neutron generators based on the Cockcroft-Walton principle and rotating water-cooled solid state Ti(T) and Ti(D) targets specially designed for high thermal loads [see contributed paper: T. Murata, C. Konno et al.]. Recently, high-current accelerators based on the radiofrequency quadrupole (RFQ) design such as Frankfurt Neutron Source (FRANZ) [8] in Frankfurt/Germany or SARAF [9] in Soreq/Israel are coming up. At these accelerators liquid lithium targets are applied to achieve high neutron

yields using the ^{7}Li(p,n) reaction. The most important project for an ultrahigh-intensity neutron source is the IFMIF facility [10] which is presently designed for testing the performance of materials at the neutron flux levels of future fusion reactors. This facility will use two 40 MeV deuteron beams incident on a liquid lithium target. The current of each beam will be 125 mA.

In general, solid-state and gas targets are used for neutron production. Target related background can be subtracted by using 'blank' targets without the reactive isotope. While exactly matched solid-state blank targets are difficult to obtain, gas targets can simply be evacuated to subtract such background neutrons. Today the use of gas targets is, however, restricted to non-radioactive gases at most installations. Only at very few facilities, for example at the University of Kentucky in Lexington/USA [see contributed paper: J. Vanhoy] or at the China Institute of Nuclear Energy (CIAE) in Beijing/PR China, tritium gas targets are still available.

3.1.3. Characterization of neutron fields

The techniques for precise measurement of the neutron fluence were already documented around 1950 [11]. A more recent summary can be found in [12]. The primary instruments are usually directly based on the differential n-p scattering cross section which is the primary reference for neutron measurements. Examples are the recoil proton telescope or the proportional counter filled with hydrogenous counting gases [see contributed papers: S. Oberstedt et al., R. Nolte et al.]. At some facilities, calibrated transfer devices are employed, for example long counters, Bonner sphere detectors [see contributed papers: Y. Tanimura et al., R. Nolte et al.] or activation foils [see contributed paper: V. Vlastou]. When neutrons are produced using the ^{7}Li(p,n)^{7}Be reaction, the residual ^{7}Be activity in the target can be measured to infer the total number of neutrons produced [see contributed paper: V. Vlastou] if the degradation of the target can be controlled.

Monoenergetic neutron fields always contain neutrons of lower energy, either resulting from target scattering or from parasitic reactions in the target. Quasi-monoenergetic neutrons produced in the 'gap region' show a break-up continuum in addition to the monoenergetic peak [7]. Therefore techniques for measuring the spectral distribution are very important. The energy of the produced neutrons is usually measured using the time-of-flight (TOF) technique [see contributed papers: S. Oberstedt, R. Nolte et al., T. Katabuchi at al., V. Khryachkov, Y. Tanimura et al.]. For this technique, pulsed beams with ns time resolution are required. At low-energy accelerators this is usually achieved by using a combination of a radiofrequency chopper and a klystron buncher directly behind the ion source. In the past magnetic pulse compression using so-called Mobley magnets was also applied. Pulsed beams and the TOF technique are also required to determine the energy of outgoing neutrons in measurements of differential neutron scattering cross sections or neutron emission spectra [see contributed papers: S. Oberstedt et al., R. Nolte et al., V. Khryachkov].

Foil activation and unfolding procedures can be used to characterize the spectral neutron distribution [see contributed paper: V. Vlastou] if pulsed beams are not available. However, the energy resolution is usually worse than that achievable using the TOF method, and the distributions obtained are easily affected by artefacts resulting from the unfolding procedure.

3.1.4. Experimental facilities

Most monoenergetic neutrons beams are produced in open geometry. Hence, reduction of the room-return background by using low-mass installations is important. Reduction of background is also achieved by carrying out experiments as close as possible to the neutron production target to maximise the signal-to-background ratio. Figure 7 shows an overview over the low-scatter hall at the accelerator facility PIAF of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig/Germany. Similar facilities exist at many other laboratories [see contributed papers: Y. Tanimura et al.]

Special installations are sometimes used to vary the scattering or neutron emission angle while shielding neutron detectors for secondary neutrons against the neutron source. Examples are the beam swinger magnet at the Ohio University Accelerator Laboratory [13] in Athens/USA shown in Fig. 8, or the use of a rotatable cyclotron at the PTB time-of-flight spectrometer [see contributed paper: S. Oberstedt, R. Nolte et al.].

Special time structures with pulse durations in millisecond to second range are sometimes used to facilitate the measurement of delayed reactions products, such as fission fragments from shape isomers or the emission of β-delayed neutrons. An example is the NEPTUNE set-up recently installed at the MONNET facility of the IRMM [see contributed paper: S. Oberstedt et al.].

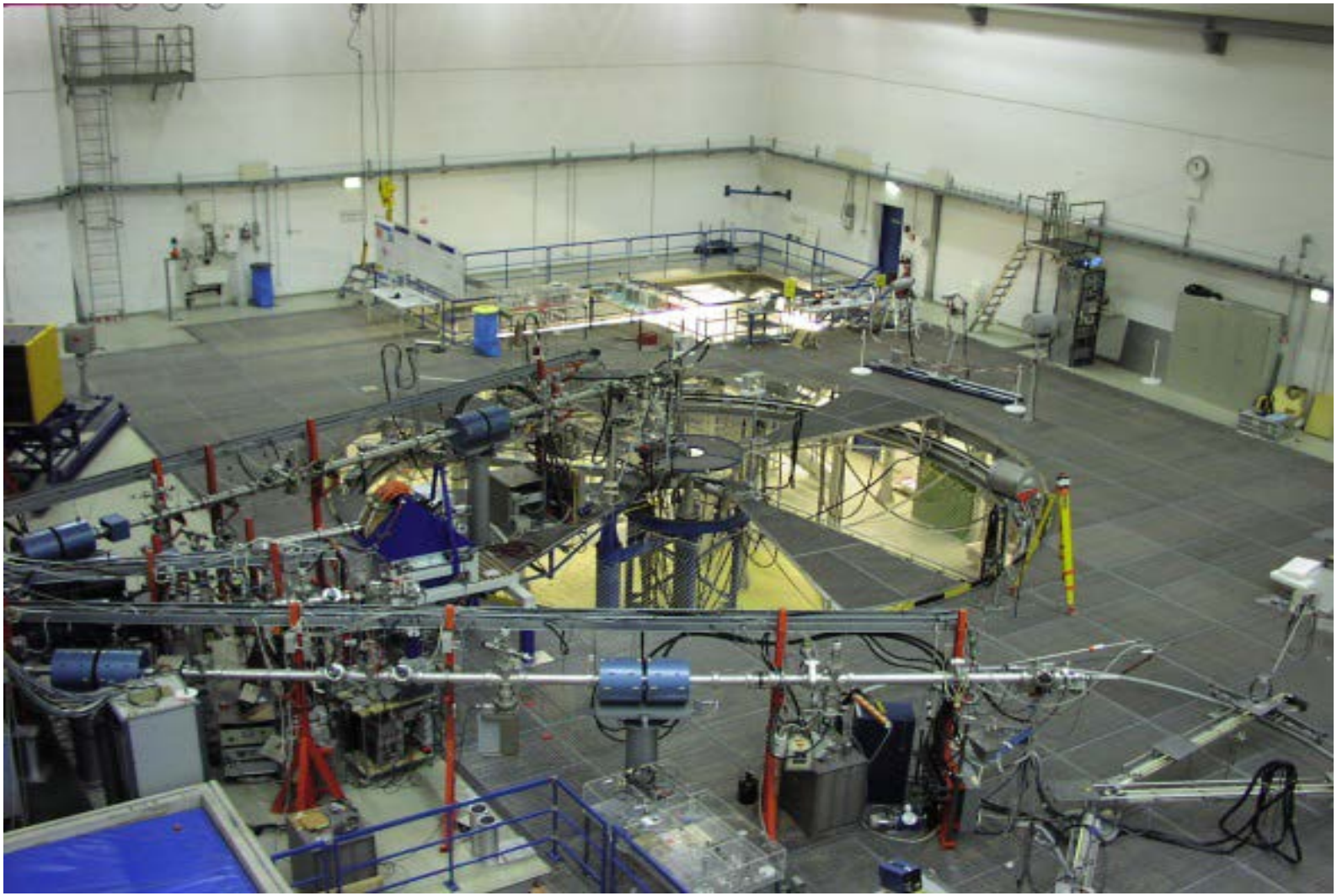


FIG.7. Low-scatter experimental hall at the accelerator facility PIAF of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig/Germany. Room-return neutrons are reduced by the large size of the hall, the grid floor and the open pit below the neutron production target.

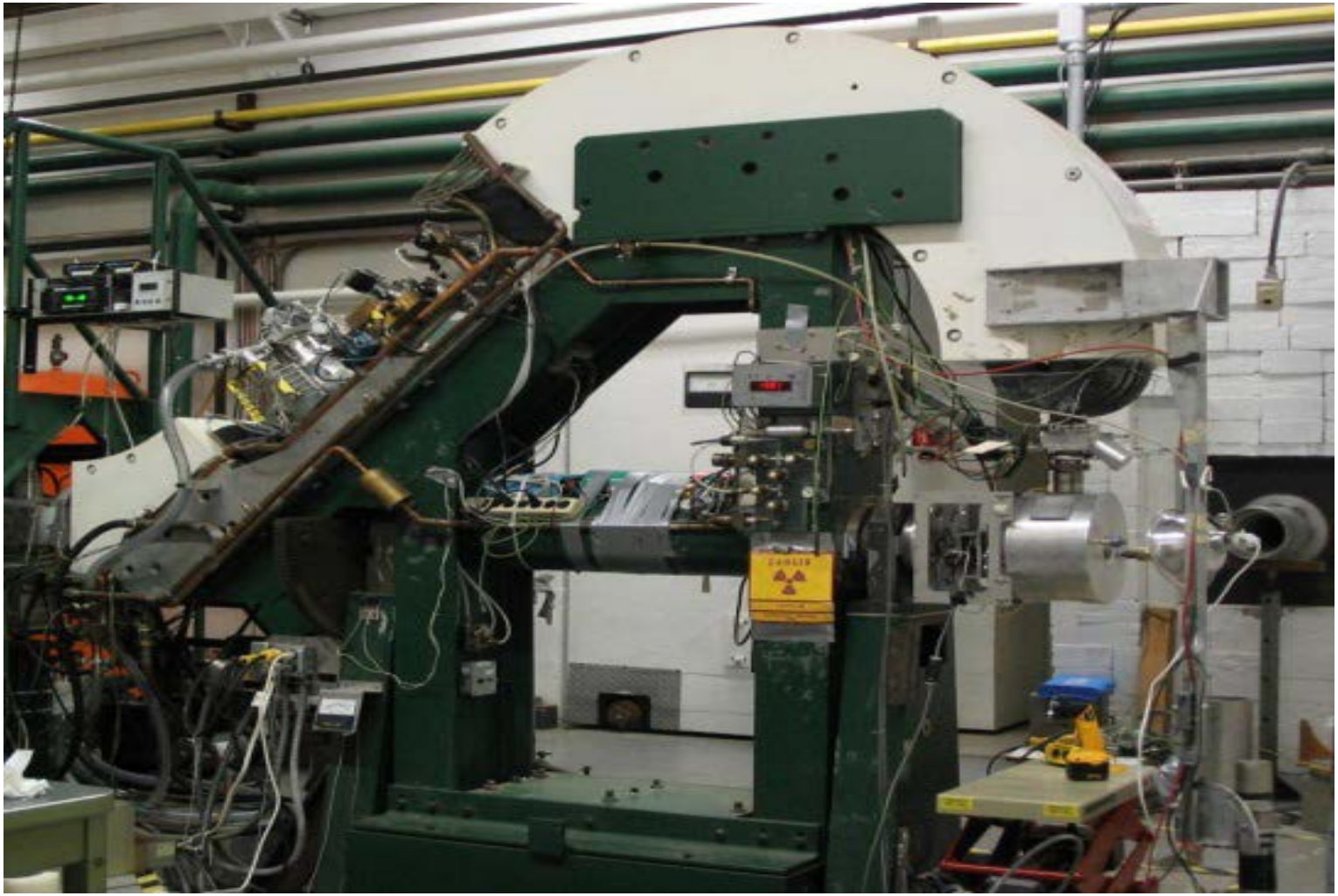


FIG.8. The beam swinger magnet at the Ohio University Accelerator Laboratory in Athens/USA. This moveable dipole magnet allows the neutron emission angle to be varied in nuclear reactions experiments while keeping the position of the neutron detector fixed.

3.1.5. Experimental programmes

The main application of monoenergetic or quasi-monoenergetic facilities are measurements of activation and differential elastic scattering cross sections [14], (see contributed paper: J. Vanhoy et al.) which are impossible or very difficult to determine using white sources. Measurements of inelastic scattering cross sections [14] [see contributed paper: V. Khryachkov et al.] offer complementary information to experiments at white sources where the de-excitation photons are detected, in particular at higher neutron energies where the level schemes become very complicated. Experimental programmes at monoenergetic neutron sources also comprise measurements of fission cross sections and other fission-related parameters, as well as measurements of charged particle emission cross sections [see contributed paper: S. Oberstedt et al.].

Cross sections averaged over Maxwellian spectral distributions are of great importance in nuclear astrophysics. Such data can be directly measured in neutron fields produced at beam energies close to the threshold of endothermic reactions, e.g. ^{7}Li(p,n) or T(p,n), if the sample covers the full neutron emission cone. When integrated over the neutron emission angle, the spectral distribution in the region of double-valued kinematics is close to a Maxwellian shape. This technique has been exploited for years at the Van de Graaf accelerator LOLITA of the former Nuclear Research Centre Karlsruhe/Germany for the measurements of activation and capture cross section of relevance for modelling nucleosynthesis.

Monoenergetic high intensity 14.8 MeV sources are mainly applied for integral experiment and for benchmarking data libraries for fusion neutronics. Other high-intensity sources, such as Soreq Applied Research Accelerator Facility (SARAF) or Frankfurt Neutron Source (FRANZ), are intended for a wide range of application, ranging from data for nuclear astrophysics to isotope production.

3.2. ION-INDUCED QUASI-MONOENERGETIC AND WHITE NEUTRON BEAMS

3.2.1. Quasi-monoenergetic neutron beams

The availability of mono-energetic neutron beams is of prime interest for the measurement of basic nuclear data as well as for numerous applications like medicine treatment, electronic irradiations or characterisation of neutrons detectors or dosimeters.

Electrostatic accelerators delivering proton and deuteron beams up to few MeV allow producing neutrons by using the ^{7}Li(p,n), ^{3}H(p,n), ^{2}H(d,n) and ^{3}H(d,n) reactions. The energy range up to 20 MeV is covered and neutrons are purely mono-energetic except between 8 and 13 MeV. Above this energy the ^{7}Li(p,n)^{7}Be reaction is used in several facilities around the world to produce quasi-mono-energetic neutrons.

The Q-value of the ^{7}Li(p,n)^{7}Be reaction is -1,644 MeV thus the neutron energy at angle 0 degree is approximately 2 MeV lower than the proton energy. At low energy, with protons above 1.92 MeV neutrons are purely mono-energetic. When the proton energy increases other reaction channels emitting neutrons open like the ^{7}Li(p,nα)^{3}He and ^{7}Li(p,np)^{6}Li whose threshold energy are 3.695 MeV and 8.292 MeV respectively. Thus at high energy (E_p>10 MeV), the neutron spectrum is quasi-mono-energetic (QMN). It is composed of a

peak and of a tail at low energy (see Fig. 9). The neutrons in the peak are produced by the ^{7}Li(p,n)^{7}Be reaction. The tail is due to the many body reactions, mainly the ^{7}Li(p,nα)^{3}He and ^{7}Li(p,np)^{6}Li. Peaks corresponding to the excited states of ^{7}Be (4.55 MeV, 6.51 MeV, 7.19 MeV and 10.79 MeV) can also appear in the low energy tail. The cross-section is quite high and the angular distribution is peaked at forward angle (see Fig. 10), making this reaction particularly attractive for neutron beam facilities.

Several facilities around the world use this reaction to produce a QMN spectrum. It is based on a proton beam in the 20 MeV to 400 MeV energy range impinging a thin lithium target. The target thickness depends on the proton energy and is a compromise between the production yield and the importance of the spectrum tail. Downstream of the target the proton beam is deflected by a magnet to a proton beam dump. The neutrons at 0 degree are cleaned of residual charged particles by a second magnet and a collimator defines the neutron beam profile. An alternative solution has been adopted at Nuclear Physic Institute at Řež where the lithium foil is fixed on a carbon backing in which the proton beam is stopped. The carbon was chosen because the neutron production in proton induced reaction is low except for the ^{13}C(p,n). The production of spurious neutrons is then low.

Because the neutron spectrum is not purely monoenergetic, a pulsed beam is advantageous in order to measure the neutron energy or at least to be able to separate neutrons from the quasi-mono-energetic peak from the tail by time-of-flight. Even with a continuous beam it is possible to perform measurements of the spectral distribution employing the activation technique; however, an unfolding procedure is needed to take into account the low energy tail.

The use of lithium induces some technical constraints. It has one of the lowest melting points (180°C) among all the metals and therefore limits strongly the maximum energy deposition in the converter. The low working temperature makes the heat evacuation by radiation very inefficient and a fixed target cooled by water is preferred to a rotating target. However, the use of liquid lithium seems to be the best solution to sustain high energy deposition. In most of the QMN facilities the limitation of neutron intensity comes from the thermal constraints of lithium and not from the proton beam intensity.

As an alternatively to the ^{7}Li(p,n) reaction, the ^{9}Be(p,n) reaction is also used at iThemba Laboratory for Accelerator Based Sciences (iThemba, South Africa) for example. The main reason is the better performance of the target at higher heat loads, i.e. the possibility to increase the neutron yield. The spectral neutron distribution of the ^{9}Be(p,n) reaction itself is less favourable than that of the ^{7}Li(p,n) reaction because the first excited states of ^{9}B have rather low excitation energies and the relative contribution of continuum neutrons is higher than for ^{7}Li(p,n).

The list of the existing facilities around the world is given in Table 2. A detailed description of all of them can be found in Ref. [15].

At iThemba labs a special technique is used to compensate the contribution of continuum neutrons if energy discrimination by the time-of-flight method is impossible, as for example in activation measurements. In order to take into account the low energy tail, two measurements are performed at 0° and 16°. The high energy peak, prominent at 0°, decreases rapidly with angle while the spectrum and intensity of the low energy part is almost independent of angle in the region between 0° and 16°. The subtraction of the yield at 16° from that produced at 0° results in a yield determined for the quasi-mono-energetic neutron energy (see Fig. 11). Hence, the cross section at the energy of the high-energy peak can be determined from a 0–16° difference measurement.

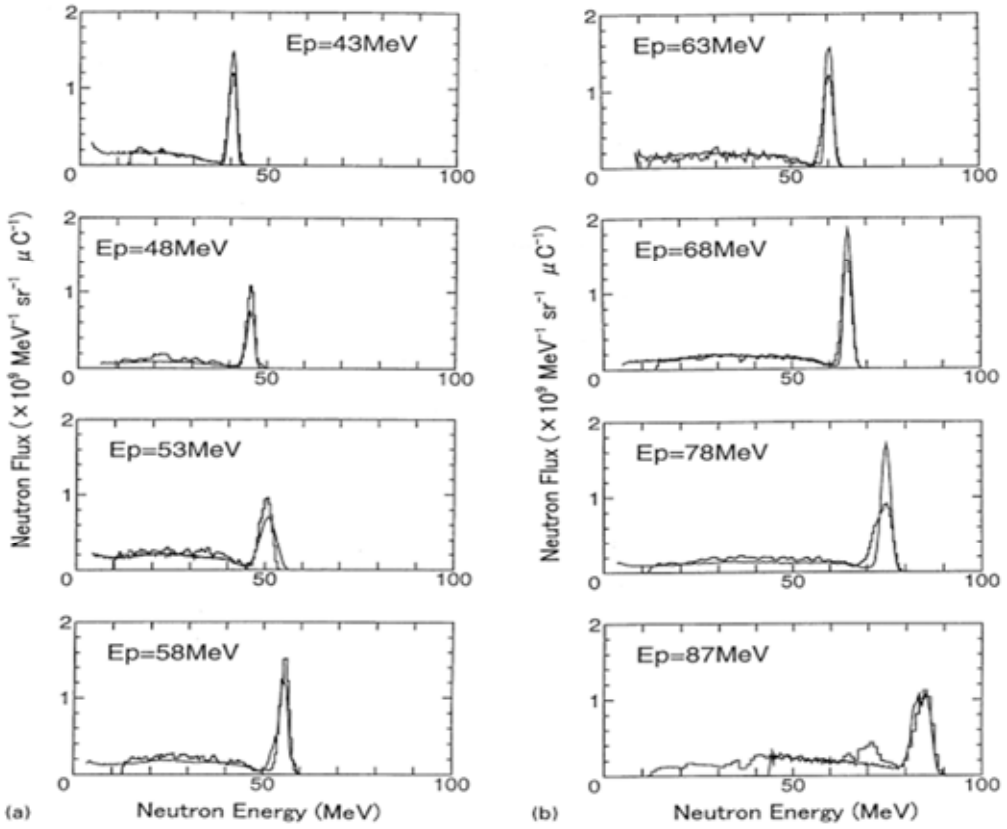


FIG. 9. ^{7}Li(p,n) source spectra by Proton Recoil Telescope (histogram) and by Time-Of-Flight technique (solid lines) for proton energy between 43- 87 MeV [16].

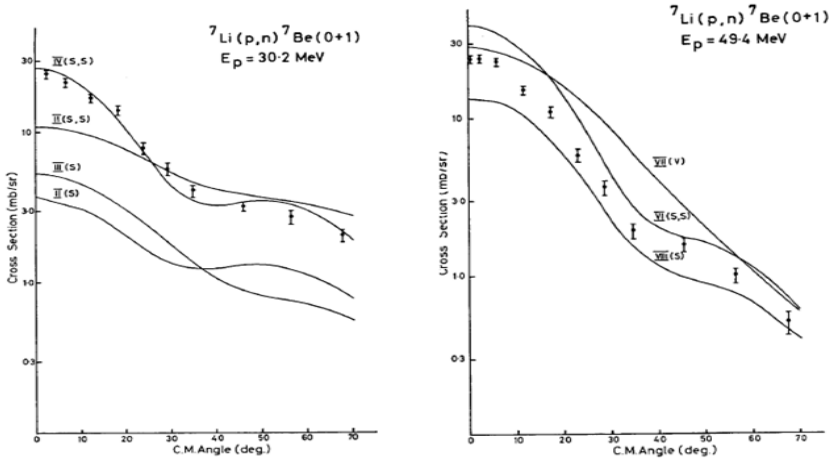


FIG. 10. Angular distribution of the ^{7}Li(p,n) reaction at 30.2 and 49.4 MeV [16].

TABLE 2. LIST OF EXISTING AND FUTURE QMN FACILITIES AROUND THE WORLD

Institute	Country	City	Facility	Beam	Accelerator	Energy Range (MeV)	Peak neutron flux (cm^{-2} s^{-1})	Collimated beam
IThemba	South Africa	Cape Town		P	Cyclotron	35-200	5×10^{3}-1×10^{4}	Y(12 m)
TSL	Sweden	Uppsala	ANITA	P	Synchrocyclotron	20-180	1×10^{6} – 1×10^{7}	Y(15 m)
NPI	Czech Republic	Rež		P	Cyclotron	37 18	1×10^{11} $sr^{-1}s^{-1}$ 1×10^{11} $sr^{-1}s^{-1}$	N N
JAEA	Japan	Takasaki	TIARA	D	Cyclotron	40-90	1×10^{4}	Y(5-18m)
Osaka University	Japan	Osaka	RCNP	P	Cyclotron	100-400	1×10^{5}	
Tohoku University	Japan	Sendai	CYRIC	P	Cyclotron	20-90	1×10^{6}	
SPIRAL-2	France	Caen	NFS	P	LINAC	10-33		Y(30 m)

iThemba: iThemba Laboratory for Accelerator Based Sciences; TSL: The Svedberg Laboratory; NPI: Nuclear Physics Institute; JAEA: Japan Atomic Energy Agency; ANITA: Atmospheric like neutrons from thick target; TIARA: Takasaki research establishment; RCNP: Research centre for nuclear physics; CYRIC: Cyclotron and radioisotope centre; NFS: Neutrons for science; LINAC: Linear particle accelerator.

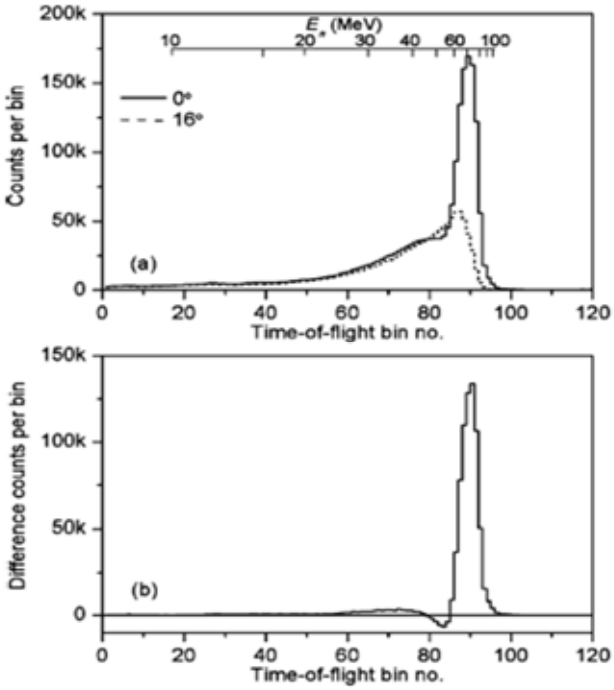


FIG. 11. Neutron TOF obtained from the bombardment of a 10 mm thick Be target by 79.4 MeV protons. The two spectra were measured at neutrons emission angles of 0° (—) and at 16° (- - -), respectively and are normalized so as to equalise the total number of counts in the continuum region (E_n < 58 MeV). The neutron detector settings were identical for the two measurements. (b) Difference spectrum obtained by subtracting the 16° spectrum from the 0° spectrum [17].

3.2.2. White energy spectrum neutron beams

Intense fast neutron sources are increasingly used for many applications from fundamental to applied physics. Such facilities are dedicated to nuclear data measurements, the production of radioactive ion beams or the study of radiation damage in materials. Medical applications for cancer therapy, radiobiology studies, and production of radioisotopes also require intense neutron sources.

Accelerator-based sources are capable of producing neutrons from a few keV up to several hundreds of MeV. Several types of spectra are available: purely mono-energetic neutrons below 20 MeV, quasi-mono-energetic neutrons produced by the ^{7}Li(p,n) reaction up to approximately 200 MeV and white sources. White sources are produced by the interaction of a light ion beam on a thick target. The goal of this section is to provide the characteristics and the limitations of white neutron sources below 200 MeV. A non-exhaustive list of such facilities running today or presently under construction is also presented. Sources of higher energy based on the spallation reaction are treated in another section.

A white source of neutrons is obtained by the interaction of a light ion beam on a thick target. A thick target means that the incident beam is fully stopped in the target (also called the converter). As ions slowdown in the converter, neutrons are produced over a continuous energy range from 0 to approximately the incident ion energy. Several target elements are used, ranging from light materials such as Li, Be, C and D_2O to heavy materials like Ta or W. When proton and deuteron beams are employed, they are usually accelerated by a cyclotron or a linear accelerator.

Neutrons are produced by direct reaction (high energy), pre-equilibrium process (medium energy) and evaporation (low energy). With a deuteron beam, neutrons are mainly produced by breakup reaction. The cross section for neutrons produced by deuteron breakup increases rapidly above the threshold value of approximately 9 MeV (see Fig.12). The choice of converter depends on several parameters like the neutron production yield or the thermal and chemical constraints. Converters made of lithium or beryllium results in roughly two times more neutrons than carbon converters. For a given energy, the neutron yield is generally higher from deuterons than from protons. However, a proton beam interacting with carbon converter, enriched in ^{13}C, might be an interesting alternative.

Neutron angular distributions from (d,n) reactions are strongly forward peaked (see Fig. 13) compared with angular distributions from (p,n) reactions. When considering a facility using a well-collimated beam on a beryllium target, deuterons produce a higher yield at 0° than protons up to twice the energy, i.e. the deuteron is the better projectile. However, using a proton beam instead of a deuteron beam can be an advantage in terms of radioprotection due to the low deuteron binding energy.

Characteristics flux and spectrum

The nature of the converter does not influence significantly the neutron spectra. Figure 14 shows examples of energy spectra obtained in deuteron-induced reactions on carbon and beryllium. The high energy component as well as the neutron flux decrease rapidly with the emission angle showing that these production reactions are particularly adapted for neutron beam facilities. The most probable energy increases with the deuteron energy, approximately 20 MeV and 26 MeV for 50 MeV and 65 MeV of incident energy respectively.

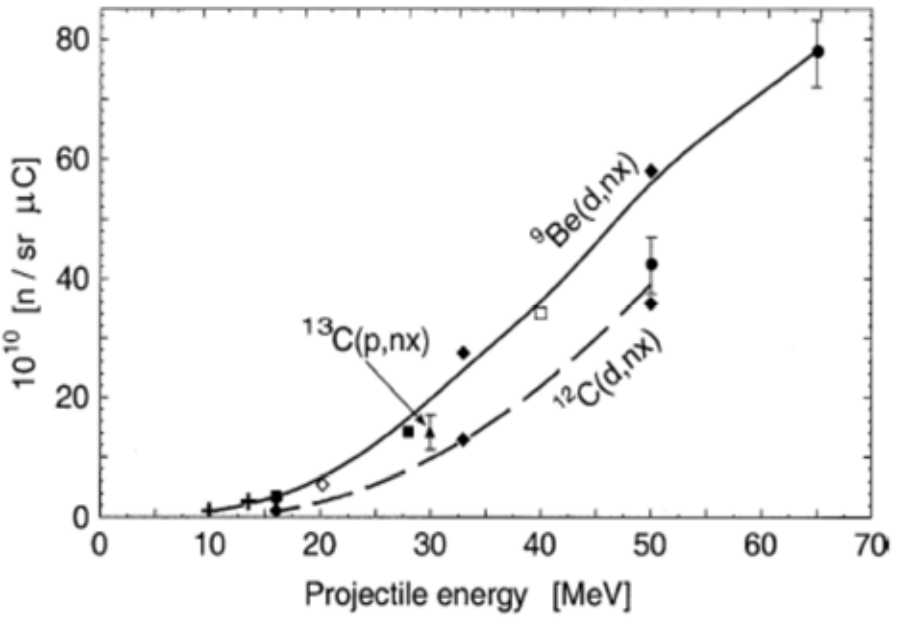


FIG. 12. Neutron yield at 0 degrees for deuteron induced reaction on a thick carbon and beryllium target [19].

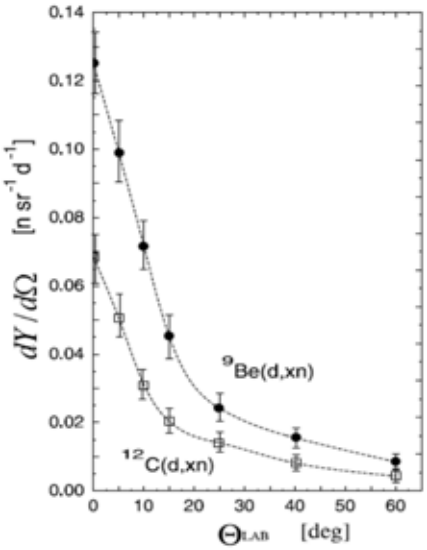


FIG. 13. Angular distributions of the ^{12}C(d,xn) and ^{9}Be(d,xn) reactions at 50 MeV [20].

The production of neutrons in 4π is usually around a few % by incident particles (ratio n/deuteron is around 0.05 at 40 MeV for d + Be source). It is very low compared to the production by the spallation reaction on a thick target (more than 20 n/proton at 1 GeV proton incident energy). As a consequence, the instantaneous flux (number of neutrons by burst) is quite low compared to the spallation neutron sources, but due to a high beam repetition rate (around 1 MHz) high average fluxes are reachable.

Beam and Time-Of-Flight

The neutron beam is created by placing a collimator downstream of the converter at the angle of 0 degrees with respect to the deuteron beam to take advantage of the forward peaked emission. The thickness and the composition of the collimator depend mainly on the maximum energy of the ion beam. The presence of the collimator decreases the available flux on the sample (by geometrical effect) but gives the advantage of making it possible to use neutron and gamma detectors around the sample.

The energy of the neutron can be measured by time-of-flight technique if the ion beam has an adapted beam time structure. The resolution of the energy measurement depends on the burst width while the overlap of the neutron beam depends on the frequency. These parameters are both strongly linked to the length of the flight path.

A continuous energy spectrum is particularly useful in measurements of excitation functions, because cross sections can be measured in a wide energy range simultaneously.

Target

Since the beam is stopped in the converter, all the beam power is deposited in the target and for very intense sources cooling requirements are a strong constraint. As an example, a beam of 40 MeV with an intensity of 50 μA will deposit 2 kW in the stopping target. A focus beam associated with the slowing down following the Bragg curve leads to a high specific power density. This power deposition induces thermal constraints which require a high-performance cooling system. Several technical solutions are used to solve this problem. A fixed target cooled by water is used at several facilities Atmospheric like neutrons from thick target (ANITA), Nuclear Physic Institute (NPS, ŘEŽ), Jyväskylä accelerator facility (JYFL).

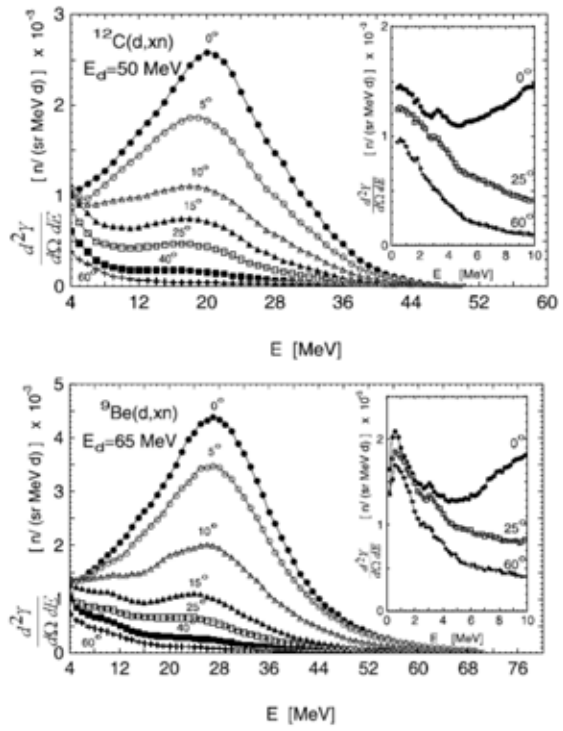


FIG. 14. Energy spectra of neutrons produced in the (d,xn) reaction on C at 50 MeV and on Be at 65 MeV [20].

This concept is compact since several converters can be mounted on the same frame, and is adapted for good conductors. The drawback is the presence of water with a risk of leak. Another solution consists in employing a fast rotating disk as a target. The principle is to increase the surface of interaction of the beam in order to decrease the specific surface energy deposition. The cooling is ensured by radiation, whose efficiency increases with temperature, and this solution is adapted for high melting point materials. The other solution adapted for low temperature melting point is the liquid target.

Existing facilities

Several laboratories have an accelerator-based neutron source. The characteristics of some of these facilities are given in Table 3, although the list of facility is not exhaustive. Energy spectra representative of the facilities are shown in the Figs. 15-20.

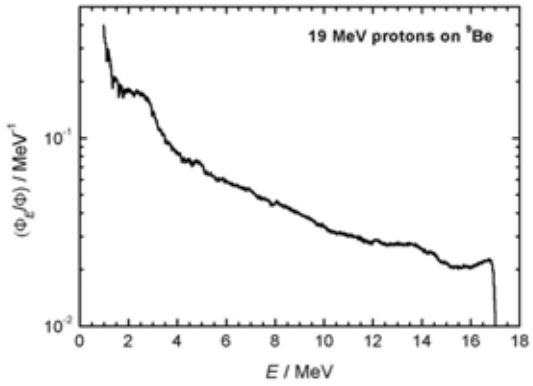


FIG. 15. Neutron spectrum of the white source of the Parallel Interactive Analysis Facility (PIAF) (PTB Ion Accelerator Facility).

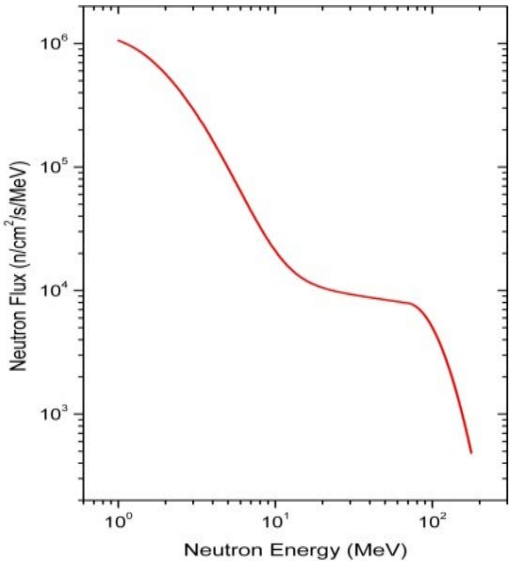


FIG. 16. Neutron spectrum of the ANITA facility (TSL) at 250 cm from the converter.

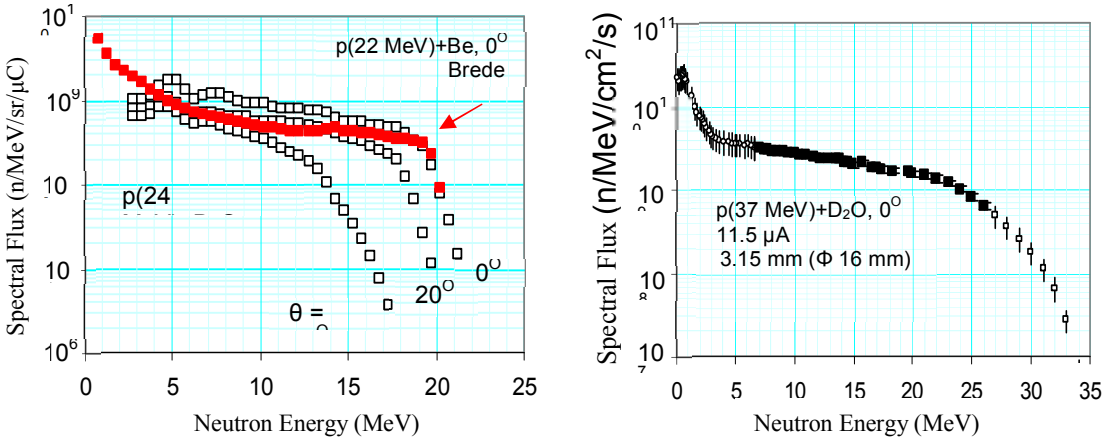


FIG. 17. Neutron spectra of the white sources of NPI with Be and D_2O converters.

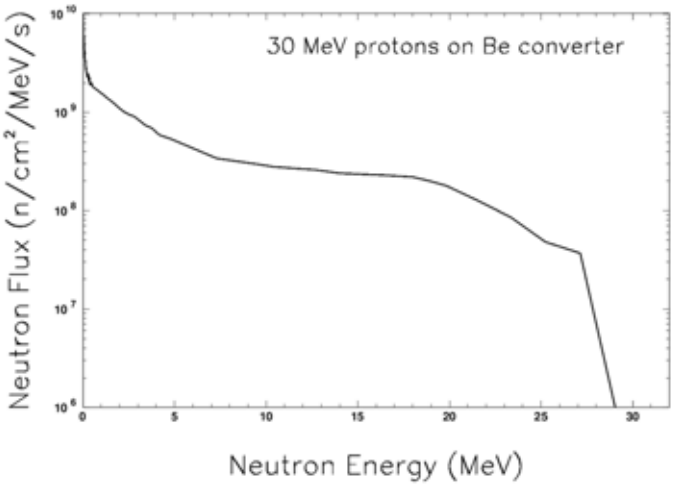


FIG. 18. Neutron spectrum of the IGISOL facility (JYFL) at 20 cm from the converter.

TABLE 3. CHARACTERISTICS OF THE WHITE NEUTRON SOURCES BELOW 200 MeV

Institute	Country	Facility	Beam	Converter	Accelerator	I_{max} (μA)	E_{max} (MeV)	Flux ($cm^{-2}s^{-1}$)	Collimated beam
PTB	Germany	PIAF	P	Be	Cyclotron	1-2	19	5×10^{3}-1×10^{4}	Y(12 m)
			D	Be		40-80	13,5	1×10^{8} – 2×10^{8}	Y(1m)
TSL	Sweden	ANITA	D	W	Synchrocyclotron	0,2-10	20-180	1×10^{6} – 1×10^{7}	Y(15m)
NPI	Czech Republic	LC & FNG	P	D_20, Be	Cyclotron	10	37	1×10^{11} $sr^{-1}s^{-1}$	N
			D	D_20, Be		20	18	1×10^{11} $sr^{-1}s^{-1}$	N
JYFL	Finland	IGISOL	P	Be	Cyclotron	200	30	1×10^{10}	N
			D	Be		62	15		N
TRIUMF	Canada	PIF	P	Pb	Cyclotron	0,006	116	5×10^{4}	N
SPIRAL-2	France	NFS	D	Be, C	LINAC	50	40	1×10^{8}	Y(30m)

PTB: Physikalisch-Technische Bundesanstalt; TSL: Theodore Svedberg laboratory; NPI: Nuclear physics institute;
JYFL: Jyväskylä accelerator facility; TRIUMF**:** Canada's National Laboratory for Particle and Nuclear Physics;
SPIRAL-2: Système de Production d'Ions Radioactifs Accélérés en Ligne; PIAF: PTB Ion Accelerator Facility;
ANITA: Atmospheric like neutrons from thick target; LC & FNG: Laboratory of Cyclotron and Fast Neutron Generators;
IGISOL: Ion Guide Isotope Separator On-Line; PIF: Proton Irradiation Facility; NFS: Neutron for science.

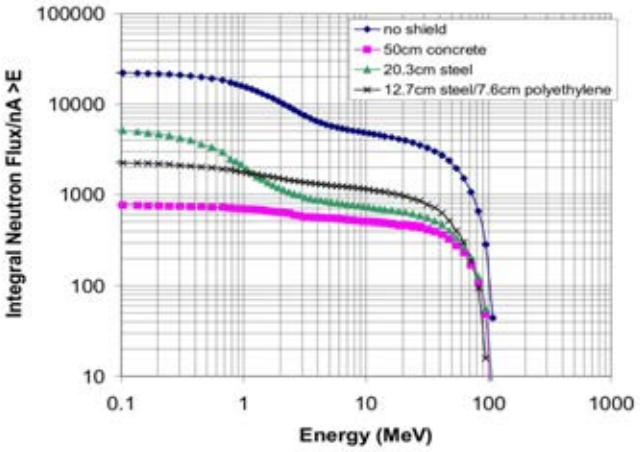


FIG. 19. Neutron spectra at The PIF facility (TRIUMF).

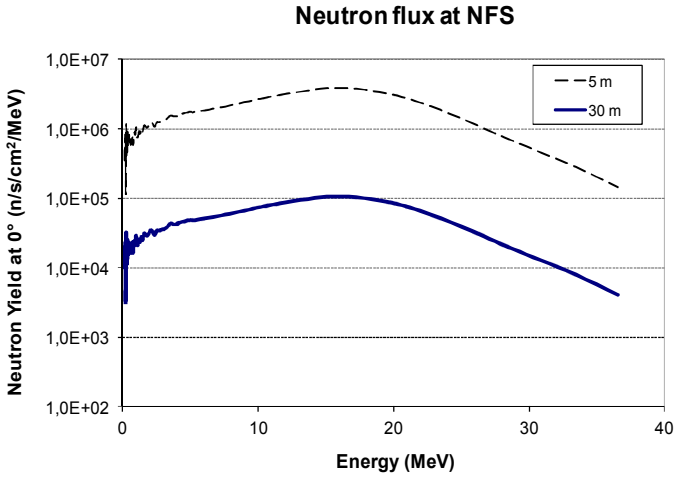


FIG. 20. Neutron spectra expected at NFS (SPIRAL-2) at 5 m and 30 m from the converter.

3.3. ELECTRON-INDUCED WHITE SPECTRUM NEUTRON BEAMS

Neutron beams can be produced by means of high-energy electron beams impinging on a heavy metal target. The bremsstrahlung produced by slowing-down electrons induces either (γ,n) reactions, e.g. in lead or tantalum, or photon-induced fission in uranium. The neutrons are emitted essentially in 4π and have a certain energy distribution, which might be modified by passing the neutrons through a moderator, e.g. water. The neutron flux of a facility is determined by the energy of the electrons, the beam intensity and the target material. Experiments make use of the neutron time-of-flight (TOF) technique to determine the velocity of neutrons, thereby their energy. The neutron energy resolution is defined by the width of the electron beam pulse, the neutron target configuration and the time-of-flight distance between the neutron source and the detector. In Table 4 characteristics of selected electron-driven white spectrum neutron sources are summarized. This table should give a flavour of the diversity of existing facilities and does not claim to be exhaustive.

TABLE 4. CHARACTERISTICS OF SELECTED ELECTRON-DRIVEN WHITE SPECTRUM NEUTRON SOURCES

(facilities indicated by * are not operational at the moment of production of this report)

Facility	Electron energy (MeV)	Target	Pulse width (ns)	Repetition frequency (Hz)	Flight path length (m)
GELINA	80 – 140	U	1	40 – 800	10 – 400
KURRI	20 – 46	Ta	2 – 100	1 – 300	10, 13, 24
	7 – 32	Ta	100 – 4000	1 – 100	10, 13, 24
nELBE	40	Pb	0.01	500000	4
ORELA *	140	Ta	2 – 30	1 – 1000	10 – 200
POHANG	75	Ta	1000-2000	12	11
RPI	60	Ta	7 – 5000	500	10 – 250

GELINA: Geel Electron Linear Accelerator; KURRI: Kyoto University Research Reactor Institute;
nELBE: neutron time-of-flight facility at Electron Linac for beams with high Brilliance and low Emittance;
ORLEA: Oak Ridge Electron Linear Accelerator; RPI: Rensselaer Polytechnic Institute.

Research programmes at electron-driven white spectrum neutron sources focus on reactions induced with neutrons at energies, which correspond to the so-called resonance region of the reaction cross-sections, e.g. transmission, capture, fission or inelastic scattering. Here the typical neutron energies range from the low eV up to a few MeV depending on the isotope under investigation. Electron-driven white neutron sources have excellent time-of-flight resolution, i.e. neutron energy resolution, and can provide a high selectivity for even individual resonances in a given neutron energy range. Energy resolutions at a flight-path length L of 12 m may be as good as 1% to 2%. Of course, the choice of L is always a compromise between TOF resolution and neutron flux on the target under investigation. For details on different experimental programmes and achievements the reader is directed to refer to the individual papers in this report and references therein.

3.4. SPALLATION PROTON-INDUCED (> 200 MEV) WHITE SPECTRUM NEUTRON BEAMS

Spallation via high energy protons incident on a heavy target (typically Hg, W or Pb) is a very efficient mechanism for the production of high energy neutron. Depending on the characteristics of the target, 1 GeV protons may produce more than 20 neutrons per incident proton, increasing linearly in the incident proton energy. It is for this reason that the last decade has seen and increasing number of neutron spallation source facilities, with more to come in the next years. The largest projects using spallation as neutron source for, mainly, material science studies are SNS (USA), ESS (Europe), J-PARC (Japan) and CSNS (China). However, this document is focused only in those used for nuclear data measurements.

The high neutron fluxes produced in spallation sources offer excellent performances when coupled to time-of-flight beam lines. In these experiments, the initially fast neutron spectrum is usually moderated with a light material such as water or polyethylene resulting in pulsed white neutron beams that can be used, for instance, to perform neutron induced reactions experiments. In comparison to electron-driven neutron sources, spallation sources provide neutrons with energies higher than 20 MeV which is the limit of electron-driven neutron sources. They also provide higher instantaneous neutron fluxes (neutrons/pulse).

As of 2013, the four spallation time-of-flight facilities that are devoted to measure neutron-induced capture and fission cross sections data in the world are n_TOF [20] at CERN (Switzerland), LANSCE (DANCE and WNR) [21, 22] at LANL (USA), ANNRI [23, 24] at J-PARC (Japan) and GNEIS [24] at PNPI in Russia. A few more are planned or even under construction, for instance n_TOF-EAR2 [25] at CERN. The performances of these facilities are very different and therefore a fare and complete comparison is not possible; however, Table 5 provides some of the characteristics of each of these facilities. Overall, the proton beam energies vary between 150 MeV and 20 GeV with frequencies from 0.4 Hz to 30 Hz and flight paths that range up to 185 meters. The question of the energy resolution is not mentioned in the table because it is not an easy comparison. In brief, the shortest the pulse width and the longest the flight path, the better energy resolution; without forgetting that the structure of the proton pulses and the geometry of the spallation target play also a significant role.

The neutron flux at the sample position for the three already existing facilities is displayed in Fig. 21 a, b where both the time averaged ($cm^{-2} \cdot s^{-1}$) and instantaneous ($n \cdot (cm^2 \cdot pulse)^{-1}$) values are given. Both values are important, being better the high integrated flux when measuring small mass samples and being more important to have a high instantaneous flux when measuring high activity radioactive samples.

TABLE 5. MAIN CHARACTERISTICS OF SOME OF THE EXISTING AND PLANNED TIME-OF-FLIGHT FACILITIES BASED ON SPALLATION

Facility/Laboratory	(p^+) [GeV]	p^+ pulse width (ns)	Freq. (Hz)	Target	Moderator	Flight Path [m]	Energy range
n_TOF/CERN	20	6	4	Pb	Yes	185	25meV – 1GeV
DANCE/LANSCE/LANL	0.8	250	0	W	Yes	20	25meV – 1MeV
WNR/LANSCE/LANL	0.8	0.15	40	W	No	10	0.1 – 400 MeV
ANNRI/J-PARC	3	100	25	Hg	Yes	22	25meV – 100 keV
GNEIS/PNPI	1	10	50	Pb	Yes	35-50	1eV – 200 MeV
n_TOF-EAR2/CERN*	20	6	0.4	Pb	Yes	20	25meV- 300 MeV
ISIS	0.81	100	50	W	These are multi-purpose/high-intensity spallation neutron sources not used (as of today) for nuclear data time-of-flight measurements.		
SNS	1	~1000	60	Hg			
CSNS*	1.6	468	25	W	* Under construction, ** Planned		
ESS**	2.5	2860	14	W			

n_TOF/CERN: European Organization for Nuclear Research; DANCE: Detector for Advanced Neutron Capture Experiments; LANSCE: Los Alamos Neutron Science Centre; LANL: Los Alamos National Laboratory; WNR: Weapons Neutron Research; ANNRI: Accurate Neutron-Nucleus. Reaction measurement Instrument; J-PARC: Japan Proton Accelerator Research Complex; GNEIS: Gatchina neutron time-of-flight spectrometer; PNPI: Petersburg Nuclear Physics Institute; EAR2/CERN: Experimental Area 2/CERN; ISIS: ISIS is not an acronym. It refers to the Ancient Egyptian goddess; SNS: Spallation Neutron Source; CSNS: China Spallation Neutron; Source; ESS: European Spallation Source.

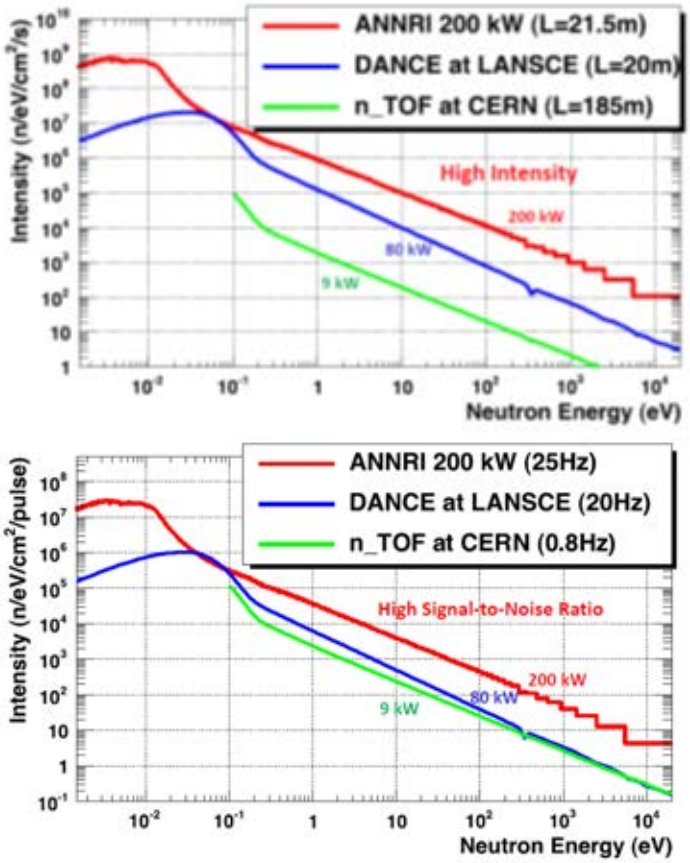


FIG. 21. Time-averaged (top), and instantaneous (bottom) neutron flux of the selected three spallation time-of-flight facilities.

Since spallation sources provide a very high instantaneous neutron flux compared to other facilities, the associated experimental programmes are mainly focused on measuring neutron induced reactions on radioactive samples, where the large intrinsic background from the sample's activity may be overcome by the high instantaneous neutron flux. Taking into consideration only the measurements related to nuclear data for nuclear technology, the measurements performed in these facilities since their construction are presented elsewhere in this report (see individual contributions under this topic in the attached CD-ROM).

3.5. NEUTRON BEAMS FROM INVERSE KINEMATIC REACTIONS

In standard reactions used for neutron production, where protons or deuterons are impinging on heavier targets made from deuterium, tritium, lithium or beryllium neutrons are emitted essentially in 4π. Whilst these reactions allow using high-intensity particle beams, with currents typically up to 50 μA, about 99% of the neutrons do not interact with the sample atoms under investigation but contribute only to background through reactions in structural materials and after room-scattering in the sample.

When using the heavier reaction partner as incident beam on a hydrogen-containing target, neutrons are emitted in a relatively small angular cone. Although the maximum ion-beam current applicable to hydrogen-containing targets is much lower, typically of the order of 100 nA, the neutron flux on target can reach levels comparable with those from standard neutron-producing reactions. Most of the possible reactions were investigated in the past by

M. Drosg and compiled in Ref. [26] but have never been applied to neutron production for nuclear data measurements.

The use of inverse reactions with ^{7}Li (or ^{11}B) beams to produce kinematically focused, mono-energetic neutrons by bombarding actinide targets offers some distinct advantages. First, neutrons from, as example, the p(^{7}Li,n)^{7}Be reaction can be focused into a forward cone of between 5 and 25 degrees depending on the incident energy of the incoming ^{7}Li beam. As a consequence, the kinematic focusing increases the available neutron flux over the non-inverse reaction by a factor of typically 30. At the same time, the background from neutron scattering in the room decreases by a similar factor. Only objects (e.g. concrete walls) in the path of the forward-focused cone will scatter neutrons. And, such a neutron beam allows placing gamma-ray detectors outside the neutron cone relatively close to the reaction target. This leads to an increase of geometrical efficiency at a considerably reduced risk to suffer from neutron-induced radiation damage. Thus no thick shielding is needed to protect gamma detectors from the neutron source background of up to 10^{7} neutrons per second (n/s) that occurs with mostly isotropic reactions such as ^{7}Li(p,n). Worth to mention here, that a neutron source based on kinematic focussing provides a much better figure of merit with respect to radioprotection issues due to a directional dose distribution.

LICORNE is a new facility for neutron production recently installed at the IPN Orsay. The ability of the 15 MV tandem accelerator at the IPN to produce intense beams of ^{7}Li, currents up to 200 nA in continuous or 50 nA in pulsed mode, is exploited to run the p(^{7}Li,^{7}Be)n reaction in inverse kinematics. Available neutron energies range from 500 keV to 4 MeV with neutron cone opening angles ranging from 5 – 25 degrees depending on the ^{7}Li bombarding energy. In this energy range the neutron beams are quasi-monoenergetic. The upper limit is given by the first excited state in ^{7}Li at 478 keV. Using thick hydrogen targets a white beam over the full range of accessible neutron energies can be produced with high intensity using pulsed ^{7}Li beams in conjunction with the neutron time-of-flight technique. Details on the facility, which, during the preparation of the technical report, started up operation, are provided in the attached CD-ROM.

4. COMPLEMENTARY REACTIONS FOR NUCLEAR DATA MEASUREMENTS

In recent years nuclear data needs for minor actinides and very neutron-rich nuclei highly radioactive isotopes attracted particular attention. Minor isotopes, like americium and curium, are relevant for spent fuel and neutron-rich nuclei of astrophysical interest and the understanding of the element synthesis. Either these isotopes are extremely radioactive or they are not available in sufficient quantities required in experiments. In consequence it is difficult or even impossible to obtain nuclear data by using neutron beams and other complementary techniques have to be considered.

In case of neutron-capture cross-section measurements on a very radioactive or scarce isotope with mass A the inverse photo-neutron cross-section on the isotope A+1 may be measured instead. For such an experiment two different photon sources are available.

The first type of source produces a photon beam by MeV-electrons hitting a converter material, e.g. Cu or W. The obtained so-called bremsstrahlung-spectrum is continuous from the maximum available photon energy, determined by the energy of the electron beam, down to zero. The cross-section values have to be deduced by using the unfolding technique (see e.g. [27-29]).

The second type of source employs an electron storage ring operated at energies typically around 1 GeV. It drives a free electron laser with tuneable wavelengths in the optical range. The high photon density inside the optical cavity provides a large luminosity for Compton scattering processes between the polarized optical laser photons and the relativistic electrons in the storage ring. Compton scattered laser photons obtain by transformation to the lab system a forward-peaked Lorentz-boost by a factor of about 10^6 to 10^8 and form after collimation a nearly monochromatic completely polarized γ ray beam with tuneable energies between 5 and 200 MeV. For a γ ray energy of 5 MeV, the energy resolution after pure geometrical collimation is of the order of 1% (for details see e.g. [30, 31]).

Another possibility to obtain nuclear data for highly radioactive or scarce isotopes is to replace the reaction (1) $A + n \rightarrow (A+1)^*$ by a so-called surrogate reaction (2) $A + a \rightarrow (A+1)^* + b$ after which the decay by fission or decay to the ground state of the A+1 compound nucleus (CN) may be investigated. The reaction product b is used to determine the excitation energy of the decaying CN, which can be related to the equivalent incident neutron energy in (1) [32]. This complementary approach to neutron-induced reaction is sometimes the only way to obtain relevant nuclear data for the isotope A+1. However, compound nuclear formation probabilities may be different from (1) and (2) and has to be obtained based on nuclear theoretical predictions.

5. TARGETS FOR HIGH-QUALITY NUCLEAR DATA MEASUREMENTS

Striving for the highest accuracy in nuclear data measurements employs attention on counting statistics, optimum incident particle flux monitoring and/or the use of a well-determined reaction standard. Beyond that, an essential ingredient for obtaining high-quality nuclear data is the precise characterization of the sample under investigation. Beside the accurate mass determination other parameters like sample homogeneity, uniformity of its thickness, isotopic composition and elemental purity might considerably matter. In particular, target homogeneity and uniformity of thickness significantly simplify data evaluation.

In general we can classify samples in two categories, being either radioactive or non-radioactive. Either of them may require a different preparation technique as well as very specific ways of characterization. Depending on the nuclear reaction quantity, target shapes may be different. Additional support backings might be required, which are also subject to the required expertise.

A cross-section measurement consists of the detection of one or more reaction products. It may allow then using a relatively massive sample provided that the particle to be measured may leave the sample and reach the counting device. Still, after processing of the material to get it into the appropriate shape a high degree of homogeneity and uniformity must be assured. For the detection of very short range reaction products very thin layer of the target material is necessary which is usually not self-supporting. Then, deposition on a support backing must be considered [33, 34].

In nuclear fission experiment the interesting quantities are the fragment mass and kinetic energy distributions. This requires that both co-linearly emitted fission fragments are detected simultaneously with least energy loss in the sample. Therefore, the target layer must be thin, usually having an areal density between 10 $\mu g/cm^2$ and 300 $\mu g/cm^2$, and deposited on a very thin support backing so that both fragments may be detected and minimally affected when passing through. This is what we call a transparent or spectroscopic target. A

challenging characteristic of such targets is homogeneity of both target layer and support backing.

Thin target layers are needed for neutron production. Here the thickness of the target layer defines the neutron yield but also the energy distribution of the neutrons through the energy loss and straggling of the ion beam in the deposit. It is, therefore, the game to find the best compromise between neutron yield and width of the energy distribution according to the requirements set out by the investigated neutron-induced reaction.

Depending on the final shape and thickness of the target-backing assembly the characterization requirements may vary. In the following, we will present different methods used for the preparation of different kinds of samples usually employed in nuclear data measurements. Characterization techniques will be discussed in connection with the sample preparation method.

Presently, to our best knowledge, there are only three laboratories in Europe, which are producing thin actinide deposits for nuclear research: *Institut für Kernchemie*, Mainz University [34], *Institut de Physique Nucleaire*, Orsay [35, 36] and the *Joint Research Centre IRMM* of the European Commission [37]. Some special isotope targets may be produced in Russia and purchased via a company in Germany [38], however, at a restricted selection of techniques. Spectroscopy targets are only available for ^{252}Cf, and only when spectroscopic support foils are prepared at IRMM prior to sample deposition. A series of actinide targets produced at Technical University of Munich is still available; however, the sample preparation activities are not supported anymore. Those actinide targets were transferred to Debrecen and makes part of a photo-fission experiment campaign at the future ELI high-intensity photon source at the Institute Horia Hulubei Institute of Physics and Nuclear Engineering in Bucharest [39]. Similar target preparation laboratories are exiting on other continents. Unfortunately, these institutions were not represented in the IAEA Technical Meeting and references to their work are limited.

Actinide target preparation and purchase has become more and more difficult for the past two decades due to the increased safety and security requirements of radiation safety regulation bodies all around the world.

5.1. Sample preparation techniques

In general one distinguishes between radioactive and non-radioactive samples. Evidently, safety and security regulations will determine what element or isotope may be treated and converted into a target for nuclear data measurements. Next, one has to make a choice between a thick, self-supporting sample and a thin layer sample, deposited on a dedicated support backing. Accordingly the preparation technique and the characterization methods will be different.

A sample characterization aims at determining mass and area, i.e. the number of atoms per unit area at an uncertainty below 0.5% at 1σ. Furthermore, one has to know the level of impurities to an extent that the impact on the final result is smaller than 0.5%. In many applications the homogeneity of the sample thickness is important as well as the knowledge on the moisture content [33].

In the following we consider the situation that sample material is available at the desired isotopic composition or purity. Still, radioactive material, in particular fissionable actinides,

may require purification to clean from decay products. In this case a dedicated laboratory infrastructure is needed allowing chemical treatment of radioactive material, which is often labelled "hot radiochemistry".

Different target requirements are presented in the following and the associated production and characterization techniques. It should be noted, that this list may not be complete and reflects the range of samples produced at IRMM [40] but should compile expertise needed in the field of nuclear data measurements.

5.2. Thin layers from stable isotopes

Thin targets from stable isotopes, e.g. from natural or isotopic enriched lithium-fluoride, Au, ^{10}B and tristearin ($C_{57}H_{110}O_6$) are characterized by an areal density ranging from 10 to 300 $\mu g/cm^2$. The deposits extend of diameters between 5 and 125 mm. The material is deposited on Al, Ag, Au or stainless steel backings. Silicon wafers, Ta and polyimide foils may also be considered for some isotopes. The lithium-fluoride, Au and tristearin samples are prepared by vacuum deposition from a resistance-heated tantalum crucible [41]. The area of the layer on the substrate is defined by a mask, which permits a design allowing vacuum deposition on several substrates simultaneously. A quartz crystal oscillator monitors the thickness of the deposited layer during evaporation process.

The advantage of vacuum deposition is that the deposited layers are thin, homogeneous and uniform. The disadvantage is the very low yield because of high material losses during the deposition.

A special application of the vacuum deposition method is the preparation of metallic lithium targets for high-resolution neutron beam production. In order to prevent the rapidly oxidizing lithium from building brittle oxides or hydroxide compounds in the presence of water vapour or rest gas in an ion-beam line a protective layer has to be added in a second evaporation cycle without interrupting the vacuum [43].

The isotope ^{10}B requires another method, because of its high melting point of 2076 ^{o}C. Here the ^{10}B is heated by electron bombardment to melt and evaporate the material on its support backing. With this technique samples on Al, stainless steel or silicon wafers may be produced routinely.

The total mass of the thin deposited non-radioactive sample is characterized by difference weighing with accuracy within 10 μg. The total deposition area is determined from the diameter of the deposition mask measured with a calliper at a readability of 10 μm. The surface homogeneity quality of the deposits on massive (polished) backings is determined by means of atomic force microscopy (AFM) with an accuracy of 1 μm. In the special case of tristearin deposits the essential quantity is the number of hydrogen atoms, which is determined e.g. by combustion analysis [41, 42].

5.3. Thin actinide layers

For the production of targets for fission-fragment spectroscopy and cross-section measurements and the requirement of having thin deposits with areal mass densities below 300 $\mu m/cm^2$ two techniques are employed, either vacuum deposition or molecular plating.

The first one is suitable for spectroscopic targets on ultra-thin backings of Al and stainless steel and also plastic foils like e.g. polyimide. Molecular plating is only possible on electric conductive "massive" support backings and not on those extremely thin foils, because of too much mechanical stress during the process which leads to the destruction of the backing.

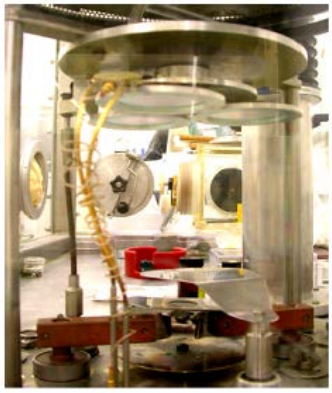


FIG. 22. Vacuum deposition equipment with three target holders for simultaneous deposition.

5.4. Vacuum deposition

For example vacuum deposition of ^{235}U is done at IRMM by sublimation of $^{235}UF_4$ from a resistance-heated tantalum crucible [40]. The original U_3O_8 is converted into a fluoride by a so-called "wet chemical precipitation" [43]. Fluorides have the advantage that the sublimation temperature is between 1000°C and 1500°C. Therefore, they may be deposited even on heat sensitive substrates used as backing materials. By contrast, oxides sublimate above 2500°C. The vacuum-deposition equipment, as shown in Fig. 22, was designed at IRMM. It consists of a tantalum crucible connected to a power supply in a closed vacuum chamber, which is connected to a pump system. Substrates and masks are mounted on a planetary rotating frame on a carrousel in the chamber. It permits simultaneous evaporation of several support backings; here e.g. on three support backings, at a maximum circular active deposit with diameter 70 mm. The thickness is monitored with a quartz crystal oscillator during the evaporation process. The whole set-up is placed in a glove box.

The advantage of vacuum deposition is that the deposited layers are thin and homogeneous [44, 45]. On the other hand there is a decrease of the material distribution from the centre to the edges which is of the order of 5% for deposits with a diameter of 70 mm [45]. The disadvantage of vacuum deposition is the low yield and the associated high loss of material during the evaporation/sublimation. In addition, practically for each (actinide) isotope a separate evaporator in a dedicated glove box has to be foreseen to avoid cross contamination.

5.5. Molecular plating

This method is relatively simple and a high-yielding method for producing thin-layer targets. The layers are formed due to the movement of ions in a solution when an electrical field is applied. At IRMM this method is based on cathode deposition of actinides e.g. $^{233\text{-}236,238}U$, ^{237}Np, $^{241,243}Am$ and $^{238\text{-}242}Pu$ deposited on Al backings from isopropanol [46, 47]. Active diameters of 80 mm are possible. Deposition yields of nearly 100% can be achieved

depending on the material. Due to the excellent adherence targets with a thickness in the mg/cm^2 range may be prepared.

In Fig. 23, ^{241}Pu target is shown, which was produced by means of molecular plating. The target was recently used for the measurement of prompt fission gamma rays in thermal-neutron induced fission of ^{242}Pu. Details on the molecular plating of plutonium isotopes may be found in Ref. [47, 48].

Compared to vacuum-deposited layers molecular-plated targets are, in general, less homogeneous. Furthermore, target substrates must be electric conductive. Finally, the final chemical composition of the deposit is not known well, but is assumed to be a hydroxide.

The total mass of the thin radioactive sample is calculated from its activity, which is measured by means of low-geometry α-particle counting. Also the sample homogeneity is checked with this counting method using a collimator placed at a small distance on top of the sample [45]. The isotopic composition is determined by thermal ionization mass-spectrometry (TIMS) of the batch prior to target preparation [49, 50].

5.6. Stable targets

Stable massive targets are prepared by mechanical transformation techniques. The reshaping may be done by means of rolling, cutting, wire drawing, punching and pressing.

With the rolling technique Al, other metals and also depleted uranium and thorium may be transformed into foils with a characteristic thickness between 0.05 and 1 mm.

In a subsequent step metal discs may be produced by punching provided the material has a maximum thickness of 0.3 mm. Discs with sizes from 1 up to 100 mm diameter may be produced by this technique.

Metallic wires as thin as 0.5 mm can be produced by a technique called wire-drawing. In different steps the metal piece is reduced to a diameter of 3.5 mm and later, by steps of 1 and 0.1 mm, to a minimum diameter of 0.5 mm. Before beginning the reduction process the metal piece has to be annealed to lower the risk of breaking.

Another shaping technique is the pressing technique. Here powders can be canned, whether or not pressed in a container. Some powders can be compacted directly; others need a binder to result in mechanically stable pellets.

Some interesting details on the different mechanical transformation techniques may be found in Ref. [39, 40]. Targets are characterized for their mass, thickness and diameter. The first one is done by weighing with a readability of 10 μg and the other two by measuring with a calliper or micrometer.

5.7. Thin foils as backings for spectroscopic targets

For fission-fragment spectroscopy the deposited material must be very thin. Also the support material should avoid absorption and keep energy loss as low as possible. Still the support should be sufficiently stable for handling whilst mounting the sample into the measurement device, e.g. into an ionization chamber.

The material of choice is polyimide, from which foils with an areal density from 100 μm/cm^2 down to 25 μm/cm^2 may be prepared by in-situ polymerization on glass plates [51-53]. More details on the preparation of polyimide foils may be found in Ref. [54]. After production on the glass plate the foil is cut in requested sizes and floated on a water surface before final transfer onto the Al-ring. A set of final polyimide support backings is shown in Fig. 24.

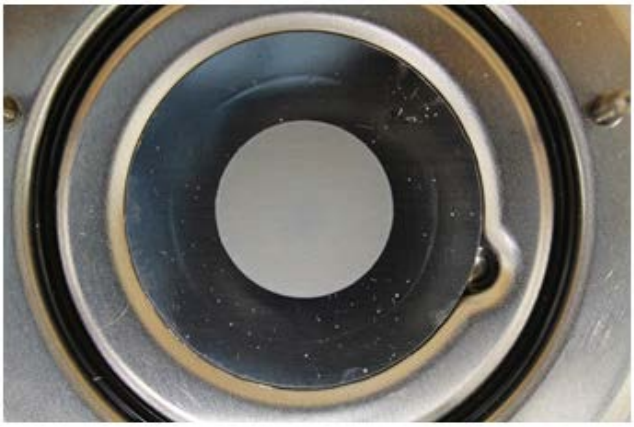


FIG. 23. ^{241}Pu deposited on a 2.5 mm thick aluminum backing (40 mm diameter) by means of molecular plating. The active (white) spot has a diameter of 20 mm.

FIG. 24. Polyimide foils mounted on an aluminum ring.

The areal density of the polyimide foils is measured with a photo-spectrometer [55-57]. This instrument measures the amount of light which is transmitted, absorbed or reflected by the foil. The method has to be calibrated before with a polyimide foil characterized by another method, e.g. by measuring the energy-loss of α-particles having passed through the foil.

5.8. Summary on targets

One very important pre-requisite for precise nuclear data measurements is the quality of the isotopic sample under investigation. Many different factors may affect the accuracy of a measured physical quantity, as e.g. a cross-section value or a transition probability. As it was elaborated in this chapter, many different techniques have to be employed to assure sample purity and homogeneity, mass determination, isotopic enrichment as well as isotopic composition. Especially for the precise investigation of fission-fragment parameters,

production yield and kinetic energy distribution, also the quality, thickness and uniformity of the sample backing are of utmost importance.

At the end, or, in fact at the beginning, the availability of sample material should be assured. Since many, in particular, trans-uranium isotopes result from production chains established for military purpose during the cold war, trading such materials is still strongly hampered.

Needless to stress, that those resources for the preparation of the different types of samples have to be available. Sample purification requires licensed laboratories with expensive infrastructure to perform the necessary "hot radiochemistry". In times of restricted budgets one should consider European- or even worldwide networks, where dedicated labs would be responsible for non-radioactive or radioactive sample preparation. For the latter both isotope specific and deposition technique related distribution amongst different laboratories might be considered, certainly to prevent the risk of cross-contamination. The unbeatable advantage of such a concept would be assuring highest competence of each dedicated laboratory staff at most cost efficient production, research and development. Therefore, a work package (WP3) has been defined in the project FP7 CHANDA (solving CHAllenges in Nuclear Data, FP7-EURATOM 605203) dedicated to the coordination of the development of a network for nuclear target preparation and characterization.

6. INSTRUMENTATION AND DATA ACQUISITION FOR NUCLEAR DATA MEASUREMENTS

This summary describes instrumentation and data acquisition for modern nuclear data measurements. In particular, we focus on systems for detecting neutrons, γ-rays and/or fission products in nuclear data measurements for neutron-induced reactions.

In most of the neutron detection methods, neutrons are commonly converted to detectable charged particles through neutron-induced reactions such as $^{1}H(n,n)^{1}H$, $^{3}He(n,p)^{3}H$, $^{6}Li(n,t)^{4}He$, $^{10}B(n,\alpha)^{7}Li$, $^{235}U(n,f)$. These neutron-induced reactions are used in proton recoil counters, ^{3}He proportional counters, ^{6}Li-glass scintillation detectors, BF_3 counters and fission ionization chambers. The neutron-induced reactions except for $^{1}H(n,n)^{1}H$ have high positive Q-values, resulting in large signal outputs of neutron events. Detectors based on these high Q-value reactions can be used in the wide energy range from thermal to fast neutron energies. Detectors using recoil protons from the elastic scattering $^{1}H(n,n)^{1}H$ can be used for only fast neutrons above a few tens keV. However recoil proton counters have one advantage that neutron spectra can be derived by unfolding the output pulse-height distribution with the detector response function (see contributed paper: Gritzay et al. and Anh et al.). For detection methods based on the high Q-value reaction, time-of-flight measurement is necessary to measure the neutron energy distribution. Recent developments of spallation neutron sources have caused a need for new neutron detectors [58, 59]. A MicroMegas neutron detector developed for monitoring the neutron beam from the CERN n_TOF spallation neutron source [59] has shown good performance as a transparent neutron detector. A neutron detector using the pixelated solid state sensor Medipix is under development [60]. For detection of scattered neutrons, arrays of liquid scintillation detectors have been constructed [61, 62].

Gamma-ray detection is done with scintillation detectors and semiconductor detectors. Recent trend of γ ray detection for (n,γ) measurements is to use large detector arrays. Several groups have used BaF_2 detector arrays as total absorption calorimeters for (n,γ) cross section measurements (see contributed paper Guerrero *et al.*). A total absorption calorimeter detects multiple γ rays and discriminates background events, based on the fact that the energy sum of

γ-rays from each capture event is equal to the sum of the neutron binding energy of the target nucleus and the incident neutron energy. Detector arrays of Ge detectors have also been constructed (see contributed paper: Katabuchi *et al.*). While a Ge detector array hardly becomes a total absorption calorimeter due to its lower detection efficiency than BaF_2 detector arrays, the superior energy resolution of Ge detectors allows for high-resolution γ-ray spectroscopy. In addition to the large detector arrays, the pulse height weighting technique (PHWT) [63] using a single detector is still useful as a reliable, established method.

Deuterated benzene (C_6D_6) detectors have been widely used for PHWT (see contributed paper: Guerrero *et al.*). NaI(Tl) detectors are also well-suited for this purpose (see contributed paper: Katabuchi *et al.*). Among potential next generation γ-ray detectors, $LaBr_3$(Ce) scintillation detectors are appealing [64].

Detection of fission fragments is important for the study of neutron-induced fission reactions. The methods for the detection of fission fragments can be categorized in two groups. One method is to detect fission products with gaseous detectors. The other method employs solid-state detectors. In both cases, energy loss of fission products is minimized. In the gaseous detector type, ionization chambers and parallel plate avalanche counters (PPAC) are widely used as fission fragment detectors (see contributed paper: Mondelaers *et al.*) [65, 66]. A sample of a thin layer of fission material is placed inside the gaseous detector. To improve counting statistics, multiple samples are often inserted. In a recent development, a MicroMegas detector for fission experiments was developed (see contributed paper: Vlastou, Chiaveri *et al.*).

In the solid state type, photovoltaic cells and silicon surface-barrier detectors have been used [67, 68]. A fission sample and solid-state detectors are placed in a vacuum chamber. Photovoltaic cells are suitable for fission fragment detection because they are radiation resistant, insensitive to γ rays and light charged particles, and available at low cost. To study physical properties of fission fragments other than production yields, on-line mass separators are useful because of their mass and charge selectivity (see contributed papers: Shibata *et al.* and Lantz *et al.*).

The technique of coincidence detection between particles (e.g. neutron vs. fission, γ vs. γ, γ vs. fission) is useful to select certain reaction chains and to suppress ambient background. An example of recent coincidence measurements is a prompt fission neutron spectrum measurement made by detecting neutrons from fission events tagged with a PPAC fission target [69].

Recent development of digital signal processing offers more flexible design of data acquisition systems. Conventional analogue devices such as shaping amplifiers, discriminators and coincidence modules can be replaced with on-chip digital signal processors (DSP). Electronics for signal processing and data acquisition can be simplified. In addition, it is possible to record raw detector signals for offline analysis with a DSP device called waveform digitizer. This allows for offline signal analysis more flexible than conventional analogue devices [70, 71]. Digital offline analysis methods using waveform digitizers such as pulse shape discrimination, particle identification and pile-up correction have been developed (see contributed papers: Khryachkov and Majerle) and also see Refs. [71, 72].

7. RESULTS, EVALUATIONS AND DISSEMINATION

The experimental data measured at various facilities worldwide provide a data base for the development and validation of nuclear reaction models and for production of the evaluated data libraries. The most complete and precise cross section data sets cover a large range of energies and isotopes and are eventually used in the practical applications.

To conserve original experimental data and to facilitate access of users, they are compiled and stored in the unique database EXFOR [73]. It contains cross sections and many other quantities for nuclear reactions induced by neutrons, charged-particles and photons. Currently the data are compiled for all low and intermediate energies ($E < 1$ GeV) and reactions induced by light ions ($A < 12$). However, heavy ions ($A \geq 12$) and photon-induced reaction data are also compiled in EXFOR on a voluntary basis. Currently, fourteen national data centres participate in the International Network of Nuclear Reaction Data Centres (NRDC) [73] and perform the compilation and exchange of experimental data in the specific exchange format under auspices of the IAEA Nuclear Data Section (NDS).

Due to such systematic and continues work of the Nuclear Reaction Data Centres - NRDCs in the past 50 years, the EXFOR database (EXFOR is the library and format for the collection, storage, exchange and retrieval of experimental nuclear reaction data) has accumulated more than 12,000,000 data points from more than 20,000 experimental works.

Based on the available measured data and advanced nuclear reaction models, evaluators perform assessment of reaction cross sections which are stored in the specific ENDF-6 format [74, 75]. Presently there are several national or international libraries for the general purpose use. The most known are Evaluated Nuclear Data File (ENDF/B-VII.1, USA) [75], Joint Evaluated Fission and Fusion File (JEFF-3.1, Europe) [76, 77] Japanese Evaluated Nuclear Data Library (JENDL-4.0, Japan) [77], Russian library of evaluated neutron data (ROSFOND, Russia) [78], China Evaluated Nuclear Data Library (CENDL-3.1, China) [79]. Since these libraries used similar experimental data and calculation tools or even sometimes copied the cross sections for some isotopes, they inevitably tend to converge.

To use resources and time efficiently, the nuclear data community now employs a new approach called Collaborative International Evaluated Library Organization (CIELO) pilot project [80]. It will bring together experts from across the international nuclear reaction data community to identify discrepancies among existing evaluated data libraries, measured data, and model calculation interpretations. It aims at making rapid progress in reconciling these discrepancies to create more accurate files. During the first three years, the project will focus on a small number of high-priority isotopes, namely ^{1}H, ^{16}O, ^{56}Fe, ^{235,238}U and ^{239}Pu.

Besides the general purpose libraries, the specific needs or practical applications require selected sets of data in the particular energy range or nuclei. Below are given a few typical examples of such data which were produced within Coordinated Research Projects or Data Development Projects leaded by NDS.

The standard nuclear reaction cross sections (Standards) [81] are the most precise cross sections often used as a reference values in the measurements of other cross sections: H(n,n) (1 keV to 20 MeV), ^{3}He(n,p) (0.0253 eV to 50 keV), ^{6}Li(n,t)^{4}He (below 2.8 MeV), ^{10}B(n,α_0)^{7}Li and ^{10}B(n,α_1)^{7}Li (below 1.0 MeV), C(n,n) (up to 1.8 MeV), ^{197}Au(n,γ)^{198}Au (from 4.8 keV to 2.6 MeV), ^{235}U(n,f) (from 25 keV to 200 MeV) and ^{238}U(n,f) (from 1 MeV

to 200 MeV). Standards have lowest uncertainties (0.5-2%) and are currently under further development aimed on the energy range expansion and inclusion of new reactions.

The International Dosimetry Library for Fission and Fusion (IRDFF) [83] is a set of 74 neutron activation reactions cross sections used for neutron spectral and total flux measurements in power and research reactors and accelerator driven neutron sources [82]. This library covers now 74 reactions in the energy range from thermal up to 60 MeV with several exceptions up to 200 MeV. It is worthwhile to note that all data in the IRDFF are derived from statistical analysis of the experimental data. The theoretical model calculations are used only for the extrapolation after normalisation to measured data. The standard and dosimetry cross sections are usually incorporated in the general purpose files.

The Ion Beam Analysis Nuclear Data Library (IBANDL) [84] is an example of the evaluated charged particle induced reactions. This is a set of elastic or gamma production differential cross sections at backward angles used in the material surface analyses. The excitation functions calculated with dedicated models fit the measured data rather well and reproduce resonance structure in MeV energy range which are not presented in general purpose evaluated files.

The typical way of data dissemination nowadays is the internet access to the Nuclear Data Servers hosted by Nuclear Data Section of IAEA [85], Nuclear Data Bank of NEA/OECD [86], National Nuclear Data Center of USA [87] and other organisations. These organisations store nuclear databases and develop retrieval tools that allow external users to receive experimental and evaluated data in different numerical formats or plot them for visualisation.

8. CONCLUSIONS

The IAEA technical meeting was highlighted as a successful and useful event by the meeting participants, representing both research reactor and accelerator based neutron source facilities involved in nuclear data measurements. The support for the meeting in terms of the number and diversity of participants as well as participating Member States is a significant indicator of the success of the broader endeavour to provide timely practical assistance and support the sharing of research reactor and accelerator based neutron source experience related to the provision of nuclear data, foster the development of new experimental techniques, establish international collaborations and facilitate exchange of information.

It was recognized that the IAEA has undertaken a number of activities, namely, management of various nuclear data libraries and databases, Coordinated Research Projects, Technical Meetings, workshops and schools and in some cases also Technical Cooperation (TC) projects to assist Member States in the domain of nuclear data measurements. Continuation and expansion, where appropriate, of such activities is desired and encouraged.

Acknowledging the prominence and success of nuclear data provision within the experimental programmes of research reactor and accelerator facilities, the meeting participants during the final discussion session drew several conclusions listed below**.**

Importance of experimental nuclear data: The following specific areas were identified with high importance for new or improved experimental nuclear data measurements:

- Reaction cross-sections and decay data relevant to production of medical and industrial radioisotopes, radiation therapy;

- Radiation effects in materials, components and systems, e.g. accelerator and reactor technology, space applications, natural radiation;
- Improved measurements of neutron cross-section standards including characterization of relevant targets;
- Improved measurements of reaction cross-sections, decay data and fission products of high importance for the nuclear energy sector, e.g. for fission and fusion reactors as well as nuclear waste reduction and management;
- Improved measurements of reaction cross-sections of high importance for nuclear astrophysics.

Complementarity: The importance of complementary nuclear data measurement facilities with diversity of on-going experimental programmes was recognized. On the other hand, some degree of overlap is unavoidable, which helps in a healthy balance between competition and complementarity to improve QA/QC practices and measures, and to ensure independent verification of experimental data. In the above context, creation of specific database on neutron beam facilities involved in nuclear data measurements would be beneficial.

Experimental programmes: Collaboration and coordination of experimental programmes among different nuclear data measurement facilities was clearly recognized in order to optimize joint efforts and reduce potential duplication in provision of high quality nuclear data for interested parties. Where international cooperation and projects already exist, continuation is encouraged.

Instrumentation: Continuous investment in development of the advanced instrumentation and data acquisition is recommended. This is necessary to achieve required uncertainties in limited experimental time, to adapt to high counting rates and highly radioactive sample environment. The experimenters should seek for registration of unprocessed detector signals and associated information for flexible post-experimental processing and analysis.

Targets: Issues related to the availability, provision and sharing of high quality/purity and, in some cases, radioactive experimental targets were emphasized, including requests for assistance and support from national and international authorities. Preservation/creation of specific laboratories and relevant database for sample preparation needs to be jointly considered to address sample provision issues.

Human resources and competence management: The need to preserve competence in the field of nuclear data measurements, modelling and evaluations is recognized for developed as well as for developing countries, both at the national and transnational level. Timely replacement of retiring staff and knowledge transfer is a common issue at most of the facilities, and it should therefore be treated with high attention. Organization of periodic technical meetings, education and training workshops/schools is necessary to ensure knowledge transfer and preservation.

Finance: Financial support from national governmental authorities and regional/international funding institutions was acknowledged, and it should therefore be continued as an indispensable source to cover the operational and running costs of experimental nuclear data measurement facilities, including their periodic modernization and upgrades.

Awareness: The need and importance of nuclear data measurements should be promoted in order to enhance awareness and facilitate requests for cooperation and support among the

Member States, national and international institutions. Preparation of a dedicated promotional brochures and flyers on the importance of nuclear data both in nuclear energy and non-nuclear energy applications is needed and therefore should be pursued.

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ABBREVIATIONS

ANITA	Atmospheric like neutrons from thick target
ANNRI	Accurate Neutron-Nucleus Reaction measurement Instrument
CARR	China Advanced Research Reactor
CENDL	China Evaluated Nuclear Data Library
CIELO	Collaborative International Evaluated Library Organization
CSNS	China Spallation Neutron Source
DANCE	Detector for Advanced Neutron Capture Experiments
EAR2/CERN	Experimental Area 2/CERN
ENDF	Evaluated Nuclear Data File
ESS	European Spallation Source
EXFOR	Exchange format for the transmission of experimental nuclear reaction
FRANZ	Frankfurt Neutron Source
FRM	Munich Research Reactor
GELINA	Geel Electron Linear Accelerator
GNEIS	Gatchina neutron time-of-flight spectrometer
HANARO	High Flux Advanced Neutron Application Reactor
HFR	High Flux Reactor
IGISOL	Ion Guide Isotope Separator On-Line
ILL	Laue-Langevin Institute
ISIS	ISIS is not an acronym. It refers to the Ancient Egyptian goddess
JEFF	Joint Evaluated Fission and Fusion File
JENDL	Japanese Evaluated Nuclear Data Library
J-PARC	Japan Proton Accelerator Research Complex
JRR	Japan Research Reactor

JYFL	Jyväskylä accelerator facility
LC & FNG	Laboratory of Cyclotron and Fast Neutron Generators
NDS	Nuclear Data Section
nELBE	Neutron time-of-flight at Electron Linac for beams with high Brilliance and low Emittance
NFS	Neutrons For Science
NIPS	Neutron-Induced Prompt gamma-ray Spectroscopy
NRDC	Nuclear Reaction Data Centres
ORLEA	Oak Ridge Electron Linear Accelerator
PGAA	Prompt Gamma Activation Analysis
PIAF	PTB Ion Accelerator Facility
PIF	Proton Irradiation Facility
PIK	Beam research complex (translated from Russian)
QA/QC	Quality assurance / quality control
ROSFOND	Russian library of evaluated neutron data
RRDB	Research Reactor Data Base
SARAF	Soreq Applied Research Accelerator Facility
SNS	Spallation Neutron Source
SPIRAL-2	Système de Production d'Ions Radioactifs Accélérés en Ligne -2
WNR	Weapons Neutron Research

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All contributed papers are available in the attached CD-ROM.

TOPIC 2: REACTOR BASED NEUTRON BEAM FACILITIES

2.1. COLD AND THERMAL NEUTRON BEAMS

Author	Affiliation	Title of the paper
Belgya, T.	Centre for Energy Research of the Hungarian Academy of Sciences, Hungary	Nuclear data measurements at the PGAA-NIPS facilities of the Budapest research reactor
Révay, Z.	Centre for Energy Research of the Hungarian Academy of Sciences, Hungary	Determination of partial gamma-ray production cross-sections in cold neutron beams
Köster, U.	Institut Laue Langevin, France	Precision Nuclear Data Measurements at Institut Laue Langevin
Furutaka, K.	Nuclear Science and Engineering Directorate, Japan	Prompt gamma-ray measurement facilities at Japan Research Reactor-3 (JRR-3)
Shibata, M.	Radioisotope Research Center, Japan	Measurements of decay data of fission products using Isotope Separator on-Line

2.2. FILTERED NEUTRON BEAMS

Gritzay, O.	Neutron Physics Department & Ukrainian Nuclear Data Center, Ukraine	Development of the Neutron Filtered Beam Technique for High Precision Nuclear Data Measurements
Anh T.	Nuclear Research Institute, Vietnam	The quasi-monoenergetic neutron spectra for nuclear data measurements on filtered neutron beams at DALAT research reactor
Hossain, S.	Institute of Nuclear Science and Technology, Bangladesh	Uses of monochromized thermal neutron beams for nuclear data measurements

TOPIC: 3. ACCELERATOR BASED NEUTRON BEAM FACILITIES

3.1. MONOENERGETIC AND MAXWELL SPECTRUM NEUTRON BEAMS (< 5 MEV)

Oberstedt, S.	Joint Research Centre, European Commission	Nuclear Research with Mono-Energetic NEUTRONS AT the JRC MONNET Facility
Nolte, R.	Physikalisch-Technische Bundesanstalt, Germany	Neutron beams and neutron metrology at the PTB ion accelerator facility PIAF and at the IThemba LABS neutron beam facility
Vlastou, R.	National Technical University of Athens, Greece	The neutron facility at the Athens Tandem Accelerator NCSR "Demokritos" and NTUA Research Activities
Murata, I.	Osaka University, Japan	Intense 14 MeV Neutron Source Facility (OKTAVIAN) at Osaka University
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Nishio, K.	Japan Atomic Energy Agency, Japan	Surrogate Reaction Study at the JAEA tandem facility
Tanimura Y.	Japan Atomic Energy Agency, Japan	Mono-energetic Neutron Fields Using 4 MV Pelletron Accelerator at FRS / JAEA
Khryachkov, V.	Institute for Physics and Power Engineering, Russian Federation	Neutron experimental facilities for nuclear data measurements at IPPE
Vanhoy, J.	University of Kentucky, USA	Measurements with Monoenergetic Fast Neutrons at the University of Kentucky Accelerator Laboratory
Lilley, S.	EURATOM, U.K.	Nuclear Data Capabilities at the ASP Neutron Generator

3.2. ION-INDUCED QUASI-MONOENERGETIC AND WHITE NEUTRON BEAMS

Katabuchi,T.	Tokyo Institute of Technology, Japan	Neutron capture cross section measurements in the keV energy region at the Tokyo institute of technology
Iwamoto, Y.	Japan Atomic Energy Agency, Japan	Quasi-monoenergetic Neutron Beam and Its Application at the RCNP Cyclotron Facility
Prokofiev, A.	Uppsala University, Sweden	High-energy Neutron Beam Facilities and Nuclear Data Measurements at The Svedberg Laboratory
Majerle, M.	Nuclear Physics Institute of ASCR PRI, Czech Republic	Fast neutron generators at Nuclear Physics Institute Řež

Ledoux, X.	Grand Accélérateur National d'Ions Lourds, France	The neutrons for science facility at SPIRAL-2
Sakemi Y.	Cyclotron and Radioisotope Center, Japan	High Intensity Fast Neutron Beam Facility at CYRIC
Lantz, J.	Uppsala University, Sweden	Design of a High Intensity Neutron Source for Neutron-Induced Fission Yield Studies

3.3. ELECTRON-INDUCED WHITE SPECTRUM NEUTRON BEAMS

Mondelaers, W.	Joint Research Centre, European Commission	Nuclear Data Measurements at GELINA
Junghans, A. R.	Institute of Radiation Physics, Germany	The NELBE Neutron Time-of-Flight Facility
Kim, G.	Pohang Neutron Facility, Republic of Korea	Activities for Nuclear Data Measurements using Pohang Neutron Facility
Hori J.	Research Reactor Institute, Japan	Nuclear data measurement at KURRI-LINAC

3.4. SPALLATION PROTON-INDUCED (> 200 MEV) WHITE SPECTRUM NEUTRON BEAMS

Ruan, X.	China Institute of Atomic Energy, Peoples Republic of China	Study of back-streaming white neutrons at CSNS for nuclear data measurement
Guerrero, C.	CERN, Switzerland	Nuclear Data experimental program at CERN for reactor physics
Chiaveri, E.	CERN, Switzerland	The N_TOF Facility at CERN: Status and Perspectives
Shcherbakov, O.A.	Petersburg Nuclear Physics Institute, Russia	Spallation neutron source of the TOF-facility GNEIS in Gatchina
Katabuchi, T.	Tokyo Institute of Technology, Japan	Nuclear Data Measurement Using the Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) in the Japan Proton Accelerator Research Complex (J-PARC)

3.5. NEUTRON BEAMS FROM INVERSE KINEMATIC REACTIONS

Oberstedt, S.	Joint Research Centre, European Commission	Nuclear Research with Quasi Mono-Energetic Neutrons at the IPNO LICORNE Facility

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