Nuclear Data Measurement Facilities for Supporting Advanced Fuel Cycle Basic Science Research Needs

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White Neutron Sources

ORELA (Oak Ridge Electron Linear Accelerator)

The Oak Ridge Electron Linear Accelerator (ORELA) is a powerful electron accelerator-based neutron source located in the Physics Division of Oak Ridge National Laboratory. ORELA has been in operation since 1969. In terms of capabilities, many types of neutron cross section measurements (total, capture, fission, elastic, scattering, and gamma ray and neutron production) can be made at this facility with extremely good energy resolution. The time-of-flight method is used to determine the energy of the interacting neutron. Detector calibrations and measurements of detector responses to neutrons are also performed, and with a flux peaked around 1 MeV neutron energy, ORELA is ideal for many types of radiation damage and activation studies.

The ORELA facility consists of a 180 MeV electron accelerator and neutron producing targets that are used to generate neutrons which are then directed through underground and evacuated flight tubes to detector-station locations 10 to 200 m from the source. Neutrons are produced via bremsstrahlung and photoneutron reactions when a tantalum target is exposed to bursts of electrons. Intense nanosecond bursts of neutrons are produced with each burst containing neutrons having energies between 10^{-3} eV to 10^{8} eV. Pulse widths from 2 to 30 nanoseconds are available at repetition rates from 1-1000 pulses per second. Moderated or unmoderated neutrons can be produced, and the spectral shape of the neutron distribution can be tailored with movable filters. Using the time-of-flight (TOF) method to determine the energy of the interacting neutron, ORELA is primarily used to measure neutron reaction cross-sections with very detailed energy resolution in the resonance region for many materials.

LANSCE (Los Alamos Neutron Science Center)

The Los Alamos Neutron Science Center (LANSCE, http://lansce.lanl.gov/) is a unique multidisciplinary facility for science and technology. The central feature of the facility is an 800-MeV linear accelerator system that accelerates both negative hydrogen ions and protons. At present the accelerator supplies up to 135 µA of H^- ions with pulsed beam timing patterns suitable for a wide variety of experimental programs at three user facility areas and up to 250 µA of proton beam at 100 MeV for isotope production. Designated as a National User Facility in 2001, the research program has expanded substantially in recent years. In the 2003 - 2004 operating period there were over 1100 user visits during which over 350 experiments were conducted during 200 days of user facility operation. Three experimental areas, the **Manuel Lujan Jr. Neutron Scattering Center (Lujan Center), the Weapons Neutron Research (WNR) Facility and the Proton Radiography Facility (pRad)**, make up the user part of the facility and cover 14 orders of magnitude in neutron energy. In addition, there is an area for isotope production and an area for Ultra Cold Neutron production for fundamental physics.

The **Lujan Center** (http://lansce.lanl.gov/lujan/) uses the 800-MeV H^- beam to produce cold, thermal and epithermal neutrons in the meV - keV range, primarily for neutron scattering and nuclear science research. To provide a suitable time structure for low-energy neutron time-of-flight experiments, a **Proton Storage Ring (PSR)** compresses 750 μs pulses from the linear accelerator to 125 ns (FWHM) at a rate of 20 Hz. The proton beam, at a current of up to 135 μA, then strikes a light-water cooled split-tungsten target with a flux trap and backscattering moderator system to give a higher peak neutron flux than is available at any other spallation source. Those neutrons are collimated to form beams for up to seventeen flight paths. Three of the 15 flight paths are instrumented for neutron nuclear science and transmission spectroscopy: (1) **DANCE** (http://wnr.lanl.gov/dance/)is an array of 160 BaF_2 detectors used for neutron capture studies on small (mg) radioactive samples is located on a 20 meter flight path; (2) Precision fission cross-section measurements from thermal to a few hundred keV are conducted on flight path 5 using ionization chambers; (3) Flight path 12 is dedicated to measurements of the neutron electric dipole moment, parity violation in neutron-proton capture and other basic physics experiments.

The **WNR Facility** (http://wnr.lanl.gov/) is primarily used for basic and applied nuclear science using higher energy neutrons. For most experiments, WNR uses up to 5 μA of H- beam that is chopped and bunched before acceleration to give an adjustable pulse-to-pulse separation; a typical pulse separation is 1.8 μs. The pulse width is approximately 125 ps (FWHM), allowing neutron time-of-flight measurements with a time resolution of less than one ns. The narrow proton bursts come within a 750-μs 'macro-pulse' supplied at up to 120 Hz, giving an overall rate of up to 50,000 source pulses per second. WNR has two experimental areas that use the proton beam, Target-2 and Target-4. At the WNR Target-4 'white' neutron source, the beam strikes a tungsten target producing neutrons with useful energies from 100 keV to 600 MeV. Those neutrons are collimated to form beams for six flight paths viewing the neutron source at angles to the left (L) or right (R) relative to the incident beam direction of 15, 30, 60 and 90 degrees. Research at the WNR is supported by a suite of flight-path instrumentation that includes: (1) **GEANIE** (http://geanie.lanl.gov/), consisting of 26 high-resolution, escaped-suppressed Ge detectors; (2) **FIGARO**, comprised of 20 liquid scintillator neutron detectors and several different gamma-ray detectors for neutron and gamma-ray emission measurements; (3) a short, high-flux flight path for precision fission cross section measurements; (4) the **NZ setup** for neutron-induced charged-particle measurements; (5) a liquid hydrogen/deuterium target for few body interaction studies; (6) facilities for neutron irradiation of electronics and for high-resolution neutron radiography; and (7) a 90-meter flight path used for a variety of basic and applied experiments.

Target-2 is a modestly shielded area where direct access to the proton beam is possible. Target irradiations and single-pulse neutron experiments are done here using either the linac beam or, for short, high intensity pulses, the PSR beam. A **Lead Slowing-Down Spectrometer (LSDS)** is installed here for measurements of neutron-induced reactions with neutron intensities over 1000 times greater than those in conventional beam-target experiments. Neutrons are produced by the pulsed 800-MeV proton beam from the LANSCE Proton Storage Ring striking a tungsten target in the center of 20-ton cube of pure lead. Nuclear reactions, such as fission, take place in samples placed inside the lead volume. Because lead has a small capture cross section, the neutrons are essentially trapped in the cube and have many chances to interact with the sample as they slow down, first by reactions and inelastic scattering, and then, more slowly, by elastic scattering. The reaction rates are measured as a function of time after the beam pulse, and there is a well-understood relationship between the time and the neutron energy. The usable neutron energy range starts below 1-eV and, with the short pulse width of the PSR proton beam pulse, extends to more than 100 keV. An energy resolution of 30% is characteristic of the LSDS. The greatly enhanced neutron intensity makes possible measurements of fission cross sections on samples of 10 nanograms or less. Hard-to-obtain samples and those difficult to handle in larger quantities can be studied with the LSDS. Innovative detectors that perform well in the intense radiation environment are being developed for fission and (n,alpha) measurements. The characterization and initial results obtained at this facility are described in D. Rochman et al., Nuclear Instruments and Methods in Physics Research, Section **A550**, 397 (2005).

Gaerttner Linear Accelerator

The Gaerttner Linear Accelerator (LINAC) Laboratory at Rensselaer Polytechnic Institute (RPI) is a major research facility used to conduct basic and applied research. The Gaerttner LINAC Laboratory has been engaged in active research continuously for nearly 45 years. Research with electrons, photons and neutrons has applications to nuclear engineering, nuclear physics, radiation effects in electronics, radiation production, radiation processing of materials, conventional radiography, computed tomography, and other industrial processes. Enhancement of materials and chemical properties and processing by high energy radiation is a growing industrial tool applicable to both environmental and commercial applications. Radiation testing of electronic materials, components and systems is of major importance for reliability and survivability in diverse environments. Current areas of research at the LINAC include thermal reactor physics, photoneutron reactions, neutron cross sections, radiation effects in electronics, and coloring of gemstones.

The laboratory's research is centered about a multi-million dollar, high power, >60 MeV, L-band traveling wave, electron linear accelerator. The facility has provided the research community with faithful service since December of 1961 and is operated and maintained by a well trained staff. The LINAC today consists of nine RF accelerator sections that accelerate pulses of electrons to a maximum energy in excess of 60 MeV with peak target currents in excess of 3 amperes. The electron beam can be extracted either after the third or ninth section. In this way it is capable of providing a high energy pulsed beam of electrons, in the range from 5 to more than 60 MeV. Typical operating conditions for three-section operation are: electron energy, 5 to 25 MeV; electron pulse width, from 7 nanoseconds to 5 microseconds; peak electron current, the order of amperes; average electron power, 10 kW or more; peak dose rate, 10 to 18 MeV,>10^{11} Rads/sec in Silicon; repetition rate, single pulse to 500 pulses per second (PPS), subject to average power restrictions. For nine-section configuration: 25 to 60 MeV or more; pulse width, 7 nanoseconds to 5 microseconds; peak electron current, the order of amperes; average power of 10's of kW; peak neutron production rate greater than 4 x 10^{13}/sec; repetition rate, single pulse to greater than 500 PPS, subject to average power limitations. These two ranges of energies allow the accelerator to be used for a variety of uses. In the range of 5 to 25 MeV the accelerator can provide an intense beam of low-energy electrons for radiation hardening and transient radiation measurements in electronics, transformation of materials through radiation, sterilization/radurization, etc. In the 25 to over 60 MeV range the accelerator can provide an intense beam of electrons for photoneutron production, nuclear reactor environment simulation, and high-energy Bremsstrahlung production.

IPNS (Intense Pulsed Neutron Source)

The Intense Pulsed Neutron Source (IPNS) located at Argonne National Laboratory (ANL) is a spallation source accelerator that has been used since 1981 for condensed matter research. The IPNS accelerator system consists of an H^- ion source, a Cockcroft-Walton preaccelerator, a 50 MeV Alvarez linac, a 450 MeV Rapid Cycling Synchrotron (RCS), transport lines and ancillary subsystems (controls, diagnostics, services). The accelerator normally operates at an average beam current of 14 to 15 μA, delivering pulses of approximately 3 x 10^{12} protons at 450 MeV to the target, 30 times per second. The preaccelerator and linac entered service in 1961 and served as the injector to the 12.5 GeV Zero Gradient Synchrotron (ZGS) high-energy physics accelerator until it was shut down in 1979. The RCS was developed and constructed in the mid

1970's as a proposed booster for the ZGS. However, with shutdown of the ZGS imminent, these plans were dropped and instead the RCS was used initially (1977-1980) to provide beam to the ZING experimental target and in 1981, began providing beam to the present IPNS target.

In terms of neutron producing capabilities, the proton beam is accelerated by two ferrite loaded coaxial cavities. Moving at 2.2×10^8 m/s (almost 75% of the speed of light), the 450 MeV protons circle the ring in just under 200 ns (2×10^{-7}s) just prior to extraction. The proton beam is bunched such that it fills just over a third of the circumference, giving a bunch about 70-80 ns long with about a 120 ns gap between head and tail. The accelerated beam is extracted in a single turn by two ferrite-loaded kicker magnets and two septum magnets, one pulsed and one dc. The extracted beam, 450 MeV, 70-80 ns pulse, peak current ~ 12 A, is then transported to the neutron generating target. The high-energy neutron pulse is correspondingly short, but the moderation process spreads it out a bit, resulting in the few microsecond pulse that is seen at the instruments. IPNS hosts about 400 users each year from all over the world, performing about 550 experiments during the running periods, which average 26 weeks/year.

SNS (Spallation Neutron Source)

The Spallation Neutron Source (SNS) is an accelerator-based neutron source at the Oak Ridge National Laboratory. At a total cost of $1.4 billion, construction began in 1999 and delivered its first neutrons on April 28, 2006. The SNS will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. The SNS project is a partnership involving six DOE national laboratories (Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge) in the design and construction of what will be the most powerful spallation source in the world for neutron-scattering R&D. The baseline design calls for an accelerator system consisting of an ion source, full-energy linear accelerator (linac), and an accumulator ring that combine to produce short, powerful pulses of protons. These proton pulses impinge onto a mercury target to produce neutrons through the spallation nuclear reaction process. The SNS will deliver 1.4 million watts (1.4 MW) of beam power onto the target, and it has been designed with the flexibility to provide additional scientific output in the future. This approach is intended to provide a facility that will meet the neutron intensity needs of the science community well into the next century.

NTOF (Neutron Time-of-Flight)

The Neutron Time-of-Flight (NTOF) facility located at the Conseil Europeen pur la Recherche Nucleaire (CERN) in Geneve, Switzerland is a spallation neutron source facility that can be used for nuclear data measurements. NTOF produces neutrons in an energy range covering more than eight orders of magnitude (between 1eV and some 250 MeV) for experiments in nuclear physics. The NTOF neutron beam makes use of both the specifically high flux of neutrons attainable using the spallation process of 20 GeV protons on an extended lead target containing practically the whole spallation shower and the remarkable beam density of the CERN Proton Synchrotron (PS), which can generate high intensities up to 7×10^{12} ppp (protons per pulse) - high enough to produce the vast number of 2×10^{15} neutrons per pulse - in the form of short (6 ns width) pulses with a repetition time varying from 2.4 s to 16.7 s and a prompt “flash” considerably smaller compared to electron machines. The neutrons produced by spallation are canalized to an experimental area located at ~ 185 m downstream through a vacuum pipe. The high neutron flux, the low repetition rates and the excellent energy resolution of 3×10^{-4} open new possibilities to high precision cross section measurements in the energy range from 1 eV to 250 MeV, for stable and, moreover, for radioactive targets.

GELINA (Geel Electron Linear Accelerator)

The Geel Electron Lineary Accelerator (GELINA) is a pulsed white spectrum neutron source facility located at the Institute for Reference Materials and Measurements (IRMM) in Geel, Belgium. GELINA combines four specially designed and distinct units: a high-power pulsed linear electron accelerator, a post-accelerating beam compression magnet system, a mercury-cooled uranium target, and very long flight paths. The GELINA neutron source is based on a linear electron accelerator producing electron beams. A typical beam operation mode uses 100 MeV average energy, 10 ns pulse length, 800 Hz repetition rate, 12 A peak and 100 µA average current. With a post-acceleration pulse compression system, the electron pulse width can be reduced to approximately 1 ns (FWHM) while preserving the current, resulting in a peak current of 120 A. The accelerated electrons produce Bremsstrahlung in a uranium target which in turn, by photonuclear reactions, produces neutrons. Within a 1 ns pulse a peak neutron production of 4.3 x 10^{10} neutrons is achieved (average flux of 3.4 x 10^{13} neutrons/s). The neutron energy distribution emitted by the target ranges from subthermal to about 20 MeV, with a peak at 1-2 MeV. To have a significant number of neutrons in the energy range below 100 keV, a hydrogen-rich moderator is added. The partially moderated neutrons have an approximate 1/E energy dependence plus a Maxwellian peak at thermal energy. By using collimators and shadow bars moderated or unmoderated neutron beams are selected for the twelve neutron flight paths. Further tailoring of the spectral shape is done with movable filters. Flight paths up to 400 m long are provided and are symmetrically arranged around the uranium target. Experimental locations are available at distances of 10, 30, 50, 60, 100, 200, 300 and 400 m. These experimental stations are equipped with a variety of sophisticated detectors, and data acquisition and analysis systems. GELINA is a multi-user facility serving up to 12 different experiments simultaneously. The facility is operated in shift work on a 24 hours/day basis, for about 100 hours per week.

Charged Particle Sources

ATLAS (Argonne Tandem Linac Accelerator System)

The Argonne Tandem Linac Accelerator System (ATLAS) http://www.phy.anl.gov/atlas/, located at Argonne National Laboratory http://www.anl.gov/ is a superconducting heavy-ion accelerator. ATLAS is a DOE National Collaborative Research Facility open to scientists from all over the world. All experiments must be reviewed and approved by the ATLAS PAC which usually meets twice per year. The beams are provided by one of two 'injector' accelerators, either a 9 million volt (MV) electrostatic tandem Van de Graff, or a new 12-MV low-velocity linac and electron cyclotron resonance (ECR) ion source called the Positive Ion Injector. The beam from one of these injectors is sent on to the 20-MV 'booster' linac, and then finally into the 20-MV 'ATLAS' linac section. High precision heavy-ion beams ranging over all possible elements, from hydrogen to uranium, can be accelerated to energies as high as 17 MeV per nucleon and delivered to one of three target areas. Information on recently accelerated beams can be found at http://www.phy.anl.gov/atlas/facility/beamlist.html (stable beams) http://www.phy.anl.gov/atlas/facility/ribs.html (radioactive beams). Information on CARIBU (CAlifornium Rare Isotope Breeder Upgrade), proposal for a major upgrade of the radioactive ion beam capability of ATLAS can be found at http://www.phy.anl.gov/atlas/caribu.html. Details on experimental equipment can be found at http://www.phy.anl.gov/atlas/research/res_equipment.html. Major facilities include the Gammasphere Germanium detector array http://www.phy.anl.gov/gammasphere/index.html, the

Fragment Mass Analyzer (FMA) http://www.phy.anl.gov/fma/index.html and the Enge split pole spectrometer.

HRIBF (Holifield Radioactive Beam Facility)

The Holifield Radioactive Beam Facility (HRIBF) http://www.phy.ornl.gov/hribf, located at Oak Ridge National Laboratory http://www.ornl.gov/ is operated as a National User Facility for the U.S. DOE, has a mission of producing high quality ISOL beams of short-lived, radioactive nuclei for studies of exotic nuclei and astrophysics research. These nuclei are produced when intense beams of light ions from the Oak Ridge Isochronous Cyclotron (ORIC) strike highly refractory targets. The radioactive isotopes diffuse out of the production target and are ionized, formed into a beam and mass selected. The radioactive ion beam is then injected into the 25-MV Tandem, the world's highest voltage electrostatic accelerator. A listing of recently accelerated RIBs can be found at http://www.phy.ornl.gov/hribf/beams/. A listing of the major research instrumentation available at HBIBF can be found at http://www.phy.ornl.gov/hribf/equipment/. All experiments at HRIBF are reviewed an approved by a PAC which typically meets twice per year. Information on submitting an experimental proposal can be found at http://www.phy.ornl.gov/hribf/proposals/.

The 88-Inch Cyclotron Facility

The 88-Inch Cyclotron Facility http://user88.lbl.gov/, located at the Lawrence Berkeley National Laboratory, http://www.lbl.gov/ supports a local research program in nuclear science and is the home of the Berkeley Accelerator Space Effects (BASE) facility. Operated by the Department of Energy's Office of Science, the Cyclotron is now jointly funded by the DOE and the National Security Space Community. The 88-Inch is a K=140 sector-focused cyclotron with both light- and heavy-ion capabilities. Protons and other light-ions are available at high intensities (10-20 pμA) up to maximum energies of 55 MeV (protons), 65 MeV (deuterons), 135 MeV (3He) and 140 MeV (4He). Most heavy ions through uranium can be accelerated to maximum energies which vary with the mass and charge state. Ion source and bean information is at http://ecrgroup.lbl.gov/. Instrumentation available at the 88-Inch Cyclotron include the Berkeley Gas Filled Separator (BGS), the STARS/Liberace charged particle/clover germanium array and a newly developed neutron beam line.

The Cyclotron Institute at Texas A & M University

A university based facility, **the Cyclotron Institute at Texas A & M University** http://cyclotron.tamu.edu/information.html is jointly supported by the U.S. DOE and the State of Texas. The K500 Cyclotron http://cyclotron.tamu.edu/K500.html is capable of supplying a variety of ion beams to the experiments at the Cyclotron Institute. Starting from the ECR ion sources, ion beams of the very lightest to the very heaviest of elements can be accelerated by the cyclotron. Beam energies for protons (ionized hydrogen) range from 8 MeV to 70 MeV, while energies for uranium ions range from 500 MeV (2MeV per nucleon) to 3.5 GeV (15 MeV per nucleon). Information on the experimental facilities at the Cyclotron Institute can be found at http://cyclotron.tamu.edu/facilities.htm Major instruments include a variety of spectrometers such as the proton spectrometer http://cyclotron.tamu.edu/psp.htm, Big Sol http://cyclotron.tamu.edu/bigsol.htm, and the MDM Spectrometer http://cyclotron.tamu.edu/mdm.htm. Information on the research program at TAMU can be found at http://cyclotron.tamu.edu/research.html.

The Wright Nuclear Structure Laboratory

A university based facility, the **Wright Nuclear Structure Laboratory**, http://wnsl.physics.yale.edu/, located on the campus of Yale University houses active research programs in nuclear structure http://wnsl.physics.yale.edu/structure/ and nuclear astrophysics http://wnsl.physics.yale.edu/astro/index.html as well as a program utilizing relativistic heavy ions http://star.physics.yale.edu/ carried out at Brookhaven National Laboratory. The laboratory is supported by the U.S. DOE Office of Science. A variety of heavy-ion beams are provided by the ESTU Van de Graaff generator, http://wnsl.physics.yale.edu/estu/. Instrumentation available at the WNSL includes the YRAST Ball Clover germanium detector array http://wnsl.physics.yale.edu/structure/equipment/yrastball.html, the SASSYER gas filled magnetic spectrometer http://wnsl.physics.yale.edu/structure/equipment/sassyer/ and the Enge split pole spectrometer http://wnsl.physics.yale.edu/astro/enge/index.html. There is no formal PAC. Beam time requests should be addressed to Prof. Peter Parker peter.parker@yale.edu.

TUNL Triangle Universities Nuclear Laboratory

The Triangle Universities Nuclear Laboratory (TUNL) http://www.tunl.duke.edu/ is a U.S. DOE funded laboratory with research faculty from three major universities within the Research Triangle area: Duke University, North Carolina State University, and the University of North Carolina-Chapel Hill. Located on the campus of Duke University TUNL draws additional collaborators from many universities in the southeast, as well as from labs and universities across the country and all over the world. The High Intensity Gamma-ray source (HIGS) http://higs.tunl.duke.edu/ is a major new facility at TUNL. A storage-ring FEL is used to produce a high-intensity and monoenergetic gamma-ray beam in the energy range from 2 to 50 MeV by intracavity Compton backscattering. The DOE has recently approved an upgrade of the injection system which will make it possible to produce gamma rays of high average flux at energies up to 225 MeV.

National Superconducting Cyclotron Laboratory

Located on the campus of Michigan State University, **The National Superconducting Cyclotron Facility** http://www.nscl.msu.edu/ is the leading fragmentation based rare isotope research facility in the United States. Funded primarily by the National Science Foundation and MSU, the NSCL operates two superconducting cyclotrons. The K500 was the first cyclotron to use superconducting magnets, and our K1200 is the highest-energy continuous beam accelerator in the world. Estimates of the intensities of rare isotope beams can be found at http://www.nscl.msu.edu/aud/exp/propexp/index.php, while a list of major experimental facilities can be found at http://www.nscl.msu.edu/aud/exp/propexp/devices.php.