7.8 Fundamental Neutron Physics

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Abstract
Neutrons appear both as composite particles and as quantum waves. Both features have been investigated with thermal, cold and ultracold neutrons at many neutron sources. The higher intensity and the pulse structure of the ESS provide new possibilities for fundamental neutron physics experiments. The questions of small right-handed contributions to our left-handed world, why is there much more matter than antimatter in the universe and how neutrons interact with each other can be tackled. Non-classical neutron states can be produced and used for novel fundamental quantum optics investigations. Intensity gains of ultracold neutrons in the order of 1000 can be anticipated at a new ultracold neutron target station where the use of a spallation process for the production of neutrons becomes especially obvious.

I. Introduction

Neutrons are known as a powerful tool for particle and nuclear physics and they are ideal probes for quantum optics investigations. The European Spallation Source is, therefore, of intense interest for fundamental studies in these fields.

Investigations of neutron's properties deliver information about strong, weak, electromagnetic and gravitational elementary forces of nature

During the past 25 years, our world-view of nature has changed dramatically, ranging from the constituents of elementary particles to the status of the universe. Neutron physics has made major contributions to this evolutionary process of understanding. On the grand scale, cosmology has evolved into an exact science and neutron physics has contributed to the understanding of element formation and of phase transitions in the history of our universe. Various data extracted from measurements of neutron beta decay have been used extensively to fix the number of particle families at three. On the scale of the very small, neutron experiments have made substantial contributions to our understanding of strong, electroweak and gravitational interactions. Neutron interferometry and neutron spin-echo experiments have shown how non-classical states of neutrons can be created and used for highly sensitive investigations in condensed matter and fundamental physics research.

Quantum optics with neutrons opens new fields

Many crucial questions remain to be answered and the increased flux from ESS will enable major progress in a range of areas. For example, unique experiments can be performed which will help (a) to determine the basic structure of the fundamental interactions acting in nature, (b) to elucidate the history of the universe and to predict its future, and (c) to study fundamental questions of quantum and measurement theory. The community in this field is about 300 scientists strong, with many young people starting new in this field.

II. Flagship experiments

The following generic experiments will become feasible at ESS. They use ultra-cold, cold and hot neutrons from the source. The results of these experiments are intended to raise the highest scientific interest and they can be published in journals with the highest impact factor but they are also rather risky.

The exotic decay of the neutron into a hydrogen atom and an antineutrino can help to find phenomena beyond the Standard Model

The question of the origin of handedness of nature

In nuclear decay experiments it was recognized in the late 1950s that one of the four fundamental forces - the weak force - is, as far as we have been able to discern so far, exclusively left-handed. Most Grand Unified Theories, however, start with a left-right symmetric universe, and explain the evident left-handedness of nature through a spontaneous symmetry breaking caused by a phase transition of the vacuum, a scenario, which, if true, would mean that the neutrinos today should carry a small right-handed component. Although limits on the right-handed currents have been derived from free neutron and muon decay experiments, what is really needed is a clear-cut "yes" or "no" experiment. Such an experiment, planned for ESS, is the two-body β-decay of unpolarized neutrons into hydrogen atoms and antineutrinos which occurs with a relative probability of $4.2 \cdot 10^{-6}$ compared to the usual β-decay.

Usual decay mode: $\mathbf{n \rightarrow p + e^- + \bar{\nu}_e}$

exotic decay mode: $\mathbf{n \rightarrow H + \bar{\nu}_e}$.

What is so interesting about this decay is that one of the four hydrogen hyperfine states cannot be populated at all if the neutrinos are completely left-handed. A non-zero population of this substate would, therefore, be a direct measure of a right-handed component.

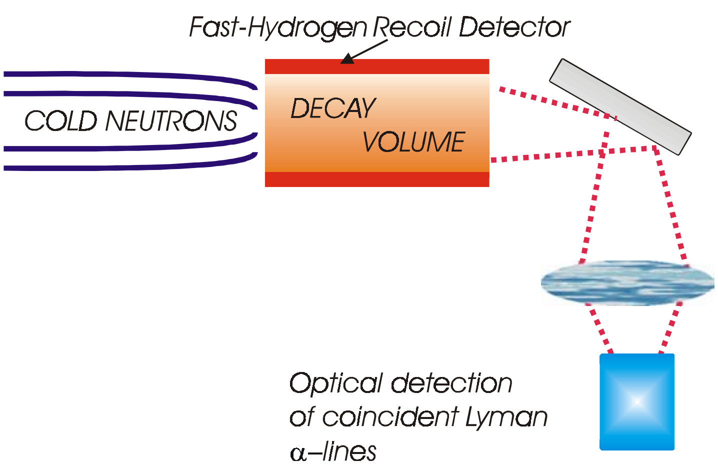

Figure1: Scheme for the measurement of the neutron decay into a hydrogen atom

This experiment has severe background suppression requirements for which the pulsed structure of ESS, allied to its intensity, is well suited. Thus, with ESS it may be possible to prove for the first time that nature does not possess an intrinsic handedness and that there is exciting new physics beyond today's Standard Model of particle physics.

In a second stage the experiment has to be done with polarized neutrons where the transition probabilites between the hyperfine levels can be changed drastically.

An intense pulsed cold neutron beam is required for these experiments, which are not tractable with current neutron sources. The long pulse ESS option is the most appropriate for this project.

The origin of the baryon asymmetry of the universe

Further measurements on the electric dipole moment of the neutron can help for the understanding of matter-antimatter asymmetry in the universe

The big bang theory presumes that equal amounts of matter and antimatter were created in the primordial explosion. In the subsequent process of annihillation of matter and antimatter only very few heavy particles ("baryons") and an equal number of antiparticles from this early period could survive. Our mere existence contradicts this expectation; there remained about 10^8 times more baryons in the universe than predicted and almost no antibaryons have survived. So far, the only viable solution of this problem is the violation of charge-parity symmetry (CP) which, on all reasonable expectations, is equivalent to a violation of time symmetry (T) that could have led to a small excess of particles before the annihilation stage.

Violation of the CP-symmetry has been observed in the decay of kaons. However, this single positive result is not sufficient to verify the above conjecture, nor to identify the origin of CP- or T-violation. Grand Unified Theories (GUT) require T-violating amplitudes that are orders of magnitude larger than can be accommodated by the present Standard Model. Therefore, another generation of experiments is needed to obtain decisive answers.

The most direct access to these questions lies in the detailed investigation of neutron decay and in measurements of its electric dipole moment. Electric dipole moment measurements started in the fifties and increased their sensitivity by one order of magnitude every seven years. They are based on searches for a deviation equal to $\pm d \cdot E$ from the well-known angular frequency of

$$h\omega = 2|\mu|B \pm d \times E$$

of a neutron spin in a magnetic field B and a parallel or antiparallel electric field E. Current theories of the baryon asymmetry of the universe is related to an EDM of about 10^{-28} e cm, a limit that is accessable with the ESS. The current upper limit is $6 \cdot 10^{-26}$ e cm.

These experiments are most effectively done with ultra-cold neutrons (UCN) where recent developments on new UCN sources predict orders of magnitude intensity gains. The possible arrangement of such a UCN station which consumes about 1% of the beam power is shown in Figure 2.

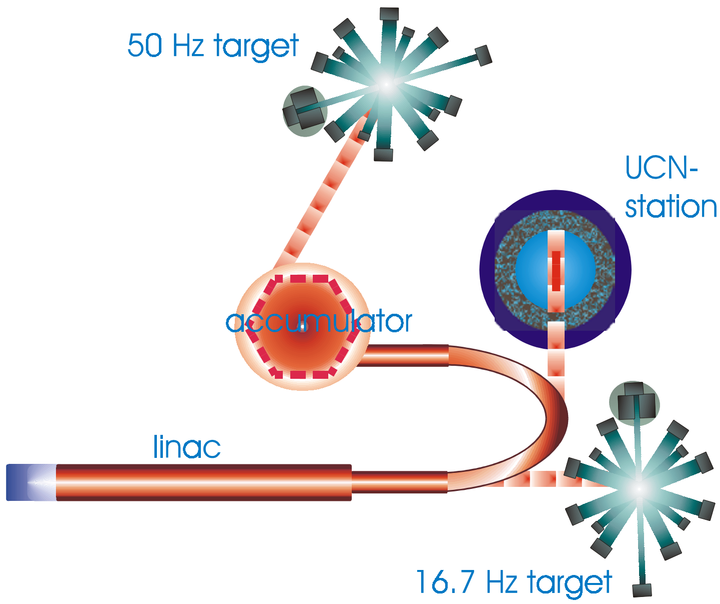

Figure 2: General layout of ESS with a dedicated UCN target station (not in scale)

A separate UCN station served by 1% of the proton beam power and the long pulse option would give new perspectives for research with ultracold neutrons.

The question of charge independence of nuclear forces

With a pulsed ESS for the first time a direct neutron-neutron scattering experiment becomes feasible

The strong or nuclear force is governed by the fundamental quark-quark interaction described by Quantum Chromo-Dynamics (QCD). It is believed that the strong nuclear force is essentially the same for protons and neutrons or, more generally, for up and down quarks. In this respect, the nuclear part of the singlet scattering length should be the same for the proton-proton and the neutron-neutron systems, and it should be similar to the neutron-proton interaction. The neutron-proton scattering length is the only precisely known quantity whereas the nuclear part in the proton-proton system is masked by the Coulomb interaction and the neutron-neutron scattering length has only been extracted indirectly from several three-body interaction processes. The best way to check, whether the deviations in the singlet scattering lengths extracted from these experiments really signal a breakdown of isospin invariance, is a direct scattering measurement of the neutron-neutron scattering at very low energy

$$\mathbf{n + n \rightarrow n + n}$$
$$\mathbf{a^s_{np} = a^s_{pp} = a^s_{nn}\,?}$$
$$\mathbf{a^t_{nn} \equiv 0\,?}$$

In a second stage a dedicated experiment using polarized neutron beams could subject the hypothesis of the flavour independence of the quark gluon interaction to a precision test at the baryon level.

As the interaction rate for a neutron-neutron scattering experiment scales with the square of the neutron flux density, the high peak intensity of ESS has huge advantages. The planned ESS-experiments make use (a) of the time structure, by allowing the fast neutrons of one pulse to hit the slower ones of a preceding pulse and (b) coincidences in time and space for the counts for each scattered pair of neutrons.

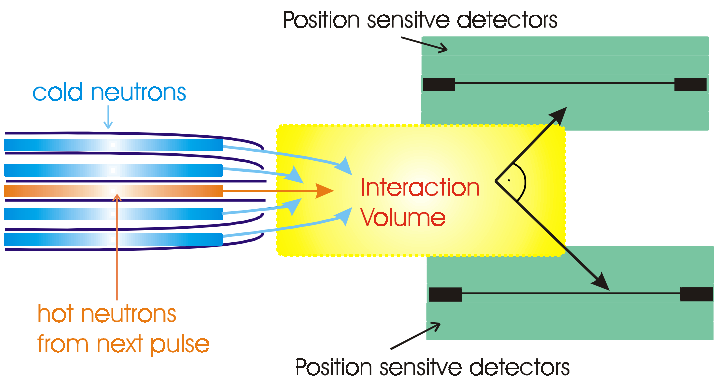

Figure 3: Sketch of the proposed neutron-neutron scattering experiments

A well focused dense cold neutron beam merging with an intense hot beam would be optimal for such experiments. The short pulse option of ESS has additional advantages due to its higher peak flux.

Neutron quantum optics

The phase of a neutron wave has become a measurable quantity since the invention of neutron interferometry. Basic tests of quantum mechanics have been performed in the past and it has been shown how neutrons can be used as a powerful tool in quantum optics. Non-classical neutron states, which are extremely fragile against any dissipation, have been created in neutron interferometry and neutron spin-echo experiments. Major interest concerns the verification of topological phases which are determined by the geometrical form rather than by the strength of the interaction. A complete quantum state reconstruction will become feasible by a simultaneous coherence function and momentum post-selection measurement procedure.

Non-classical states of neutrons can be produced and used in neutron interferometry and neutron spin-echo systems

The coupling of the neutron magnetic moment to oscillating magnetic fields permits multi-photon exchange and dressed neutron states, while the quantization of neutron states inside microscopic structures facilitates new possibilities in basic and advanced materials research. Pulsed beams can be trapped between perfect crystal plates forming narrow band neutron resonators that can be developed further as neutron accumulator systems. Inside travelling magnetic fields an advanced method of beam tailoring becomes feasible

Neutron resonators and accumulators become feasible

permitting intensity gains by another factor of ten. These new possibilities have to be exploited as a step towards advanced quantum optical devices serving as resonators and phase space transformers and compressors.

The long pulse option of ESS can surpass the existing possibilities. A cold neutron beam line adaptable for travelling magnetic fields and on vibration and thermally isolated and controlled experimental area would be desired for these experiments.

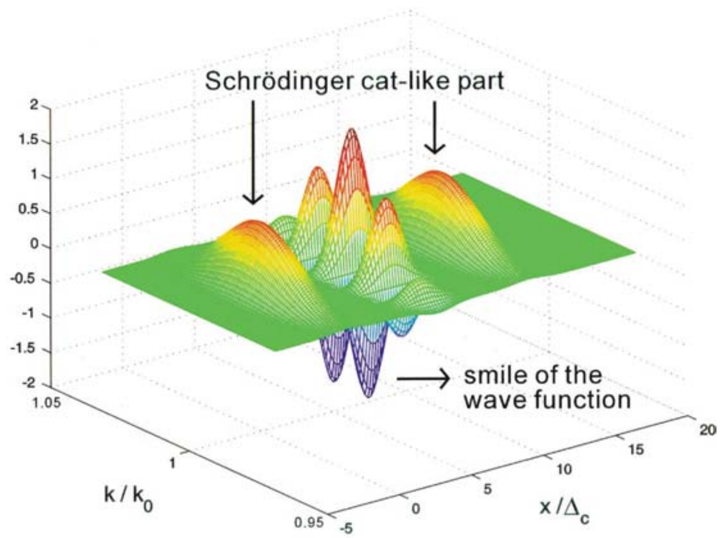

Figure 4: Wigner representation of a non-classical neutron state as it exists in neutron interferometry and neutron spin-echo arrangements

III. Various other scientific achievements anticipated at ESS

So far the flagship experiments for ESS have been discussed. There is a rich variety of other topics in the field of fundamental neutron investigations of which we mention only a few.

Research on fundamental phenomena is rather popular for young students and researchers

Neutron decay experiments, in particular measurements of the neutron lifetime and angular correlation coefficients determine certain free parameters of the Standard Model complementary to high energy physics research. The V_{ud} parameter of the quark mixing matrix for the d-u transition in neutron decay plays a key role in testing the unitarity of this matrix, which yields information on possible physics beyond the Standard Model. The experiments determine the strength and structure of the weak quark current and provide the possibility of observing new processes generated by scalar and tensor components, with or without T violating terms or right handed currents.

Today all weak semileptonic phenomena with significance for cosmology, astrophysics and particle physics must be calculated from neutron decay data. Certain neutron decay experiments can make use of the pulse structure of ESS for background subpression.

Another topic of high interest is the investigation of the weak interaction between nucleons may be carried out by means of coherent spin rotation of transversely polarized neutrons or by differential absorption of a longitudinally polarized neutron beam interacting with unpolarized nuclei of hydrogen or helium.

- The proposed ultracold neutron factory will host besides two long-term projects: the search for an electric dipole moment of the neutron and measurements on free neutron decay. Ultra-cold and very cold neutrons will be used for elastic and inelastic surface reflections and as probes for nano-structured materials. Quantum gravitational states have been measured and weak gravity effects become accessable. New bunching, cooling and trapping systems will be developed.

- Neutron quantum optical experiments will become feasible where the time structure of the beam can be used to produce a steady beam with an intensity governed by the peak flux of ESS. Topological phenomena could be tackled in a new way. The transition from a quantum to a mixed state could be studied in detail contributing to our understanding of a quantum measurement. Quantum Zeno-effect experiments will show how a quantum state can be frozen when a continuous measurement is performed.

IV. Issue of target station and beam lines

For Fundamental Physics with ultracold neutrons the following additional target is needed:

The proposed ultracold neutron target station has unique features and opens new fields of research

(a) UCN-station accepting the whole beam power for about 1% of the time (1 second on, 5 minutes off).

For Fundamental Physics with neutrons the following beam lines and experimental areas are needed:

(b) A beam line for producing high dense neutron gas at the cold moderator of the 16.6 Hz target station.

(c) A beam line for neutron optics at a thermal guide associated with an experimental area with special environmental conditions (vibration-free, air-conditioned, humidity-controlled etc.).