Technische Universität München

REPORT ON

PARTICLE- AND FUNDAMENTAL PHYSICS AT ESS

TUM personnel involved **March 2017**

Bastian Märkisch
Camille Theroine

1 – Fundamental Physics at ESS: context and background

Over the past years three different instruments for particle and nuclear physics have been identified that would profit from the ESS and are actively pursued by the community:

- the cold beam line: ANNI,
- a beam UCN source, and
- the neutron-antineutron experiment: NNbar.

Today, all three instruments are pushed by specific consortia. For ANNI, a design is available and a full ESS instrument proposal was submitted jointly by scientists from ILL, TU Wien, SMI Wien, Heidelberg University and TU München. For the other two instruments detailed designs are not yet finalised but letters of intent (LoI) with preliminary gain factors were submitted. Development of all instruments is ongoing.

A Scientific and Technical Advisory Panel (STAP) for fundamental physics has been established and met three times, first to advise and later to review the instrument proposal and letters of intent.

The Scientific Advisory Committee of the ESS (SAC) received the proposal and the two LoIs but only discussed the proposal. The SAC recognised that ANNI '*would make full use of the brightness and pulse structure'* and *'enable an order of magnitude improvement […] which would be an important leap forward for this community*'. The SAC did not recommend the construction of a fundamental physics beam line at this point in time, but highlighted the '*important community which should be included in the ESS'*.

As a consequence, the community and ESS representatives met for the "Strategy Meeting on FP at ESS", organised by T. Soldner, C. Theroine, H. Abele, Gustaaf Broojmans, Mats Lindros, and B. Märkisch on 8 July 2016 at the ESS to discuss the future perspectives for fundamental physics at the ESS, see https://indico.esss.lu/event/607. The community was strongly encouraged by A. Schreyer to be a part of the ESS.

The purpose of this report is to present the current status of fundamental physics at ESS. This document shows the progress of the consortia including the evolution of technical needs, funding possibilities and opportunities, and the establishment of schedules. The participation in consortia meetings on behalf of ESS are also mentioned. The last part of this report deals with a discussion regarding the user community for fundamental physics.

This document was conceived as part of a R&D contract between ESS ERIC, Lund, and TUM. It focuses on the time period 2015-2017.

2 – Fundamental Physics at ESS: current status

The current status of the ANNI, NNbar and UCN collaborations are detailed in this part.

A – ANNI Collaboration

Current list of people/institutes involved in the collaboration

Hartmut Abele, Technische Universität Wien; Gertrud Konrad, Technische Universität Wien and Stefan Meyer Institute Wien; Bastian Märkisch, Technische Universität München; Ulrich Schmidt, Universität Heidelberg; Torsten Soldner, Institut Laue Langevin; Camille Theroine, Technische Universität München.

Contextual summary

(Extract from the executive summary from the ANNI proposal)

"ANNI is a cold neutron beam facility for particle physics at the ESS. This instrument will outperform all existing and planned cold neutron beam facilities in the field. It makes full use of the ESS pulse structure. User experiments which used pulsed beams at continuous sources will gain between one and two orders of magnitude in event rate. The time structure of the neutron beam enables powerful techniques to suppress systematic effects. These were rarely employed in the past due to related large intensity losses at continuous sources. At the proposed beam line they will be a natural asset.

The instrument will enable new science. Measurements in neutron beta decay will gain one order of magnitude in accuracy. Experiments will probe a broad band of new physics models beyond the Standard Model at mass scales from 1 to 100 TeV, far beyond the threshold of direct particle production at accelerators. For the first time, the tiny effects of hadronic weak interaction will be resolved for calculable systems and studied systematically. This will enable quantitative tests of the non-perturbative limit of quantum chromodynamics. Beam methods to measure electromagnetic properties of the neutron will improve substantially. This promises a systematically different access to these fundamental properties which are related to matter formation in the Universe or the unification of fundamental forces. Science at this instrument will cover a wide range at the precision frontier of particle physics.

Users develop their own instruments and install them at this new facility for extended measurement campaigns of months to years. Eligible experiments will be selected by an independent committee. The proposed initial scientific program covers more than a decade of research. Due to the outstanding and unique properties of this new beam line, it is expected to attract science groups not only from Europe but from all over the world.

ANNI is optimized for measurements of correlation coefficients in neutron beta decay. It includes an ep/n separator that collects charged neutron decay products from a long volume and guides them to secondary spectrometers built by the user community. The ep/n separator optimizes and extends the concept of the Proton Electron Radiation Channel PERC to the pulse structure of the ESS. Unprecedented accuracy of 10^{-4} on correlation coefficients in neutron beta decay will be reached and allow to explore the mass scales mentioned above.

To fully exploit the time structure of the ESS, the instrument will have a short curved guide of 20 m length and final cross-section of 112×70 mm^2. Radiation from the spallation target will be efficiently suppressed. Using frame overlap choppers, the beam line will provide full wavelength information in a selectable wavelength band of 6 Å width. The main working region of 2 Å to 8 Å includes about 90% of the total cold flux. Pulse defining choppers tailor the pulse to the installed user experiment. Pulse multiplication will be applied for experiments using spatial localization of neutron pulses. All neutron beam components are standard ESS technology and hence the risk is low."

Meetings and seminars

The proposers of ANNI work together closely within the PERC and PERKEO collaborations and hence meet frequently for discussions.

Since the official proposal to ESS in April 2015, ANNI is discussed frequently at national and international workshops and conferences. Below we list the most important ones within the last two years:

- H. Abele (TU Wien), *"Particle physics at ultimate precision with cold and ultra-cold neutrons",* 6th International Symposium on Symmetries in Subatomic Physics (SSP2015) in Victoria, Canada, from 08/06 to 12/06/2015

- E. Klinkby (ESS, DTU) presented the ANNI instrument proposal at the ECNS conference in Zaragoza from 30/08 to 04/09/2015. At this occasion a proceedings paper has been published in J. Phys. Conf. Ser. 746. The abstract of this paper is given below.

- T. Soldner, *"A cold neutron beam facility for Particle Physics at the ESS",* 2nd status meeting of the DFG Priority Programme "Precision Experiments in Particle and Astrophysics with Cold and Ultracold Neutrons" (SPP 1491, see Section 3), Wildbad Kreuth, Germany, 3-6 November 2015.

  This meeting assembled the German and Austrian communities working in particle physics with neutrons and was organized by TUM.

- C. Theroine, *"A Versatile Cold Pulsed Neutron Beam Facility for Particle Physics at the ESS: ANNI",* DPG spring meeting on Hadronic and Nuclear Physics, 14-18 March 2016, Darmstadt, Germany.

- B. Märkisch, *"A cold neutron beam facility for Particle Physics at the ESS",* International workshop *"Probing fundamental symmetries and interactions with UCN"*, Mainz, Germany, 11-15 April 2016, https://indico.mitp.uni-mainz.de/event/59/

- T. Soldner, *"A cold neutron beam facility for particle physics at the ESS"*, ESS, 7 July 2016.

- G. Konrad, *"Cold and ultra-cold neutrons as probes of new physics",* Plenary Talk, International Nuclear Physics Conference INPC2016, Adelaide, Australia, 11-16 September 2016. She also gave a dedicated presentation on ANNI. Proceedings were published in PoS (INPC2016) 359.

- T. Soldner, *"A cold neutron beam facility for particle physics at the ESS"*, Physics of fundamental Symmetries and Interactions - PSI2016, 16-20 October 2016, Paul Scherrer Institut, Switzerland, http://www.psi.ch/psi2016. In addition a dedicated poster on the design and performance of ANNI was presented.

At this occasion there was a dedicated discussion session on “Fundamental Physics at the ESS” organized by T. Soldner and G. Konrad with the aim to provide the community with an update on the progress on ANNI and the LoIs.

- B. Märkisch, “Correlations in neutron beta decay”, “Workshop on symmetries in light and heavy flavour”, 7-8 November 2016, co-organised by B. Märkisch and H. Abele, workshop in the framework of the “Flavor Physics at High Luminosity Experiments” programme of the Munich Institute for Astro- and Particle Physics (MIAPP)

  This workshop investigated the complementarity, competition and synergies between searches for new physics in light and heavy quarks in the light of future instruments. It aimed at a future joint research and funding programme.

Publication

Esben Klinkby for the N-Nbar Collaboration, Torsten Soldner for the ANNI Collaboration, “Fundamental physics possibilities at the European Spallation Source”, Journal of Physics: Conference Series, Volume 746, Number 1 (2016)

> *The construction of the European Spallation Source ESS is ongoing in Lund, Sweden. This new high power spallation source with its long-pulse structure opens up new possibilities for fundamental physics experiments. This paper focusses on two proposals for fundamental physics at the ESS: The ANNI instrument and the neutron-anti-neutron oscillation experiment.*

Current status and outlook

The ANNI instrument perfectly profits from the time structure of the ESS, e.g. offering gains in statistics as large as 30 for the ep/n separator using pulse multiplication. The ANNI proposal was prepared on the basis of the pancake moderator. Hence, optimisations and simulations have to be performed for the final ESS moderator configuration and the now assigned potential position of the instrument at the ESS. Furthermore, reference experiments will have to be simulated in more detail. For these tasks, the ILL currently offers a 6 months internship that will be supervised by T. Soldner.

The instrument PERC, which is currently under construction by the proposers of the ANNI proposal at the FRM II, Garching, Germany, is the predecessor of the ep/n separator which is part of the ANNI proposal. Its main component is a 12 m long superconducting magnet system with magnetic fields up to 6 T. This magnet is currently in production and will be delivered by the end of 2017. The detailed design of the ep/n separator will certainly profit from the experience with PERC.

The next step for the collaboration will be to prepare a paper on ANNI, which will include the scientific context of ANNI, the updated design of the beam line and the results of the simulations regarding the reference experiments. The evolution of the proposal would profit from further exchange with the STAP.

The ANNI Collaboration intends to submit an updated proposal to the next ESS instrument round. The goal of the collaboration is to get the instrument built at the ESS.

B – NNbar Collaboration

Current list of people/institutes involved in the collaboration

(Extract from the NNbar Expression of Interest (EoI))

Torsten Åkesson, Lund University; David Baxter, Indiana University; Gustaaf Brooijmans, Columbia University; Hans Calen, Uppsala University; Lorenzo Calibbi, Université Libre de Bruxelles; Luis Castellanos, University of Tennessee; Joakim Cederkäll, Lund University; Peter Christiansen, Lund University; Christophe Clément, Stockholm University; Brian Cole, Columbia University; Caterina Doglioni, Lund University; Claes Fahlander, Lund University; Gabriele Ferretti, Chalmers University of Technology; Peter Fierlinger, TU Munich; Matthew Frost, University of Tennessee; Franz Gallmeier, University of Tennessee, Oak Ridge National Laboratory; Kenneth Ganezer, California State University Dominguez Hills; Richard Hall-Wilton, ESS; Vincent Hedberg, Lund University; Lawrence Heilbronn, University of Tennessee; Andreas Heinz, Chalmers University of Technology; Go Ishikawa, Nagoya University; Håkan Johansson, Chalmers University of Technology; Tord Johansson, Uppsala University; Leif Jönsson, Lund University; Yuri Kamyshkov, University of Tennessee; Masaaki Kitaguchi, Nagoya University; Esben Klinkby, ESS, Technical University of Denmark; Balasz Konya, Lund University; Andrzej Kupsc, Uppsala University; Mats Lindroos, ESS; Else Lytken, Lund University; Bernhard Meirose, University of Texas, Dallas; David Milstead, Stockholm University; Rabindra Mohapatra, University of Maryland; Thomas Nilsson, Chalmers University of Technology; Anders Oskarsson, Lund University; Robert Pattie, Los Alamos National Laboratory; Christoffer Petersson, Chalmers University of Technology; David Phillips, North Carolina State University; Amlan Ray, VECC, Kolkata, India; Filippo Resnati, CERN; Arthur Ruggles, University of Tennessee; Utpal Sarkar, Physical Research Laboratory, Ahmedabad, India; Alexander Saunders, Los Alamos National Laboratory; Hirohiko M. Shimizu, Nagoya University; Robert Shrock, Stony Brook University; David Silvermyr, Lund University; Samuel Silverstein, Stockholm University; Oxana Smirnova, Lund University; Per Erik Tegner, Stockholm University; Camille Theroine, TU Munich; Lawrence Townsend, University of Tennessee; Rick Van Kooten, Indiana University; Albert Young, North Carolina State University.

Contextual summary

(Extract from the executive summary from the NNbar EoI)

“A sensitive search for neutron-antineutron oscillations can provide a unique probe of some of the central questions in the particle physics and cosmology: the energy scale and mechanism for baryon number violation, the origin of the baryon-antibaryon asymmetry of the universe (with implications for static electric dipole moments), and the mechanism for neutrino mass generation. The decay of a proton (or of a neutron that is otherwise stably bound in a nucleus) is an obvious candidate for baryon number violation studies, violating baryon number by 1 unit, $\Delta B = 1$, and current limits probe very high energy scales (~10^{15} – 10^{16} GeV). Neutron-antineutron oscillations, on the other hand, violate baryon number by 2 units, and can take place even if proton decay is absent. They can be induced by new physics at energy scales as low as a few TeV. In fact, some models which predict $n \to \bar{n}$oscillations also predict measurable signatures (due to "colored scalars") within reach of the Large Hadron Collider. Neutron-antineutron oscillations provide an experimentally accessible window on a variety of sources of new physics at moderate energy scales, such as theories with extra spatial dimensions and viable models for baryogenesis at or below the electroweak symmetrybreaking scale. The ΔB=2 selection rule relates $n \to \bar{n}$oscillations to Majorana neutrino mass generation in models which unify quarks and leptons, providing another window on the origin of neutrino mass.

Experiments designed to detect $n \to \bar{n}$oscillations fall into two categories: large volume, low background underground experiments and experiments with cold neutrons. In both cases, the experimental signature that an oscillation has taken place is striking: the annihilation of the antineutron, releasing roughly 2 GeV of energy, typically in the form of pions (4 to 5 pions on average). At present, the best limits on $n \to \bar{n}$oscillations come from water Cerenkov detectors (SuperKamiokande), where limits are derived from oscillations of neutrons bound in oxygen nuclei. These experiments, however, are already limited by an irreducible background from atmospheric neutrinos, making large increments in sensitivity prohibitively difficult. Experiments with cold neutron beams do not suffer from this limitation, in that the oscillation amplitude develops "in-flight" as a cold neutron beam propagates freely from a focusing optic to an annihilation target. The target is surrounded by a detector capable of accurately reconstructing the annihilation vertex position and release energy, providing essentially background free detection of the annihilation signature. The most sensitive cold neutron experiment to date was performed at ILL in 1990, and is about three times less sensitive to antineutron annihilations than the SuperKamiokande experiment. With the advances in neutronics technology over the last 25 years, a new cold neutron experiment can now be performed with a very large increase in sensitivity.

A remarkable opportunity has emerged to pursue this objective with the construction of the European Spallation Source (ESS). The envisioned experiment's goal is to have at least a factor of 1000 greater sensitivity to the oscillation probability than the ILL experiment (after 3 years of operation). The critical technologies (advanced neutron optics and high resolution trackers and calorimeters) already exist, and the ongoing work towards a technical proposal is focused on a cost-effective optimization of the experiment."

NNbar is not a standard instrument but a specific experiment of very large scale (in contrast e.g. to ANNI and UCN). NNbar is currently seeking funding from outside the ESS instrument construction budget.

Meetings and seminars

The NNbar collaboration organises meetings and workshops regularly about every 6 months. The last one was the 5th NNbar workshop, which took place at the ESS, Lund, Sweden on December 15-16, 2016. During the workshop progress on instrument design (e.g. beam extraction, collimation and simulations) have been presented. A focus of the meeting was the proposal of a HIBEAM facility as prototype of the full NNbar instrument and an extended physics programme. The possibility of a HIBEAM instrument proposal was discussed. In addition, the collaboration discussed the collaboration board.

NNbar uses the ESS indico site: **https://indico.esss.lu.se/category/20/**

Monthly phone and video meetings are organised to discuss the design of the experiment, the physics case and the preparation of the Technical Design Report (TDR).

Members of the collaboration frequently present NNbar at international conferences, which can be also be seen from a number of conference proceedings listed in the next section.

Publications

C. Theroine on behalf of the NNbar collaboration, “A New Experiment to Search for Neutron–Antineutron Oscillations at the European Spallation Source”. Nuclear Physics News Vol. 25, No. 3, pages 13-18, 2015.

The discovery of neutron–antineutron oscillations could answer crucial questions of particle physics and cosmology. Why do we observe more matter than antimatter in the Universe? At what energy scales do new phenomena occur? Another related intriguing subject potentially accessible with this process concerns the mechanism responsible for neutrino mass generation. The construction of the European Spallation Source (ESS) offers a remarkable opportunity to perform a sensitive experiment dedicated to the search of such oscillations. Indeed, the high neutron flux expected at this facility, combined with the important progress made in neutron optics, will enable this experiment to gather all the necessary conditions for establishing possible new physics coming from energy scales beyond the reach of colliders that can have a strong impact on our understanding of the Universe.

The NNbar EoI was presented at the ECNS conference which took place in Zaragoza from 30/08 to 04/09 2015 by E. Klinkby. For the paper abstract see section 2.A.

NNbar white paper: “Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects”, Phys. Rept. 612 (2016) 1-45, and arXiv:1410.1100.

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. Observing the n–n̄ transition would show that baryon number (B) is violated by two units and that matter containing neutrons is unstable. It would provide a clue to how the matter in our universe might have evolved from the B=0 early universe. If seen at rates observable in foreseeable next-generation experiments, it might well help us understand the observed baryon asymmetry of the universe. A demonstration of the violation of B–L by 2 units would have a profound impact on our understanding of phenomena beyond the Standard Model of particle physics.

Slow neutrons have kinetic energies of a few meV. By exploiting new slow neutron sources and optics technology developed for materials research, an optimized search for oscillations using free neutrons from a slow neutron moderator could improve existing limits on the free oscillation probability by at least three orders of magnitude. Such an experiment would deliver a slow neutron beam through a magnetically-shielded vacuum chamber to a thin annihilation target surrounded by a low-background antineutron annihilation detector. Antineutron annihilation in a target downstream of a free neutron beam is such a spectacular experimental signature that an essentially background-free search is possible. An authentic positive signal can be extinguished by a very small change in the ambient magnetic field in such an experiment. It is also possible to improve the sensitivity of neutron oscillation searches in nuclei using large underground detectors built mainly to search for proton decay and detect neutrinos.

This paper summarizes the relevant theoretical developments, outlines some ideas to improve experimental searches for free neutron oscillations, and suggests avenues both for theoretical investigation and for future improvement in the experimental sensitivity.

M. J. Frost on behalf of the NNbar Collaboration, “The NNbar Experiment at the European Spallation Source”, Proceedings of the Seventh Meeting on CPT and Lorentz Symmetry (CPT’16), Indiana University, Bloomington, June 20-24, 2016, arXiv:1607.07271 [hep-ph]

> *The observation of neutron to antineutron oscillation would be the first experimental evidence to show that baryon number is not a conserved quantity. It also provides an answer to the hypothesized post-sphaleron baryogenesis mechanism shortly after the Big Bang. The free oscillation time $\tau_{n-\bar{n}}$ has a lower limit at 8.7 x 10^7 seconds determined at ILL in 1994. Current beyond Standard Model theories of this oscillation time estimate the value to be on the order of 10^{10} seconds. A new experiment is proposed at the European Spallation Source that has 1000 times the sensitivity of the previous experiment, and would confirm the viability of those beyond Standard Model theories.*

Current status and outlook

The preparation of the TDR is in progress and its progress is regularly discussed by the collaboration. A task list is being compiled to help the collaboration understand what the most pressing issues for a timely completion of the TDR are and how to optimise the distribution of manpower. The collaboration is open for new members and has defined a formal structure. The main parameters of the experiment have been defined. The optimisation of the design and study of the experimental sensitivity versus costs are ongoing and will be part of the TDR. Intermediate recommendations as well as a review of the TDR by the STAP should be envisaged.

The NNbar collaboration is currently preparing an updated version of the document called *“Technical Summary and Status of NNbar Experiment for ESS”,* which was originally sent to ESS in October 2014.

Members of the collaboration are actively searching for external funding for preparatory work. The NNbar consortium is very active and motivated. Their main goal is the preparation and the submission of a TDR for NNbar at ESS in 2018.

C – UCN collaboration

Current list of people/institutes involved in the collaboration

Hartmut Abele, Technische Universität Wien; Peter Fierlinger, Technische Universität München; Tobias Jenke, Technische Universität Wien; Stephan Paul, Technische Universität München; Oliver Zimmer, Institut Laue Langevin.

<u>**Contextual summary**</u>

(Extract from the executive summary from the UCN EoI)

“Ultra-cold neutrons (UCN) play an important role to address key questions of particle physics at the low-energy, high-precision frontier, complementary to experiments done at high-energy particle accelerators. UCN are an excellent tool for precise measurements. Experiments using UCN provide values of observables important for applications ranging from particle physics to cosmology. Moreover they challenge the Standard Model of particle physics.

Visible projects employing UCN are the search for a neutron electric dipole moment (EDM) and the investigation of quantum states of the neutron using gravity spectroscopy. The neutron EDM investigates violation of the fundamental CP-symmetry and the baryon asymmetry of the Universe, whereas gravity resonance spectroscopy (GRS) addresses gravitation at short distances in the micrometre range in order to probe scenarios of extra-dimensions that might explain why gravitation is so much weaker than for instance the electrostatic force between two charged bodies. These experiments have huge potential for improvement at the ESS and are therefore considered as flagship experiments. They require an experimental area with excellent magnetic shielding and low vibration conditions.

Further examples of projects using UCN with strong potential for improvement at the ESS are the neutron lifetime, which impacts the abundances of light chemical elements in big-bang nucleosynthesis, clock comparison experiments addressing questions of Lorentz invariance, dark matter and quantum-mechanical effects that can be excellently studied in optics with very slow neutrons.

Best current UCN sources deliver densities of the order of only a few tens per cm^3, so that many fundamental physics projects are statistically limited. Key goals of the UCN source proposed for the ESS are a UCN density exceeding 10^4 per cm^3 and provision of experimental conditions necessary for the flagship experiments in order to push down systematic effects accordingly.

The UCN source proposed at ESS takes advantage of ten years of development work of superfluid-helium UCN sources started at FRM2 and continued at the ILL. In addition, with ILL's Endurance project SuperSUN it will have an important precursor, for which a UCN density of 10^3 per cm^3 has been projected. With one order of magnitude higher UCN density, the ESS source will provide to the community a valuable new tool with strong impact.

UCN production is based on the well-established conversion of cold to ultracold neutrons via inelastic scattering in superfluid helium. A magnetic multi-pole reflector drastically enhances the UCN density with respect to the prototype superfluid-helium UCN source installed in a cold neutron beam at ILL. The reflector repels low field seeking UCN and thus strongly reduces losses due to UCN collisions with the material walls of the converter. A special feature is an intrinsic high UCN polarisation provided due to spin dependent trapping by the multi-pole magnet, which is very welcome for the flagship experiments but also for projects employing external magnetic traps."

Meetings and seminars

The general developments of beam UCN sources are going on. That includes technical realisation (e.g. SuperSUN) and new basic research (e.g. inelastic paramagnetic scattering).

O. Zimmer presented the "*New superfluid-helium based UCN sources at ILL",* the precursor of the proposed UCN source at the ESS, at various conferences (e.g. 2nd status meeting of the DFG Priority Programme 1491, 3-6 November 2015) and discussed novel ideas e.g. at the Physics Department at TUM on 18 January 2016. The abstract of this presentation is given below:

"Ultra cold neutrons at the ILL and perspective for a very-cold neutron source based on cascaded neutron cooling in paramagnetic systems"

Conversion of cold to ultracold neutrons (UCN) via single-phonon emission in superfluid helium provides a viable mechanism to achieve high densities of UCN at the end of a neutron guide. The first part of the talk presents current developments of new sources at the ILL based on this *mechanism that have led to new record UCN densities. Further gains are expected using a magnetic reflector around the helium converter. This will be implemented in the project SuperSUN which might serve for the panEDM neutron EDM experiment. The second part of the talk presents a proposed new neutron-cooling mechanism with a perspective to drastically improve intensities of neutrons with wavelength larger than 2 nm, covering the whole energy range down to ultra cold neutrons. It employs inelastic magnetic scattering in weakly absorbing, cold paramagnetic systems. Kinetic energy is removed from the neutron stepwise in constant decrements determined by electronic Zeeman energy or by zero-field level splitting in magnetic molecules. Molecular oxygen with its triplet ground state appears particularly promising, notably when densely packed as a host in fully deuterated O2-clathrate hydrate. This material possesses an experimentally established non-dispersive inelastic neutron scattering signal with 0.4 meV energy transfer due to the zero-field splitting. Based on calculated cross sections for magnetic neutron scattering and a stationary neutron transport equation for an infinite, homogeneous medium with Maxwellian neutron sources, strong cooling effects are to be expected, requiring only ordinary liquid-helium temperatures, no external magnetic field and no neutron polarisation.*

Current status and outlook

In its last report the STAP advised the UCN consortium to work on the design of the beam line in order to prepare for the last ESS proposal round. The UCN source proposed at ESS is a superfluid helium target at the end of a cold neutron beam. The neutron beam should be extracted from the cold moderator with a large solid angle in order to maximise the flux, possibly similar to the NNbar extraction. With this in mind, the collaboration was also encouraged to consider to place their source at the NNbar beam extraction after the NNbar experiment is finished. This option was also positively discussed at the meeting at ESS in July 2016. The design statements and calculations for the UCN extraction and distribution need to be corroborated by simulation and experiments and compared with existing beam lines. The strategy, including various ongoing and near-future R&D steps, should also be outlined and explained in detail. Of course, the costing should be refined during this process accordingly.

The scientific impact of a beam UCN source at the ESS is convincing and there is a large demand for UCN within a large user base in Europe and world-wide. However, a strategy to collect a large fraction of the international UCN user community to perform experiments at the ESS is still lacking. The UCN collaboration is encouraged to work on aligning the community efforts toward their goals.

The STAP should accompany this development of the EoI into a full instrument proposal.

3 – User community

A – German, Austrian and Swiss user communities

The German and Austrian user communities received substantial funding for novel scientific instruments and experiments from the DFG Priority Programme SPP 1491 “Precision Experiments in Particle and Astrophysics with Cold and Ultracold Neutrons“. The research of this programme is focused on five priority areas, which are directly related to specific (astro)physics issues and instrumentation:

- Priority area A: CP-symmetry violation and particle physics in the early universe (addressed mainly by the search for the neutron electric dipole moment).

- Priority area B: The structure and nature of weak interaction and possible extensions of the Standard Model (addressed mainly by precise beta decay studies of the neutron).
- Priority area C: Relation of gravitation and quantum theory (probed by investigations of low energy bound states in the gravitational field).
- Priority area D: Charge quantization and the electric neutrality of the neutron (probed by a precision test of the neutron's electric charge).
- Priority area E: New measurement techniques: particle detection, magnetometry, neutron optics.

At the SPP meeting in November 2015, and the Workshop on "Symmetries in Light and Heavy Flavour" in November 2016, future perspectives have been discussed. The ESS, and in particular the proposed cold beam line, would provide infrastructure that would boost the research field and attract new partners.

The following institutes are participating in the discussions:

- FRM II, München,
- Institut Laue-Langevin, Grenoble,
- Johannes Gutenberg Universität, Mainz,
- Universität Heidelberg,
- Max Planck Institute for Nuclear Physics, Heidelberg,
- Physikalisch-Technische Bundesanstalt, Berlin,
- Stefan-Meyer Institute for Subatomic Physics, Wien,
- Technische Universität München,
- Technische Universität Wien.

An effort is being made by a number of participants to augment their cooperation by applying for a coordinated funding programme with the DGF / FWF.

Currently the number of "young" groups in the field of particle physics with cold and ultra-cold neutrons is growing considerably: At the end of 2014, G. Konrad was awarded with a "New Frontiers Group" of the Austrian Academy of Sciences (ÖAW) for her project "NoMoS: Beyond the Standard Model Physics in Neutron Decay" which started in June 2015 and is hosted at the Stefan Meyer Institute. In April 2015, TUM established the group of B. Märkisch "Fundamental particle physics at low energies". In March 2016, F. Piegsa (then at ETH Zurich) succeeded with his proposal presenting "a new concept for a neutron electric dipole moment search using a pulsed beam" to the Swiss National Science Foundation (SNSF) and was awarded with a new professorship at the University of Bern and an ERC starting grant. The University of Mainz opened a W1 position for "Fundamental research with ultracold neutrons" and their search for a successor to W. Heil, a position previously opened at the W3 level, wasn't successful so far.

We note that in Germany ESS instruments are currently funded by the German Federal Ministry of Education and Research (BMBF).

B – Strategy Workshop on Particle Physics at the ESS

On 8th July the "Strategy Workshop on Fundamental Physics at ESS", organized jointly by Torsten Soldner, Camille Theroine, Hartmut Abele, Gustaaf Brooijmans, Mats Lindroos, Bastian Märkisch, and Anders Oskarsson took place in Lund. More than 20 participants, with many more excused, discussed cold neutron physics, NNbar and UCNs, as well as the complementarities between these topics. The main aim of the meeting was to prepare for successful particle physics projects at the ESS in the future.

At the workshop the status and prospects of all three instruments were presented. For the cold neutron beam line in particular the result of the proposal in the last round was critically reviewed. For the UCN source new ideas and concepts were discussed which could profit from the neutron optics of the NNbar experiment. At this stage there are no concrete plans to move forward, though. The NNbar is supported by a sizeable collaboration and makes steady progress. The required budget does not fit the ESS instrument scheme and funding will largely have to come from other sources.

In his presentation and the subsequent discussion the director of science of the ESS, Andreas Schreyer, pointed out that at this stage "fundamental & particle physics" is missing completely from the portfolio of instruments, but expressed the clear vision that this should be changed. He outlined a possible scenario of funding of additional instruments beyond the currently selected 16 from pre-operations and operations budget, pointing out the cold beam line "ANNI" as one of six existing instrument proposals. A possible new call for proposals might be scheduled for 2019 and a final one in 2021.