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The Past and the Future of the TRIGA Reactor in Vienna

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Abstract: During the past five decades, the TRIGA reactor Vienna has reached a top place in utilization among low power research reactors. This paper discussed the highlights of the major neutron physics experiments in the field of neutron interferometry and ultra-small angle neutron scattering as well as in the field of radiochemistry, education and training and research in the field of nuclear safeguards and nuclear security. Potential further directions of research are outlined where the Atominstitut of Vienna might concentrate in future.

Key words: TRIGA reactors, research reactors, neutron and solid state physics, neutron interferometry, ultra small-angle neutron scattering, education and training.

1. Introduction

After the "Atoms for Peace" speech of President Eisenhower in December 1963, many low power research reactors were built all over the world, this was the boom-time for TRIGA reactors. Totally about 70 TRIGA reactors were built world-wide, later some other research reactors were converted to TRIGA type fuel, today about 35 TRIGA reactors are still in operation. The contract for the Vienna TRIGA was signed in 1958, the foundation was laid in August 27th, 1959 and the reactor reached first criticality after 2.5 years on March 7th, 1962, being located only five metro stations from the city centre, a fact which would be totally impossible today. Other than the 10 MW ASTRA reactor in Seibersdorf, the TRIGA reactor was fully devoted to university education in the nuclear field, a mission which was strictly followed throughout the last five decades. All technical data of the TRIGA reactor in Vienna were published at many conferences and can also be found in the Atominstitute's webpage [1]. During the past 49 years, the most important and internationally recognized experiment was carried out in the field of neutron interferometry [2-6] that is discussed in detail in Section 2.1.

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2. Major Neutron Physics Experiments

2.1 Interferometer

In 2011, 37 years have passed since the first perfect crystal neutron interferometer was tested by an Austrian-German cooperative group at the 250 kW TRIGA reactor in Vienna [1, 2]. Since that time, neutron interferometry became a laboratory for quantum mechanical test experiments. The key feature of this technique are two widely separated coherent beams of thermal neutrons (λ ~ 1.8 Å, E ~ 0.025 eV) which are produced by dynamical Laue-reflection in a properly shaped perfect silicon crystal (Fig. 1). Analogies exist to the Mach-Zehnder type interferometers used in light optics and to the Bonse-Hart interferometers developed for X-rays [3].

Neutron interferometry has been used for a series of quite spectacular fundamental quantum mechanical experiments, a most complete synopsis of results is given in Ref. [4]. Recent achievements are the demonstration of Bell's inequality with single neutrons [5], measurement of topological phases [6], and of confinement induced quantum-phase [7]. One remarkable experiment with the neutron interferometer

Fig. 1 All neutron interferometers used at the Vienna TRIGA reactor or at the high flux reactor of the ILL, Grenoble were manufactured and tested at the Atominstitut.

was the determination of the coherent neutron scattering length of gaseous natural krypton and its isotope ^{86}Kr [8]. While the result for natural krypton was in excellent agreement with existing literature, the result for the isotope represented the first experimental value, and in fact the first experimental value for any of the krypton isotopes. During data analysis, it was found that the accuracy of the results was mainly determined by the stability of the setup and not by the limited neutron flux. These results obtained at the small reactor proved that competitive neutron interferometric results may be obtained also at small neutron sources provided that a stable setup is used. It may be added that for these measurements the reactor was unconventionally operated 24 h a day.

Although the majority of these experiments had to be performed on the high flux reactor of the ILL (Institute Laue-Langevin), Grenoble, simply because of intensity reasons, it was essential to conceive and to prepare them at the TRIGA reactor in Vienna as well as to test the functionality of the various components of the final setup.

2.2 USANS (Ultra Small-Angle Neutron Scattering)

USANS (ultra-small-angle neutron scattering) is a technique which enables to follow neutron diffraction to extremely small angles, and when cleverly done, even into the forward direction where it overlaps with the non-scattered transmitted incident beam. It relies on the very narrow angular reflection width of perfect single-crystals and is realized as a multi-bounce perfect silicon double crystal diffractometer. While primarily designed for materials characterization in the μm-range—which follows from the use of thermal neutrons and widths of a typical instrument resolution function of the order of μrad—these instruments may also be used for fundamental investigations related to the coherence properties of neutron beams and the macroscopic limits of neutron diffraction. A beautiful example of such measurements was diffraction and multi-beam interference from artificial lattices [9]. Corresponding experiments were performed at the USANS facilities of the Atominstitut and of the S18 instrument at the ILL in Grenoble. There, we observed diffraction patterns from samples being periodically structured in one and two dimensions. These measurements took advantage of the extended coherence function of the setup and the high quality of the manufactured silicon sample lattices. The diffraction pattern of a line grating with 32 μm lattice constant was obtained at both instruments in Grenoble and Vienna. Due to the much narrower resolution function, resulting from the (331) silicon reflections employed, the interference orders were completely resolved with the Viennese instrument while the diffraction pattern recorded at S18 was a superposition of several interference orders. This showed that, given the proper experimental context, neutrons may be coherently diffracted by structures whose size is of the order 0.1 mm. It is clear, specifically at the small reactor, that all these phenomena are related to multi-beam self-interference of the neutrons.

USANS has been extended to the study of magnetic structures by using polarized neutrons in recent years (USANSPOL). The initial instrument arrangement and first experimental results are closely connected with the Vienna TRIGA reactor [10]. The neutrons are loss-free polarized by permanent magnetic prisms located between the monochromator crystal and the sample. Neutrons with opposite spin states are separated by the diffraction angle of the prisms and their different scattering behavior may be studied in a single measurement without additional manipulation of the neutron spin. In this manner, the authors are able to separate the magnetic and nuclear contribution to the scattering. In Ref. [10], the authors presented first exemplifying measurements on ferromagnetic rods and wires, and on soft-magnetic ribbons. Again, these experiments were performed at the USANS facilities in Vienna and at the combined neutron interferometer/USANS instrument S18 at the ILL, Grenoble. With the measurements in Vienna, e.g., the authors could beautifully demonstrate the birefringent nature of magnetic lens refraction.

The use of polarized neutrons in neutron optical instruments like neutron interferometers and USANSPOL diffractometers relies on the practically loss-free polarization of the incoming neutron beam. Spin-dependent birefringence of neutrons upon passage through the air gap of a prism-shaped permanent magnet yoke can be used to split a thermal neutron beam in two polarized sub-beams with slightly different directions. Using then a sequential arrangement of two such prisms, a splitting larger than twice the width of the instrument resolution function is achieved and yields a maximum beam polarization of about 97%-98%. This was first demonstrated at the Vienna TRIGA reactor [11]. Such polarizes are now routinely employed in the neutron optics instruments in Vienna and Grenoble.

Model samples with known parameters, especially silicon phase gratings will help to better understand the basic features of the USANS technique and clarify the performance of the instruments involved [12-14]. Corresponding measurements were performed at the USANS facility of the Atominstitut. These experiments are of fundamental interest as well since the diffraction patterns result after quantum mechanical multiple-beam interference of the neutron particle waves.

3. Other Major Reactor Applications

3.1 Radiochemistry

The radiochemistry group of the Atominstitut has a long tradition in neutron activation analysis. Some highlights of this work illustrate the wide applicability of this method. The geological event at the Cretaceous-Tertiary Boundary had caused global environmental as well as climatic changes. Its traces have been found in geological formations in the Gosau Basin (Austria) and could be characterized by NAA (neutron activation analysis). The abundance of geomarkers such as iridium—an element that can be determined by NAA with extreme sensitivity—makes a “meteorite hypothesis” most likely for this galactic event [15].

Since many years, the radiochemistry group is working in the field of archaeometry. Originally, this work was primarily focused on provenance studies of pumice (a volcanic rock)—more than 500 pumice lumps could be provenance over the past decade, however, the group is constantly expanding the focus of analytical techniques for archaeometric challenges. Recent topics are provenancing of obsidian, ceramics, clay tablets and still pumice. The data obtained by the radiochemistry group allow the establishment of chronologies, trade routes and relative age determination and hence are of great importance for archaeologists and historians [16-19].

The main future focus will be environmental analysis, especially the environmental impact of the Fukushima reactor accident in the environment. In this project, information will be gathered from official statements and measurements to provide a sound chronology and identify the seismic and nuclear reasons for the accident. The current scientific prognosis of long-term healthy and environmental consequences will be explored, focusing on the effects attributable to radionuclide release and dispersion. Advice will be provided for implementation of future programs on disaster management and mitigation.

3.2 Education and Training

Since the mid-1980s, the Atominstitute is engaged in training and educational courses not only for national students but also for international course participants. The first institution taking advantage of the TRIGA reactor in Vienna was the IAEA (International Atomic Energy Agency) starting with a Safeguards Traineeship program carried out in a two years cycle since 1984. Since that year, the Atominstitute has trained over 90 junior safeguards inspectors. Parallel to this courses, the Atominstitute hosted more than 125 IAEA fellows from all over the world being attached to one of the researchers as coordinator for a period between one to twelve months. Since the early 1990s, an increasing number of courses for external participants were organized such as retraining of NPP (nuclear power plant) staff from NPP Bohunice and Mochovce, retraining for Mol research reactor operators and regular courses for the UK NTEC (Nuclear Technology Educational Consortium) with two courses per year. Another Central European initiative is the EERRI (Eastern European Research Reactor Initiative) under the coordination of the IAEA where junior technicians and engineers from nuclear emerging countries are trained at several research reactors in this region. The duration of the training program is 6 weeks and covers about 30 topics ranging from theoretical lectures to practical experiments at the reactors grouped into three main areas; organizational matters, research reactor operation & maintenance and radiation protection. Currently, the following institutes are involved in this project:

- VUT/Atominstitute (Vienna University of Technology/Atominstitute), Austria;
- KFKI Budapest, Hungary;
- Budapest University of Technology, Hungary;
- Institute Jozef Stefan, Ljubljana, Slovenia;
- Technical University of Prague, Czech Republic;
- Research Centre Rez, Czech Republic.

Beyond academic education both education and early information at the college level are very important to attract the young generation to basic nuclear knowledge which may later lead towards further academic nuclear education. Due to these factors, besides its regular academic programs, the ATI has recently established a new program for college students just before their certificate for university studies (17 to 18 years of age). In co-operation with dedicated physics teachers, two full day courses have been carried out in December 2010 to interest potential future university students in nuclear physics and nuclear technology.

3.3 Safeguards and Security

Another important cooperation with the IAEA is Nuclear Safeguards and Nuclear Security research. As closest nuclear facility to IAEA, the ATI has a number of SNM (samples of special nuclear material) stored for the IAEA which is regularly used for test measurements, re-calibration of various safeguard instruments and for IAEA retraining of safeguards inspectors. These samples are also used to test and improve hand-held RID (radioisotope identifier devices) used as anti-smuggling devices. At the ATI about 20 Master Thesis projects and five Ph.D. Thesis projects have been carried out in this field with special focus on environmental effects on these detectors and on tests and improvement of the installed software. A typical example is the suppression of medical isotope signals in hand-held portable gamma spectrometers to avoid unnecessary alarms at ports of entry, in this case trespassing patients with incorporated radionuclides can be distinguished from malevolent smugglers. Another interesting experiment was the detection of SNM behind several tons of fertilizer on a truck to determine the minimum detectable amount of SNM by hand-held radioisotope identifiers.

4. Potential Future Use as Neutron Source

4.1 Neutron Optic Experiments

Quite recently, the station NIS (neutron interferometry station) is renovated by modifying and re-adjusting a focusing monochromator [20]. Now an optical bench is completely renewed, which is much more compacted than the old one and equipped with new anti-vibration and thermal insulation systems, more intensity with higher stability is expected. This interferometer setup is essential for students to directly access a matter-wave interference instrument on a macroscopic scale: A number of practical courses as well as Master Theses were carried out recently. It should also be emphasized that the interferometer setup has also been used for preparation and test of individual optical elements, which were used for measurements at the high flux interferometer setup S18 at the ILL, Grenoble in France. Major neutron interferometer experiments are performed at the ILL and it is essential to develop optical elements "at home" in advance due to limited beam time at the ILL.

New developments and application is expected in the field of ultra-small-angle neutron scattering both in the unpolarized USANS and the polarized USANSPOL versions. Due to the limited neutron flux, specifically with neutron beams monochromated by perfect single-crystal reflections, large diffracted or scattered intensities are necessary for application at the Vienna TRIGA reactor. Phenomena related to this include multi-beam interference [21], refraction [10] and strong nuclear/magnetic contrast combined with intermediate structure size [22]. The issue of coherence properties of thermal neutron beams holds still potential for a considerable amount of future work and artificial lattice microstructures in one and two dimensions represent one of the proper keys to tackle this topic. These structures may be manufactured as phase gratings, partly absorbing entities or from magnetic materials to produce birefringent phenomena. The investigation of domain sizes in novel magnetic materials of technological relevance, often with exceptional magnetostriction properties [22], can profit from the ultra-high resolution of the Viennese instrument. Application of external parameters like magnetic field and mechanical stress is indispensable for a complete neutron characterization of these materials. With increasing magnetic order within the sample, the domains evolve towards macroscopic dimensions which concentrates neutron scattering increasingly around the forward direction and compresses the scattering signal around the instrument resolution function [23]. The very-low scattering vector limit of our instrument allows to follow the evolution to the largest domain sizes which are possible by this technique. An overlap with imaging techniques is the ultimate goal which would connect real space measurements with traditional SANS investigations and provide for a complete picture from atomic clusters to macroscopic sample structure. The development of an appropriate sample environment for related USANSPOL studies is currently underway [24]. These studies may be complemented by 3D neutron depolarization measurements where a corresponding experimental setup is also available at the Vienna TRIGA reactor. Related studies for an implementation of this scheme are currently carried out by our group.

The development of new experimental methods in polarized neutron physics and instrumentation has always been at the forefront of neutron research activities at the Atominstitut. Such new techniques will be of particularly renewed interest in the context of the upcoming European neutron spallation source ESS. A recent project which shows prospects in that direction but offers also exciting possibilities at reactor-based continuous neutron sources is the revival of the concept of spatial magnetic spin resonance [25], a concept which dates back to the 1960s and was invented by Drabkin in Russia. By this method, wavelength selection of polarized neutrons becomes possible based on the fast electronic switching of magnetic fields. When combined with travelling magnetic waves, very versatile polarized neutron instruments are feasible that may change their key parameters in an instant. It was shown recently at the Atominstitut where a prototype resonator was realized and tested experimentally with microseconds resolution that this technique actually works [26]. This development has created immediate interest for triple axis spectroscopy and the beta decay instrument PERC which is built at the FRM-II in Munich. Considering the millisecond long neutron pulses foreseen for the ESS, such a resonator could be easily employed for arbitrary pulse shaping at various polarized neutron instruments. But this resonator is one example for the development work which is foreseen in the near future at the TRIGA reactor in Vienna.

Following in this respect, there is rapid international development in the field of polarized neutron imaging [27, 28]. Since the neutron physics group at the Atominstitut has a long tradition in both polarized neutron physics as well as neutron radiography and tomography imaging, the setup of an polarized neutron imaging instrument is an important issue for future activities at the Vienna TRIGA reactor, especially since fundamental methodic work from our group has contributed to this field in recent years [29].

A particularly attractive addition to the instrument suite of the Atominstitut would be the installation of a beamline for UCN (ultra-cold neutrons). The successful implementation of a UCN source into a TRIGA beam port was demonstrated at the Mainz 100 kW TRIGA reactor [30]. This UCN source, again at a small reactor, is competitive in ultra-cold neutron phase space density with much larger installations that defined the best achievable UCN density values so far. Such a facility may be used for fundamental investigations [31] as well as methodical development [32] as demonstrated in Mainz. This methodical work could directly influence the development of new projects, having again the ESS in mind.

4.2 Neutron Polarimetry

The neutron polarimeter apparatus turned out to be used for quantum interference experiments by taking a spinor rotation as a consequence of interference between up and down spin eigenstates, in contrast to the interference between the beams in path I and II in the interferometer. It is a big advantage of polarimetry that high intensity and high stability of the system is easily attainable also with a small reactor like a 250 kW TRIGA reactor. Needless to mention educational use, typically for practical courses, the neutron polarimeter setup for advance studies of quantum mechanical phenomena: i.e., a peculiar property of quantum in Physical Review Letters [33]. Quite simple configurations and easy access of the setup allow students to develop and improve individual optical elements by themselves, which is a reason why the setup is almost ideal for the use of Master and Ph.D. students. Recent works cover investigations of an alternative model of quantum mechanics with high precision [34] and a new form of Heisenberg's uncertainty relation [35], both give significant insight in the field.

Both neutron interferometer and polarimeter setups at the Atominstitute exploit the dual nature of neutrons, sometimes a particle and sometimes a wave, this enables wonderful manifestation of entanglement in addition to superposition in quantum physics. Such studies—not only on coherent interactions but also topological, non-local, gravitational, effects as well as contextual models of quantum mechanics—will be carried out further.

5. Conclusions

As it was shown in the previous chapters, there are many interesting projects to further increase the basic and applied research around the TRIGA reactor in Vienna. International cooperation with powerful neutron sources and with international organizations are of utmost importance. This past five decades have shown the obvious benefits, and this positive symbiosis is expected to continue beyond the US spent fuel return program.

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