SPALLATION NEUTRON SOURCE AT THE 1 GeV SYNCHROCYCLOTRON OF PNPI

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Abstract

A description of the spallation pulsed neutron source and neutron TOF spectrometer GNEIS based on the 1 GeV proton synchrocyclotron of PNPI in Gatchina is presented. The main parameters of the GNEIS are given in comparison with the analogous world-class facilities. The experimental capabilities of the GNEIS are demonstrated by the examples of some nuclear physics and applied research experiments carried out during four decades of its operation.

DESCRIPTION OF NEUTRON SOURCE

The 1 GeV proton synchrocyclotron SC-1000 at the PNPI was commissioned in 1970 [1]. A few years later (1975), spallation neutron source and TOF spectrometer GNEIS have been developed at the accelerator and put into operation [2]. Since that time GNEIS was effectively used for neutron-nucleus interaction studies utilizing the time-of-flight technique over a wide range of neutron energies from thermal up to hundreds of MeV, both for basic nuclear physics and applied research.

The water-cooled lead target (40×20×5 cm^3) of the GNEIS neutron source is located inside the accelerator vacuum chamber (Fig. 1) below the median plane of the accelerator magnet magnetic field.

When the circulating proton bunch is deflected to strike the target, the short (~10 ns) pulses of fast neutrons are produced at a repetition rate of ≤50 Hz. At the average internal proton current of 3 μA and neutron yield of ~20 n/p for 1GeV protons, the average intensity of fast neutrons is equal to ~$3\cdot10^{14}$ n/s. Neutron source is supplied with a polyethylene moderator (30×10×5 cm^3) located above the target and median plane. The target and moderator are moved remotely in vertical and radial directions for optimum position during the accelerator and neutron source tuning. Five neutron beams are transported using evacuated flight tubes through the 6 m thick heavy concrete shielding wall of the accelerator main room into the experimental hall of the GNEIS. The beams are equipped with brass/steel collimators, steel shutters and concrete/steel beam dumps. Measurement stations for experimental installations are located in the GNEIS building (15×30 m^2) at the flight path distances of 35-50 m. Neutron beams #1- 4, whose axes pass through the moderator, are characterized by a $1/E^{\alpha}$ (α = 0.75-0.95) neutron spectrum shape (Fig. 2) being well suited for measurements at resonance energies (1 eV – 100 KeV). Neutron beam #5, whose axis “looks” at the surface of “bare” lead target, has a typical spectrum shape with spallation and cascade components in the neutron energy

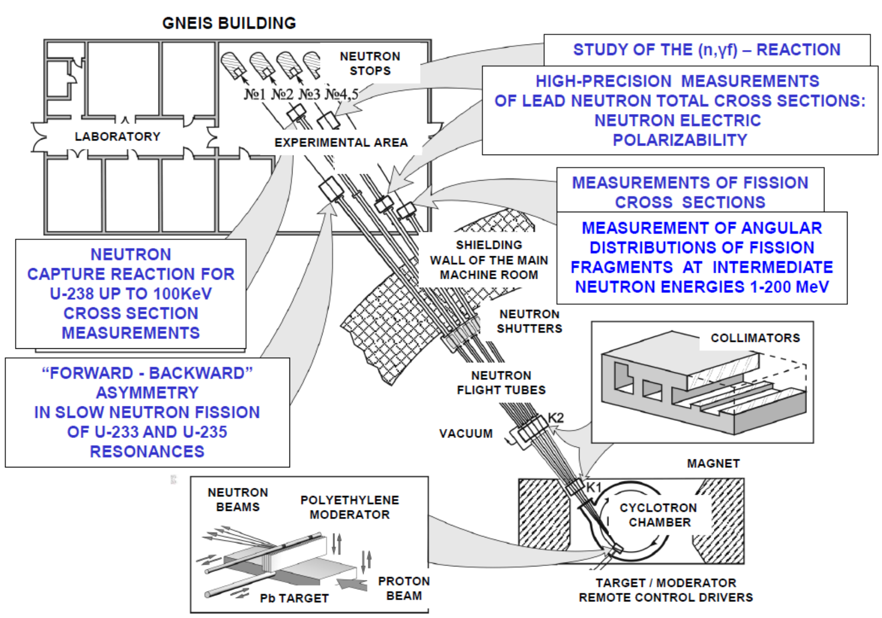

Figure 1: General layout of the GNEIS facility.

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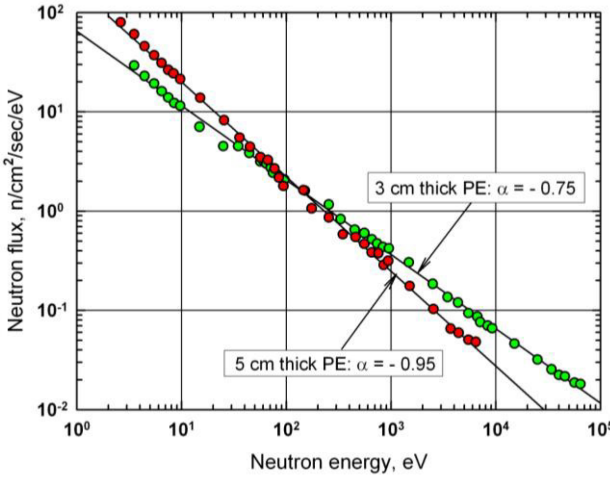

Figure 2: The neutron spectra of the beam #3 measured at the 40 m flight path station with 3 cm and 5 cm thick polyethylene (PE) moderators. The data are normalized to an average neutron production rate of $1.5{\cdot}10^{14}$ n/s.

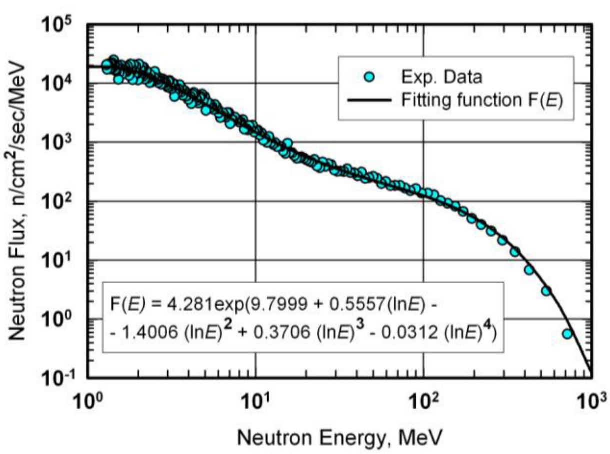

Figure 3: Neutron spectrum from the "bare" lead target measured at the 36.5 m flight path station of the beam #5. The data are normalized to an average neutron production rate of $2.5{\cdot}10^{14}$ n/s.

range 0.1-1000 MeV (Fig. 3). The cascade component extends up to the energy of the incident protons (1 GeV) and is strongly peaked in the forward direction. The evaporation component which is dominant below ~ 20 MeV has the shape of a Maxwell distribution with a characteristic temperature of 1-3 MeV and is practically isotropic.

For non-relativistic neutron energies below ~ 10 MeV, the commonly used expression for evaluation of the energy resolution of a neutron TOF-spectrometer is

$$\Delta E / E = 2.78 \cdot 10^{-2} E^{1/2} (\Delta t / L), \tag{1}$$

where E (eV) is the neutron energy, L (m) is the flight path length and Δt (μs) is the total timing uncertainty. It is convenient to approximate the resolution function by a Gaussian-type curve

$$R(E / E') = \frac{1}{W\sqrt{\pi}} \exp\left(-\frac{(E-E')^2}{W^2}\right). \tag{2}$$

The relation of the practically used quantity H (full width at half-maximum) and parameter W is defined by

$$H = 2W\sqrt{\ln 2}. \tag{3}$$

The basic components of the total width of resolution function are as follows

$$W^2 = W_D^2 + W_M^2 + W_T^2, \tag{4}$$

where W_D is the width of Doppler broadening due to the thermal motion of investigated nuclei, W_M is the moderator contribution, and W_T is determined by the various timing uncertainties, such as the neutron burst width τ_n, the TDC's channel width τ_{ch}, the electronic jitter τ_j, etc. The energy resolution of the GNEIS (relative half-widths of the resolution function) and its basic components are shown in Fig. 4 for the 40 m flight path length, the 5 cm thick PE moderator, and the accelerator burst width of 10 ns. For comparison, the resolution functions for similar TOF facilities with 100 ns and 1μs neutron burst widths are also shown. It should be noted that inclusion of other timing uncertainties mentioned above leads to the broadening of resolution function.

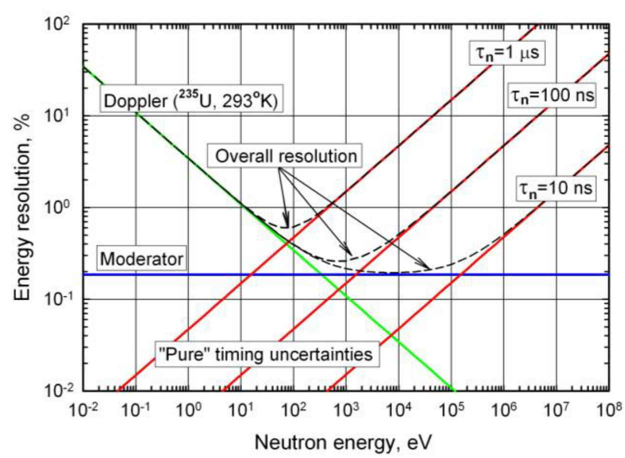

Figure 4: The energy resolution of the GNEIS facility.

COMPARISON WITH OTHER FACILITIES

At present, on the European neutron landscape, 4 pulsed neutron sources located in Russia can be specified, namely: GNEIS (Gatchina), IREN and IBR-2 (Dubna), IN-06 (Troitsk). Currently, only first 2 facilities are used for neutron resonance TOF spectroscopy and only the GNEIS can effectively compete with the best neutron sources/TOF facilities operated in other countries. In a Table 1 below, a comparison of the GNEIS with the

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world-class facilities is given. It should be emphasized that the GNEIS and other spallation neutron sources have much higher upper limit of neutron spectra (up to 1 GeV) than those based on the electron Linacs (below 100 MeV). This feature makes spallation neutron sources indispensible for investigations at intermediate energies (several hundred MeV).

Table 1: Parameters of the GNEIS and other neutron sources. The quality coefficient of the neutron source is defined as: intensity/(pulse width)^2. The quality coefficient value marked by $^{*)}$ corresponds to 10 ns pulse width.

Neutron source (laboratory)	Intensity (10^{15} n/s)	Pulse width (ns)	Quality (10^{30} n/s^3)
GNEIS (PNPI, Gatchina, Russia)	0.3	10	3.0
IREN (JINR, Dubna, Russia project)	1.0	400	0.0062
n_TOF (CERN, Switzeland)	0.4	6	11
LANSCE (LANL, USA)	10	1-125	$100^{*)}$
ORELA (ORNL, USA)	0.13	2-30	$1.3^{*)}$
GELINA (IRMM, Belgium)	0.025	1	25

EXPERIMENTS AT THE GNEIS

High intensity and energy resolution of the GNEIS enable to perform measurements of neutron total and partial cross sections (e.g. capture, fission, etc.) with high precision and reliability. In the inserts of Fig. 1 are shown titles of the main experiments carried out at the GNEIS. The first one was dedicated to study of the (n,γf)-reaction in ^{235}U and ^{239}Pu in energy range 1-200 eV, which means a neutron-induced fission after preliminary emission of one or more γ-quanta [3-5]. In the other experiment, a so-called "type-II" 720 eV-resonance was investigated in the subthreshold fission of ^{238}U [4]. An accuracy of the cross section measurements of the next experiment was increased from 1-2% to 0.2-0.5 % with the aim to evaluate effect of "forward-backward" asymmetry of fission fragments and parameters of the very weak p-resonances non-observed by usual methods in slow neutron fission of ^{233}U and ^{235}U [6, 7]. A value of neutron electric polarizability was reliably obtained from the results of high-precision measurements of the total cross sections of lead isotopes ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb below 10 keV [8, 9]. The unique experimental data for a number of actinides (^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{243}Am) and non-fissile nuclei (^{nat}Pb, ^{209}Bi, ^{nat}W) have

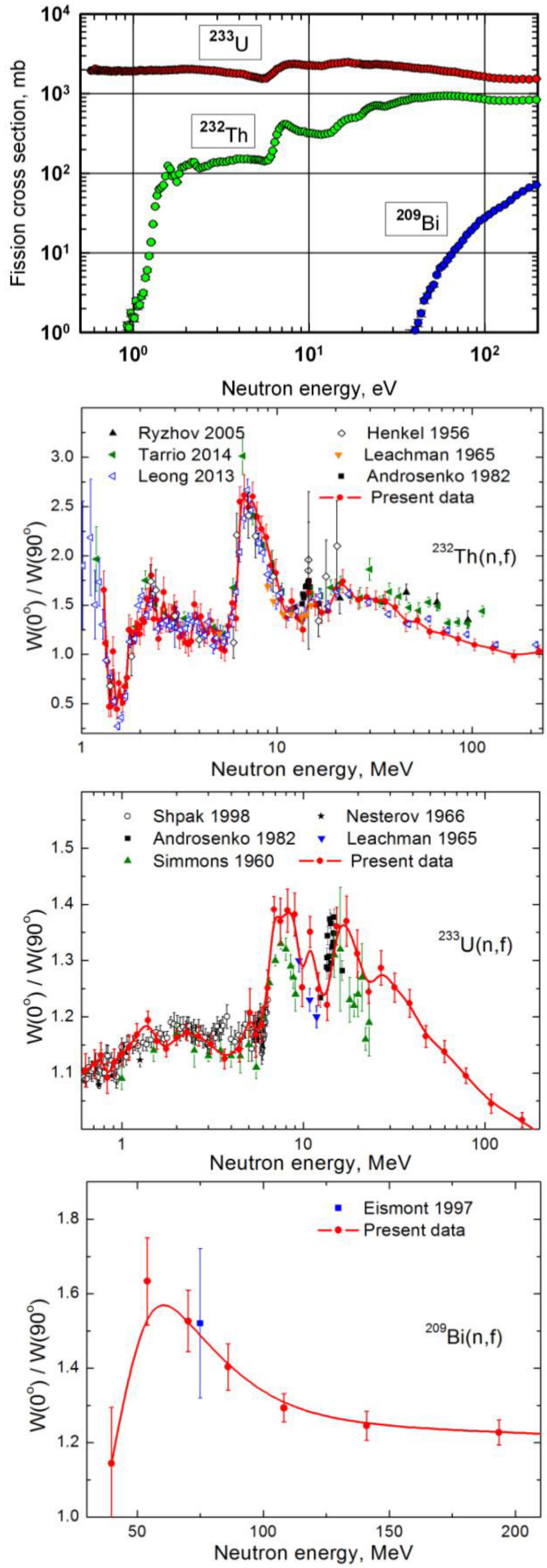

Figure 5: Fission cross sections and fission fragment anisotropy measured at the GNEIS spectrometer.

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been obtained from the measurements of fission cross sections [10-12] and fission fragment anisotropy [13,14] in the energy range 1-200 MeV (Fig. 5), where the GNEIS facility successfully competes with LANSCE and n_TOF. During the last years, a neutron beam #5 of the GNEIS with atmospheric-like neutron spectrum is intensively used for SEE (single event effect) radiation testing of the electronic components.

NEUTRON TEST FACILITY

The ISNP/GNEIS test facility is operated since 2010 at the neutron TOF-spectrometer GNEIS [15, 16]. The main feature of this facility is a neutron spectrum resembling that of terrestrial neutrons in the energy range of 1-1000 MeV. The ISNP/GNEIS test facility is located inside the GNEIS building on the neutron beam #5, which has the following parameters:

- neutron energy range: 1-1000 MeV;
- neutron flux: $4\cdot10^5$ n/cm$^2\cdot$s (at 36 m flight path);
- beam diameter: 50-100 mm (at 36 m flight path);
- uniformity of the beam profile plateau: ± 10%.

The neutron beam profile (Fig. 6) is measured by means of MWPC - the 2-coordinate position sensitive multiwire proportional counter used for registration of fission fragments from the ^{238}U target deposited on the MWPC's cathode. The neutron flux of $4\cdot10^5$ n/(cm$^2\cdot$s) is an integral over neutron spectrum in the energy range 1-1000 MeV. It corresponds to the maximum value of 3μA of the internal average proton beam current. The neutron flux and shape of the neutron spectrum are measured using FIC (neutron monitor) and TOF-technique (Fig. 7). The FIC is a fast parallel-plate ionization chamber which contains two targets of ^{235}U and ^{238}U. The neutron fission cross sections of these nuclei are recommended standards in the energy range 1-200 MeV. These data are taken

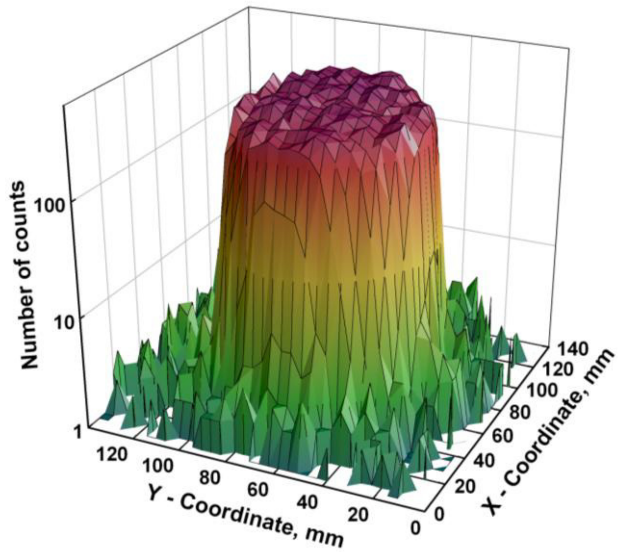
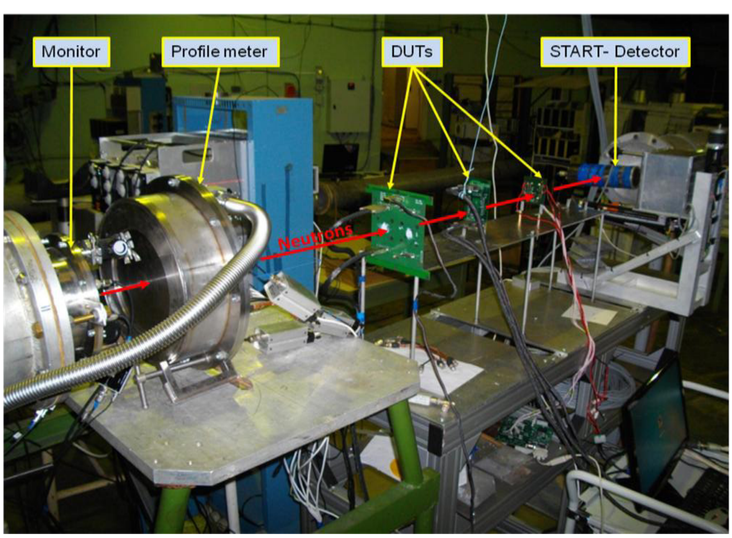


Figure 6: Neutron beam profile measured using MWPC.

from the ENDF/B-VII.1 Library [17] while the data above 200 MeV are taken from the JENDL High Energy Library [18]. The neutron spectrum of the ISNP/GNEIS is shown in Fig. 7 together with the JEDEC standard terrestrial neutron spectrum from JESD89A [19] referenced to New York City and multiplied by scaling factor $7\cdot10^7$, as well as the neutron spectra of leading test facilities [21-25]. The corresponding values of 1-hour neutron fluence in the energy range above 1 MeV are given in Table 2. Both the shape of the neutron flux and neutron intensity demonstrate that the ISNP/GNEIS is successfully competing with the other first-grade test facilities with the atmospheric - like neutron spectrum. It should be noted that presently in Russia the ISNP/GNEIS test facility is the only one with atmospheric-like neutron spectrum.



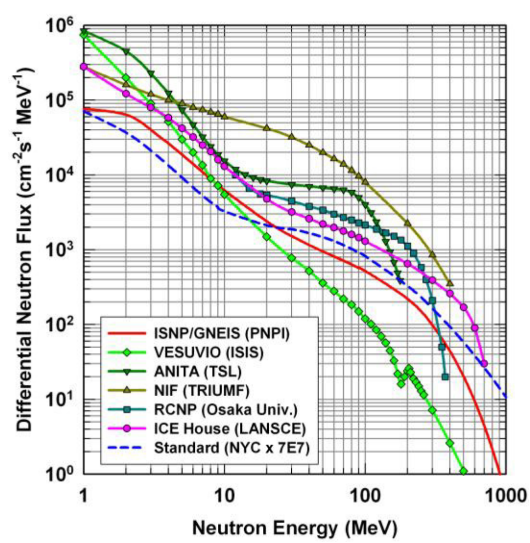


Figure 7: Left: General layout of the ISNP/GNEIS test facility. Right: Neutron spectrum of the ISNP/GNEIS comparison with standard terrestrial neutron spectrum [5] and spectra of other world-class test facilities [6-10].

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Table 2: Integrated (E_n > 1 MeV) neutron flux of various neutron test facilities and Standards.

Standard/Facility (location, proton energy, target material)	Neutron Flux (n/cm^2 hour)
JEDEC (NYC, sea level, outdoors, mid. solar activity) JESD89A [19]	20
IEC (altitude 12 km, latitude 45^o) IEC TS 62396-1 [20]	8760
ISNP/GNEIS (PNPI, Gatchina, 1000 MeV, lead)	$1.5 \cdot 10^9$
ICE House (LANSCE, Los Alamos, USA, 800 MeV, tungsten) [21]	$3.4 \cdot 10^9$
RCNP (Osaka University, Japan, 180 MeV, lead) [23]	$5.4 \cdot 10^9$
ANITA (TSL, Uppsala, Sweden, 400 MeV, tungsten) [22]	$9.9 \cdot 10^9$
NIF (TRIUMF, UBC, Vancouver, Canada, 500 MeV, aluminum) [24]	$1.3 \cdot 10^{10}$
VESUVIO (ISIS, RAL, Chilton, UK, 800 MeV, tungsten/tantalum) [25]	$2.5 \cdot 10^9$

The SC-1000 possesses a potential of the neutron intensity growth. A new irradiation station located at a distance of 5-6 m from the neutron-production target operated on the extracted proton beam enables to increase neutron flux at least 10 times at the DUT (device under test) position. Simultaneously, an irradiation of the bulky equipment will be possible.

CONCLUSION

Four decades of operation have showed that owing to its unique parameters, the GNEIS neutron source and TOF spectrometer still occupy an important place in the world list of neutron facilities effectively used for science and technology. High neutron intensity up to $3 \cdot 10^{14}$ n/s and short neutron burst of 10 ns, as well as a convenient repetition rate of 50 Hz, enable to cover neutron energy range from thermal up to hundreds of MeV in a single TOF-measurement. At present, the same experimental conditions are achievable only at the n_TOF facility at CERN. Also, it is important that both low-energy (< 10 KeV) and high-energy (above 10 MeV) measurements are carried out simultaneously due to availability of a few flight paths with different neutron spectra. Nuclear data measured using the GNEIS, primarily the high accuracy neutron cross sections, demonstrate the unique experimental capabilities of this spallation neutron source.

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