China Spallation Neutron Source - an overview of application prospects*

WEI Jie(韦杰)[1;1)] FU Shi-Nian(傅世年)[1] TANG Jing-Yu(唐靖宇)[1] TAO Ju-Zhou(陶举洲)[1]
WANG Ding-Sheng(王鼎盛)[2] WANG Fang-Wei(王芳卫)[2] WANG Sheng(王生)[1]

1 (Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China)
2 (Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China)

Abstract The China Spallation Neutron Source (CSNS) is an accelerator-based multidisciplinary user facility to be constructed in Dongguan, Guangdong, China. The CSNS complex consists of an H^- linear accelerator, a rapid cycling synchrotron accelerating the beam to 1.6 GeV, a solid-tungsten target station, and instruments for spallation neutron applications. The facility operates at 25 Hz repetition rate with an initial design beam power of 120 kW and is upgradeable to 500 kW. Construction of the CSNS project will lay the foundation of a leading national research center based on advanced proton-accelerator technology, pulsed neutron-scattering technology, and related programs including muon, fast neutron, and proton applications as well as medical therapy and accelerator-driven subcritical reactor (ADS) applications to serve China's strategic needs in scientific research and technological innovation for the next 30 plus years.

Key words proton beam, pulsed neutron source, neutron scattering, national science facility

PACS 29.20.-c, 28.20.Cz, 25.40.Sc

1 Introduction

1.1 Neutron scattering

In 1932, Chadwick discovered neutron, and nuclei are proven to consist of positively-charged protons and uncharged neutrons. Neutron's discovery and application have become one of the most significant scientific achievements of the 20th century.

When a neutron beam is incident on the material of investigation, neutrons interact with nuclei kinetically and via magnetic moments leading to neutron scattering. Measurement of neutron energy and momentum transfer through the scattering process enables studies of microscopic structure and dynamic behavior on the atomic scale, telling people "where atoms and molecules are", and "what they are doing". Neutrons utilized in such neutron-scattering technique have wavelength on the order of 1/10 to 10 Å, energy on the order of MeV to eV, the same range as interatomic distance and energy in typical condensed-matter systems.

Neutron carries no electrical charge, yet possesses magnetic moment. It penetrates easily, and is sensitive to differences in light elements, neighboring elements, and isotopes. Neutron provides an ideal non-destructive probe to investigate structural and dynamic properties of material systems, and neutron-scattering method becomes a powerful tool to study microstructure and atomic motion in many fields of physical sciences. Since the first successful neutron-diffraction study in 1936, neutron-scattering technique has been applied to a wide range of research areas such as physics, chemistry, material science, bioscience, geoscience, energy, health, medicine and environment sciences.

The high-flux X-ray generated as synchrotron radiation mainly interacts with electrons outside nuclei, while uncharged neutron interacts mostly with the nuclei. These two major microscopic probes happen

Received 18 December 2008

* Supported by Chinese Academy of Sciences, Guangdong Provincial Government, Dongguan Municipal Government, CAS Hundred People Initiative (KJCX2-YW-N22) and Overseas Outstanding Youth Program of National Natural Science Foundation of China (10628510)

1) E-mail: weijie@ihep.ac.cn

to scan corresponding two halves of a matter system. This fortunate combination has been exploited to solve many scientific problems of atomic position, ordering, motion and interaction. In complement to X-ray/synchrotron radiation, neutron scattering also has unique features: (1) a wide continuous spectrum: the scattering process corresponds to a range of wavelength from 10^{-11} to 10^{-6} m tuneable to measure condensed matter microstructures; (2) appropriate energy coverage: thermal neutrons have kinetic energy from meV to eV comparable to that of most dynamic processes in condensed matter systems, making neutron scattering an ideal method to study various interatomic interactions; (3) capable of determining the position of light elements; (4) sensitive to isotopes: the number of neutrons in nuclei makes great difference to the neutron-scattering cross-section; (5) magnetic scattering: capability to directly measure microscopic magnetic symmetry and spin motion; (6) large scattering intensity at high Q (large momentum transfer); (7) high penetration power: penetration length to typical industrial steel and aluminum are about 7 mm and 65 mm, respectively; (8) non-destructive: thermal neutron scattering doesn't destruct bioactivity of bio-samples, making it highly desirable to bioscience research.

1.2 Spallation neutron source

Advanced neutron source is the basis of neutron science. Since the discovery of neutron in 1932, scientists have been building and developing neutron sources with ever higher flux.

High-flux neutron sources come in two types: reactor sources and spallation sources. As continuous-wave (cw) sources, nuclear reactors have played tremendous roles in neutron scientific research. Typically with ^{235}U as the fuel, a large amount of heat (one effective neutron per fission reaction releasing 180 MeV energy) needs to be efficiently removed from the reactor core to ensure stable operation. Due to this technological bottleneck, neutron flux in reactor sources have reached a plateau since 1960s. The research reactor of the highest flux is at the Institut Laue-Langevin (ILL) in Grenoble, France, with a flux of about $1.5\times10^{15}cm^{-2}s^{-1}$.

Many objects studied by today's cutting-edge science, such as thin film, nanoscale atomic cluster, biomolecule and protein, are available in wide range of dimensional scale yet very small sample amount. Efficient neutron scattering measurements of small samples call for a new generation of high-flux, wide-spectrum neutron source. Spallation neutron source has arisen out of such demands, raised neutron flux to a new level and witnessed rapid developments.

A spallation neutron source is a large-scale scientific facility where high-energy protons produced by accelerators bombard heavy metal target to generate neutrons. Through a complex series of intranuclear and extranuclear cascade reactions (spallation), each high-energy proton generates 20—40 protons. The energy released by each spallation reaction is only about 1/4 ($\sim$ 45 MeV) of that released by the fission reaction, yet the number of neutrons produced by each spallation reaction is much larger than that of fission. Spallation source can generate pulsed neutrons of higher flux in a small volume with wider wavelength spectrum, greatly extending the capability of neutron scattering methods.

In China, high-flux neutron source started about half a century ago. The first experimental heavy-water reactor was constructed in 1958 laying the foundation for nation's atomic energy sciences. Early neutron-scattering researches were conducted on this reactor source. Compelled by the urgency of reducing the gap between China and the world leaders in neutron science research, more Chinese scientists have been calling for the development of domestic advanced neutron sources since the beginning of this century. As part of the strategic build-up of national scientific infrastructure to support advanced researches, construction of national advanced neutron sources and building of corresponding national laboratories became top priorities.

The China Advanced Research Rector (CARR) is currently under construction and expected to be commissioned at the China Institute of Atomic Energy (CIAE) in 2009 as one of the leading neutron-scattering centers in Asia. In the mean time, the China Spallation Neutron Source (CSNS) was proposed and supported by Chinese Academy of Sciences, the Guangdong Provincial Government and the Dongguan Municipal Government of China[1]. CSNS and CARR will complement and reinforce each other for a great leap forward in neutron sciences in China. For example, the CSNS' instruments will measure momentum and energy transfer over a wide range facilitating the overall characterization of matter systems, while CARR's instrument will measure energy and momentum transfer at specific points appropriate for precise determination of certain material's special properties; CSNS diffractometers will emphasize data at higher momentum transfer while CARR diffractometers can focus on data at smaller momentum transfer; time-of-flight (TOF) spectrometers of CSNS will measure elementary excitations and corresponding densities of states in polycrystalline materials, while the CARR triple-axis spectrometer can determine dispersion relationship of various excitations in single crystals. CSNS and CARR also hold complementary advantages in many other research areas, such as CSNS applications in proton beam therapy, muon scattering, fundamental neutron physics and accelerator-driven subcritical transmutation, and CARR applications in isotope production, semiconductor irradiation, and neutron radiography.

Internationally, accelerator-driven spallation neutron sources started as large-scale multidisciplinary platforms since 1980s. Currently, two earliest pulsed neutron sources (KENS of the High Energy Accelerator Research Organization of Japan, KEK, and IPNS of the Argonne National Laboratory of USA) just retired; four spallation neutron sources are in operation (ISIS of the Rutherford-Appleton Laboratory of UK, LANSCE of the Los Alamos National Laboratory of USA, SNS of the Oak Ridge National Laboratory of USA, and the continuous-wave source SINQ of the Paul Scherrer Institut of Switzerland), one multipurpose facility is in beam-commissioning stage (J-PARC of Japan Atomic Energy Agency JAEA and KEK). Proposed sources are CSNS of China, ESS of Europe, PEFP of South Korea, and ISNS of India. Fig. 1 shows the spallation neutron sources in the world[2, 3].

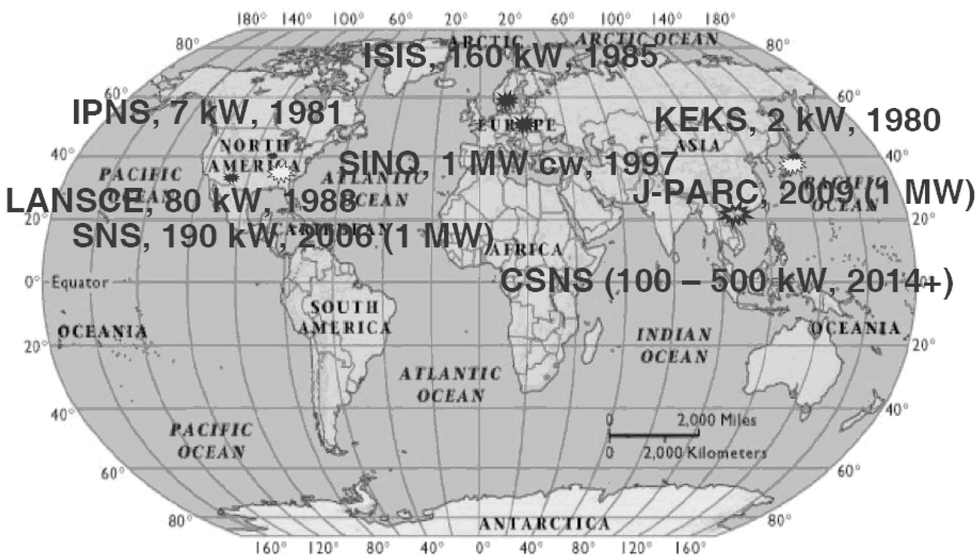

Fig. 1. Spallation neutron sources in the world. The facility names are listed along with the achieved beam power on the target. The design beam power is indicated in the parenthesis.

As one of the most productive spallation neutron sources in the world, ISIS of UK generates a flux of $8\times10^{15}cm^{-2}s^{-1}$ neutrons, almost one order of magnitude higher than that of the highest-flux reactor source. The pulsed nature of a spallation neutron source enables wider spectrum utilization of neutrons using the time-of-flight method compared with single-wavelength neutron scattering on a reactor source, improving neutron scattering efficiency by up to three orders of magnitude.

The 21st century witnesses the developed countries such as USA, Japan and UK/Europe to pursue higher flux and efficiency spallation neutron sources in cutting-edge science and technology, and to construct or propose facilities of megawatt beam-power level. These spallation sources are capable of generating effective neutron flux up to a hundred times that of a reactor source, providing powerful platforms for multidisciplinary scientific research and technological innovation. In USA, six national laboratories under the Department of Energy collaborated to construct the SNS[4]. The SNS has a design beam power of 1.4 MW to provide neutron flux up to $10^{17}cm^{-2}s^{-1}$ at a total cost of approximate US$1.4 Billion. The first beam of neutrons was generated for SNS on April 28th, 2006 after seven years of construction. The SNS beam power is being raised to the present 600 kW, setting the record as the most powerful pulsed neutron source in the world. Implementation of neutron instruments is also in order.

In Japan, the J-PARC project is constructed jointly by JAEA and KEK at a cost of 1527 Oku Yen[5]. A 3-GeV rapid cycling synchrotron (RCS) will provide proton beams of 1 MW design beam power to drive the spallation source.

With ISIS of UK, an upgrade program is funded to increase the proton beam power of the accelerator from the operating 160 kW to 240 kW, and to construct the second target station[6]. 10 out of 50 proton pulses per second will supply the second station yielding 48 kW of beam power.

The CSNS has a design beam power of 100 kW and is upgradeable to 500 kW. Operating at 25 Hz repetition rate, the design pulsed neutron flux overpasses that of ISIS. The approved construction cost is 1.4 Billion CNY. Upon completion, CSNS will be the first spallation neutron source in developing countries, and among the top four of such facilities in the world. It is expected to be a leading national facility for frontier fundamental research and high-tech development, forming an advanced multidisciplinary platform for scientific discovery and technological development. Comparing to the SNS and J-PARC, only very a limited amount of research work, such as those related to ultra-thin film, ultra-rapid reaction and phase transition, would be limited by the CSNS beam flux. The minimum sample amount for CSNS is designed to be at milligram level, while the minimum data collection time is designed to be at minute level, covering more than 90% of expected research demands. With a fraction of the world-standard construction cost, CSNS is a world-class large-scale scientific user facility optimized for the conditions in China to meet the nation's science and technology needs.

2 Scientific significance and social benefits

2.1 Scientific significance

Neutron scattering is an important tool to investigate the microstructure and dynamics of matters. It was used to directly measure the natural occurrence of antiferromagnetism (AFM), confirming French scientist Neel's hypothesis on the AFM interaction for which the 1970 Nobel Prize in physics was awarded. Neutron-diffraction measurement of magnetic ordering helped to lead the magnetic interaction theories to maturity and contributed significantly to many-body condensed matter theories and experiments. The neutron-scattering spectrum of electron self-energy in tradition superconductors is amazingly consistent with the results of superconducting tunneling experiments, confirming the electron-phonon interaction BCS theory. Shull (USA) and Brockhouse (Canada) were awarded the 1994 Nobel Prize in physics for their pioneering neutron-scattering techniques[7]. The third-generation Nd-Fe-B rare-earth permanent magnet, whose fabrication and application have given rise to a billion-dollar industry, has its crystalline and magnetic structure first determined by neutron scattering. In a wide range of research areas including physics, chemistry, bioscience, material science and nanoscience, neutron scattering has important applications, striving for scientific breakthroughs in topics like quantum modulation and control, protein interaction, and high-temperature superconductivity mechanism.

Spallation neutron sources arrived later than reactors but developed rapidly. The much higher flux of short-wavelength neutrons and the TOF method provide special advantages, resulting in productive applications and research results like rapid acquisition of high-resolution structure data at large momentum transfer enabling ab-initio structural determination, detailed study of phonon density of states, and investigation of the function of hydrogen bonds in organic molecules. The structure of Y-Ba-Cu-O high-temperature superconductor at liquid nitrogen temperature was determined through IPNS powder diffraction experiment[8]. Using ISIS instruments, scientists measured the phonon and spin fluctuation over the full Brillion zone of high-temperature superconductor, hydrogen motion in inorganic materials and hydrogen bonds in organic molecules, providing direct experimental observation for the understanding of high-temperature superconducting mechanism and hydrogen dynamics.

CSNS project is expected to be completed around 2015, providing a powerful multidisciplinary research platform to study structures and dynamics of material systems in a wide range of areas. Chinese scientists are expected to conduct cutting-edge scientific researches at the CSNS, pushing for breakthroughs in research areas where the nation has made notable progress, like high-temperature superconductivity and its mechanism, rare earth magnets, nanoscience and technology, gene and protein engineering. For example, high-temperature superconductivity is believed to be closely linked to phonon and magnetic excitations, for which neutron scattering is the ideal experimental tool. Such a tool, when used at multiple levels in combination with other methods, would reveal subtle interactions in the charge, spin, orbit, and lattice of studied systems to determine the microscopic mechanism of high-temperature superconductivity and, eventually, provide practical guide to develop novel high-temperature superconductors. The other example is on the hydrogen ion (proton), like formation and dynamics of hydrogen bond which plays crucial role in life activity. Hydrogen ion has the same charge as electron but a mass between that of electron and other heavy ions. Description of hydrogen dynamics appears to be beyond the scope of current condensed-matter theory. Neutron's sensitivity to hydrogen atoms made neutron scattering the ideal method to provide convincing experiments enabling development of new condensed-matter theories for hydrogen motion.

2.2 Social benefits

CSNS will not only enhance the nation's capability in frontier science to raise country's fundamental research and technology level, but also stimulate the technological development in energy, national defense, and industry. The so-called "combustible ice" is a clathrate or cage compound consisting of ice trapping and containing small organic molecules like methane, a new type of fossil fuel with considerable future potential. As notable amount of "combustible ice" sea beds was found in the South Sea of China, identifying technological means to exploit the natural resources comes onto the national research agenda. In the recent report by the National Development and Reform Commission (NDRC) "China Alternative Energy Development Review", the nation is investing 800 million CNY in the next decade to develop survey technologies for clathrate exploration. CSNS's neutron-diffraction instrument at high-pressure environment will enable the study of formation mechanism and stability behavior of such clathrates, laying the scientific foundation for safe and efficient extraction and utilization of this alternative-energy source.

China is actively developing the advanced nuclear energy technology of accelerator-driven subcritical reactor systems (ADS) to overcome the nation's shortage of fission fuel and the technological bottleneck of nuclear waste treatment. CSNS's technological developments in high-intensity accelerators and high-power neutron target station and the experience in project integration will serve ADS directly.

The proton beam produced by the high-intensity accelerator of CSNS can be used to study space-irradiation effects on astronomical devices, assessing radiation damage of special materials and electronics and improving service lifetime and reliability of space devices. Protons and neutrons generated by the CSNS are also advanced radiation sources for cancer therapy, contributing to the nation's health and medical services.

Developing efficient small-angle-scattering instrument at CSNS serves petrochemical industry in crude oil grade and ingredient analysis, as well as morphology and efficiency study of fuel additives. By measuring the stress and defects in engineering materials and components, neutron scattering assists in reliably determining durability and product lifetime. Neutron scattering also has wide industrial applications such as stress distribution and occurrence study in welds, multiple-phase distribution and property analysis in deep-draw metal plates, structural analysis of high-density material of electroplating, and for material manufacturing and processing control. The high penetration power of neutrons from spallation sources facilitates neutron radiography application, a non-destructive method complementing X-ray and gamma-ray radiography, applicable to a wide range of engineering fields such as aerospace, space and missile components' structural examination, nuclear reactor component defect study, and archaeological and geological investigations. A pulsed neutron source like CSNS is especially suitable to conduct experiments under extreme conditions such as high temperature, high pressure, sample in rapid motion and under high radiation environment.

As a national multidisciplinary scientific facility, CSNS will provide an excellent platform for knowledge integration and advanced learning in China's physical sciences. Phase I of CSNS will witness its three world-class neutron-scattering instruments supporting collaborative research work of hundreds of scientists and engineers from multitudes of research institutes, departments, disciplines, and fields across the entire China, and the user number is expected to grow along with the gradual completion of all planned instruments and upgrades.

3 Neutron scattering applications

The wedge diagram of Fig. 2 illustrates the growth by decade of application fields of neutron scattering since about 1960s. When ISIS was first commissioned in the 1980s, it served about 300 users per year. Nowadays the number of annual users exceeds 1500. We expect similar growth trend of domestic users served by CSNS. As neutron scattering techniques are developed and comprehended, ever increasing demands are expected for spallation neutron sources from the domestic scientific community.

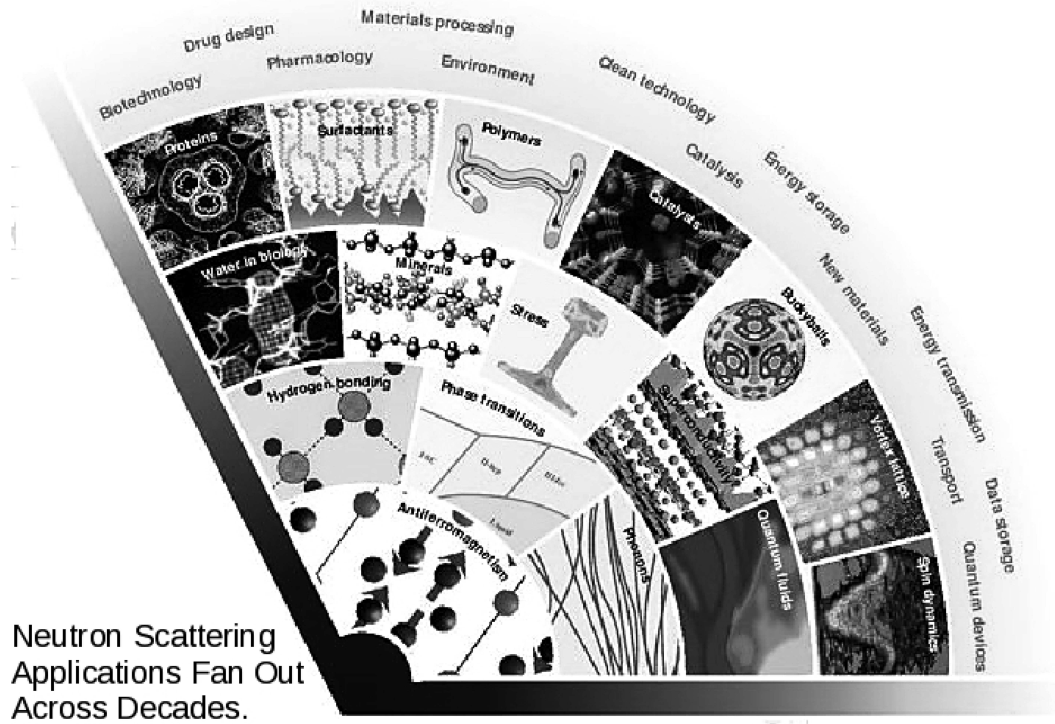

Fig. 2. Fields of application of neutron scattering during the past four decades (courtesy of ISIS, http://ts-2.isis.rl.ac.uk/scienceCase/isisTS-2Summary.pdf).

According to the fields of application of spallation neutron sources, some notable examples are given below.

3.1 Physics

Condensed matter physics is where neutron scattering research started. Development of the field and improvements in neutron-scattering techniques have greatly extended applicable subjects: (1) The high pulsed flux of spallation source compensates the disadvantage of small sample size of single crystals, so that measurements can be made to deliver complete data on magnetic correlation and fluctuation, driving exploratory research on high-temperature superconductor theory and material discovery[9]; (2) High-flux epithermal neutrons and energy selection techniques of spallation sources are ideal to the study of hydrogen dynamics under various conditions and in different environments, developing new condensed-matter theories for hydrogen; (3) Neutron magnetic scattering enables the study of quantum systems and effects like quantum criticality, quantum Hall effect, and heavy fermions to lay the scientific foundation for quantum control of electron and spin. It is also widely applied in the research of magnetic ordering and phase transition in d and f electron systems; (4) Features like the intrinsic pulsed time structure and high flux distribution of epithermal neutrons are especially advantageous to the study of relationship between microscopic structure and magnetic, thermal, electrical, and optical properties of organic polymer materials; (5) High-flux cold neutrons and neutron reflectivity techniques enables the study of surface physics and surface magnetism. (6) Neutron's high penetration power of and the time-of-flight technique make the pulsed neutron source an ideal platform to study material behaviors under extreme conditions like high temperature, high pressure, cryogenic temperature, and high magnetic field[10].

3.2 Nanoscience

Nanoscience as a research frontier covers a wide range of fields including physics, chemistry, bioscience, material science and surface/interface science. The intense cold neutrons generated by CSNS cover the full nano-scale of wavelength, providing an ideal probe to investigate morphology, dimension, and structural and kinetic behaviors of nanomaterials. Some selected research topics are: (1) Study of self-assembly of DNA in molecule recognition on the nanometer scale; (2) Identification of topographic features of carbon nanospheres and nanotubes, and study of their attachment behavior and property with atoms and small molecules[11]; (3) Investigation of the growth mechanism of nanometer crystallines in amorphous metallic materials, the effects of the annealing process, and the effect of nanometer crystalline dimension, morphology and distribution on material properties; (4) Recording of chemical self-growth process of nanostructure, and the effects of structural features and external conditions on such growth; (5) Study of magnetic nanostructure, magnetic interaction between such structures, and superparamagnetic and macroscopic quantum effects.

3.3 Life sciences

Breakthroughs in protein research are anticipated in the post-genome area. In complement to synchrotron X-ray scattering, neutron scattering provides new research tools to study protein structure: (1) The high-resolution reflectivity technique can be used to study membrane protein morphology and metabolism; (2) In combination with hydrogen isotope contrast-enhancing method, the neutron-diffraction technique can be used for structural determination of protein functional groups, protein labeling, and enzyme kinetics study; (3) High-resolution inelastic and quasielastic neutron-scattering techniques can be used to investigate protein folding and configuration dynamics; (4) High-flux small-angle-scattering technique can be used to map protein shape, size, interaction, and enzyme reaction sites; (5) The combination of small-angle and reflectivity techniques enables the study of viruses under different conditions, the entry mechanism of viruses into a cell through membrane and subsequent pathological reactions, and the effects of external conditions on cell membrane morphology and function.

3.4 Chemistry

Neutron-scattering techniques are widely applied in chemistry assisting in the study of complex chemical reactions and associated products. (1) The intense epithermal neutrons and the collection of neutron-scattering techniques can be applied in the study of a wide range of complex hydration, hydrolysis, and hydrocatalytic reactions; (2) The excellent pulsed time structure and the high-flux epithermal neutrons are especially appropriate for the study of chemical and crystalline structures of large molecules; (3) Small-angle scattering and reflectivity techniques can be used to study synthesis of co-polymers, polymer reactions with tunable structures, dynamics of polymer structures, and polymer morphology, structure, and their relationship to macroscopic properties; (4) Diffraction and small-angle scattering techniques can be combined to study the structural features and catalytic mechanisms of porous materials and other catalytic systems.

3.5 Material science

Neutron scattering strongly supports the research, development, and application of advanced materials: (1) Clean-energy materials can be studied by the isotope contrast method in topics pertaining to hydrogen position, bonding, and release; (2) Using neutron-diffraction and quasielastic-scattering methods, ion diffusion and electrochemical behaviors of high-energy-density fast ionic conductor battery materials can be studied; (3) Single-crystal diffraction and inelastic scattering can be applied to the study of phase transitions in ferroelectric and pizzoelectric materials, and softening of special phonon modes; (4) Magnetic neutron scattering can be used to study magnetic structure and magnetic domain change in magnetic functional materials leading to discovery of new materials; (5) The high-penetration and high-flux features can be used to develop neutron computed-tomography (CT) scan applicable to bulk industrial material with resolution up to millimeter level to guide material processing; (6) The high momentum transfer (Q) limit reachable by the spallation diffractometers provides a direct and reliable means to determine the phase composition of composite materials.

3.6 Environment science

(1) The neutron-reflectivity technique provides the means to study polymer surfaces in their attachment, reaction processes, and reaction efficiencies to different gases and liquids, which are essential to the development of environment-friendly polymer materials; (2) The high-pressure neutron-diffraction technique can be applied to the study of hydrate formation and stabilization of green-house gases, e.g. CO_2, elucidating scientific feasibility of deep-sea greenhouse gas disposal. (3) The high Q data of the diffractometers can be used for direct, quantitative study of heavy-element concentration and their chemical environment in the pollutant of toxic-metal complexes.

3.7 Medical science

(1) The neutron-scattering technique can be used to study structures of drugs and drug-receptor interactions, providing scientific basis for drug selection, improvements, and discovery; (2) Proton beams generated by the accelerator can be used for popular isotope production and new-isotopes development for medical purposes.

4 China spallation neutron source

4.1 CSNS facility

The overall scientific goal of the China Spallation Neutron Source (CSNS) project is to build a world class multidisciplinary research platform meeting the national needs by providing powerful neutron-scattering experimental means in research areas including life science, material science, physics, and chemistry. CSNS facility consists of an 80 MeV H^- linear accelerator (linac), a 1.6 GeV rapid cycling synchrotron (RCS), beam transport lines, a target station, and three sets of instruments with auxiliary equipments. CSNS has a design beam power at 25 Hz repetition rate of 100 kW upgradeable to 500 kW. The effective neutron flux is expected to be up to $2\times10^{16}\mathrm{cm^{-2}s^{-1}}$.

CSNS adopts the design of a relatively low energy linac followed by a RCS ring. In comparison to an alternative design of full energy linac in combination with an accumulator, such a design has a lower construction cost while providing excellent upgrade capacity. CSNS' target station newly adopted a rotating-disk design made of solid tungsten material to generate spallation neutrons. Three day-one instruments are high-flux power diffractometer, small-angle diffractometer, and multipurpose reflectometer.

The CSNS design incorporated the latest developments in world-wide accelerator, target station, and instrumentation technology, aiming at building a world-class neutron facility. The choice of 25 Hz repetition rate significantly increases the effective long-wavelength neutron flux and scattering-neutron efficiency per pulse, which are especially helpful for the biological and chemical study of large molecules and clusters; selection of the first batch of instruments meets the urgent research needs from life science, material science, nanoscience, physics, and chemistry.

Figure 3 shows the CSNS facility layout. Negative hydrogen beams generated by the ion source (IS) are first bunched and accelerated by the radio-frequency quadruple accelerator (RFQ). The beam energy is further raised by the drift tube linac (DTL). After charge-stripping injection, the proton beams are injected into the RCS and then accelerated to the final energy of 1.6 GeV. The extracted proton beams are transported to the target station bombarding the tungsten target to generate spallation neutrons. After moderation, the neutrons are directed to the instruments through neutron guides for neutron-scattering experiments.

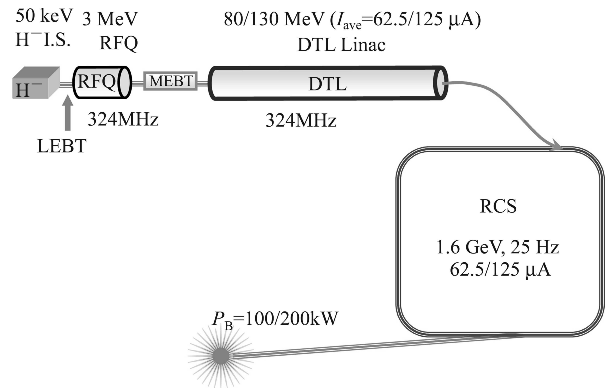

Fig. 3. Schematic layout and parameter configuration of the CSNS accelerator complex.

4.1.1 Accelerator system

Accelerator system is the foundation of a spallation neutron source, which largely determines the technical performance of a facility and incurs the majority of its construction cost. Operation stability of the accelerator system also determines the overall facility efficiency. The CSNS accelerator design was conducted with the philosophy of leading-edge technology, stable operation, reasonable expenses, and excellent upgradeability. RFQ is an accelerator structure increasingly used in a wide range of applications at low beam energy capable of beam focusing, bunching, and acceleration at the same time. It helps to overcome space-charge effects on a low-energy high-intensity beam and significantly improves beam quality. The CSNS DTL uses a higher frequency (324 MHz) of radio-frequency (RF) power supply, rather than the traditional 202 MHz, to help accelerate the beam under higher peak current, shorten the linac length and lower the construction cost. The CSNS RCS design includes a series of advanced technologies including large-aperture ceramic vacuum chamber, main magnet of aluminum stranded coil with inner water cooling and resonant white-circuit power supply and ferrite-loaded RF cavity. Most of these technologies are developed domestically in China for the first time, significantly enhancing the technological capabilities of related domestic industries.

4.1.2 Target station

A neutron target station converts high-energy proton pulses into pulsed, lower-energy neutron beams suitable for neutron-scattering experiments. When a high-energy proton beam from the accelerator system strikes the heavy-metal target, a large number of neutrons are generated through the spallation process. These neutrons are subsequently slowed-down by moderators to proper energies for neutron-scattering experiments. CSNS adopts a three-moderator design to output high-flux pulsed neutron beams of three different characteristics. The design is optimized for technical requirements on neutron wavelength, energy, flux, and resolution demanded by various research subjects. These three moderators supply a total of 18 beam ports for instruments, among which three will be constructed for the phase I of the project.

4.1.3 Neutron scattering instruments

Neutron-scattering experiments are carried out on various instruments surrounding the target station. The CSNS design adopts many state-of-art neutron instrumentation features such as super-mirror guides and novel detector layout to improve the experiment efficiency and instrument resolution. Besides the conventional T0 chopper to lower the background noise, curved guides are also used to remove the fast-neutron and gamma-ray signal noise. Sample environment equipments will be built according to the international standard to facilitate sharing among instruments. Advanced scientific computing methods and the latest information technology tools are also planned for online and offline data control, visualization, analysis, and management.

4.2 Longer term planning

The CSNS is the first large-scale scientific project strategically located in southern China. The construction site is on a hilly green field of approximate 160 acres within the Dalang Township, Dongguan City, Guangdong Province. Phase-I of the project will use about 70 acres of land. Fig. 4 is the landscape rendering of the planned CSNS facility.

Although lagging behind the megawatt-level spallation facilities currently under development in USA and Japan, CSNS ranks among the world's top-class facilities with the design beam power and neutron flux, which are capable of meeting most neutron-scattering experiment needs in China. With the expected service lifetime of over 30 years, careful considerations were made in the design stage to maintain upgrade capacity at the minimum initial cost.

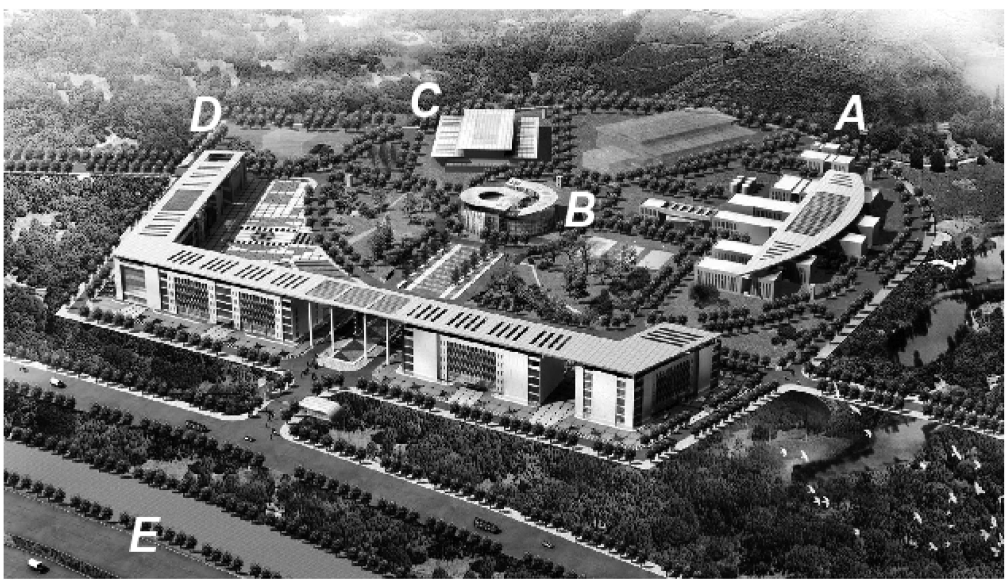

Fig. 4. The planned CSNS facility layout.
A. linac; B. RCS; C. target station; D. user building; E. Changhu highway.

A segment of space is resered after the 80 MeV linac so that the linac beam energy can be increased in the future to 130 MeV or 250 MeV. Consequently, the beam power incident on the target station can be raised to 240 kW and 500 kW, respectively. The number of neutron instruments will gradually grow to the full 18 set for the first target station. Land is also allocated for the construction of a second target station.

To better serve scientific users, a complete set of conventional laboratories will be built on the CSNS site for sample preparation and pretreatment. Future development also anticipates a multidisciplinary research center covering wide areas in physics, chemistry, material science, and computational science evolving around core neutron applications.

The CSNS accelerator will be the nation's first high-energy, high-intensity proton accelerator complex. A wide range of potential applications exist for such a device. In the project's technical design and facility planning stage, such possibilities were taken into consideration. Correspondingly, the upgrade path was reserved.

For example, besides the injection into the RCS, the hydrogen beam accelerated by the linac can serve many other research works: (1) The 80 MeV proton beam can be used for superficial carcinoma therapy; (2) After the linac beam energy is upgraded to 250 MeV, or with the addition of a booster ring, full-body proton beam therapy becomes available; (3) The proton beam can be used for the boron-neutron capture therapy (BNCT) and fast neutron therapy; (4) Assessment of space-irradiation effects including bio-effects of space irradiation, radiation dosimetry, irradiation damage on electronics and instruments, and single-particle effects, as well as topics that are especially important to the nation's space science and technology advancement; (5) Other research work serving national interests, e.g. radiation breeding.

Besides being transported to the neutron target station, the high-energy beam extracted from the RCS at 1.6 GeV energy can be branched to serve research areas beyond the conventional neutron scattering: (1) Build a muon and fast-neutron research platform by passing a high-intensity proton beam through one muon thin target and a subsequently placed white-neutron-source target to generate high-flux muon beam and wide-spectrum neutron beam. Muon's special property of spin rotation, relaxation, and resonance can be applied to a wide range of research topics including microscopic magnetic-structure study and muon-assisted nuclear fusion. QED study using muon-atom (muon capturing one electron) and pulsed laser is an interesting subject. Cross section measurements of fast/high-energy neutrons interacting with nuclei in the energy range from a few eV up to several hundreds of MeV provide fundamental data to fields of nuclear technology, astrophysics, and particle physics. High-flux neutrons can also be used in neutron radiography and material irradiation studies; (2) Conduct researches on high-energy space-irradiation effects; (3) Conduct researches on proton radiography for applications in national defense, medical imaging and material structure researches.

The accelerator driven subcritical systems (ADS) R&D can be carried out on CSNS using either the 80—250 MeV linac beam or the 1.6 GeV RCS beam. A subcritical reactor needs to be built for the tests.

Larger-scale research facility can be further constructed based on the CSNS accelerator complex. For example, the proton beam from the CSNS RCS at 1.6 GeV energy can be injected into a new, higher-energy synchrotron accelerator (about 1200 m circumference, 30 GeV output energy) enabling fundamental researches including neutrino and antiproton physics.

In summary, a world-class national scientific research center based on a spallation neutron source is to be constructed at Dongguan, Guangdong to serve the nation's strategic needs in scientific research and technological innovation for the next 30 years.

References

1 CSNS Project Team. China Spallation Neutron Source Project Proposal. Institute of High Energy Physics and Institute of Physics, Chinese Academy of Sciences, 2007 (in Chinese)

2 Lengeler H, WEI J. Spallation Neutron Source. In: Chao A and Tigner M ed. Handbook of accelerator physics and engineering: a compilation of formulae and data. Singapore: World Scientific Publishing Co., 1998; third Printing, 2006. Section 1.6.17

3 WEI J. Reviews of Modern Physics, 2003, **75**(4): 1383—1432

4 Spallation Neutron Source: The Next-generation Neutron Scattering Facility for the United States. Department of Energy, 1998. SNS website: http://www.sns.gov, 1998

5 Oyama Y. Nucl. Instrum. Methods Phys. Res. A, 2006, **562**(2): 548—552; J-PARC website: http://j-parc.jp/index-e.html

6 A Second Target Station at ISIS. Council for the Central Laboratory of the Research Councils, 2000. RAL-TR-2000-032; website: http://ts-2.isis.rl.ac.uk/

7 Brockhouse B N. Slow Neutron Spectroscopy and the Grand Atlas of the Physical World; Shull C G. Early Development of Neutron Scattering. In: Ekspong Ggosta ed. Nobel Lectures in Physics 1991—1995. Singapore: World Scientific Publishing Co., 1997

8 Jorgensen J D, Veal B W, Nowicki L J et al. Physical Review B, 1990, **41**(4): 1863—1877

9 DAI P, Mook H, Hayden S M et al. Nature, 2000, **406**(6799): 965

10 MAO W L, MAO H, Goncharov A F et al. Science, 2002, **297**(5590): 2247—2249

11 Kolesnikov A I, Zanotti J M, Loong C K et al. Phys. Rev. Lett., 2004, **93**(3): 35503-1-4