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Fundamental physics possibilities at the European Spallation Source

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Abstract. 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.

1. ANNI

Pulsed beams have tremendous advantages for precision experiments with cold neutrons. In order to minimize and measure systematic effects, they are used at continuous sources in spite of the related substantial decrease in intensity. At the European Spallation Source ESS, such experiments will gain 1-2 orders of magnitude in event rate. Novel concepts become feasible. The cold neutron beam facility for particle physics ANNI [1] is designed to make full use of the pulse structure of the ESS. It has been proposed for construction as one of the public instruments. ANNI is a versatile instrument. In contrast to instruments for neutron scattering experiments, ANNI “only” delivers a neutron beam with well-defined properties (pulse structure, polarization) or, via the included Electron-Proton/Neutron (ep/n) separator, a beam of charged neutron decay products. Spectrometers for measurements will be designed and constructed for specific scientific questions (see section 1.1) by the external visitors. This operation mode is similar to that of existing facilities for particle physics at other neutron sources (see, e.g., [2, 3, 4]).

1.1. Scientific case

Science at ANNI will cover a wide range at the precision frontier of particle physics. The scientific program builds on three pillars: (i) neutron beta decay, (ii) hadronic weak interaction, and (iii) electromagnetic properties of the neutron. Furthermore, similar cold neutron beam facilities are also used for nuclear physics experiments (nuclear spectroscopy for structure and symmetries in nuclei, cross-section measurements), fission studies (understanding of the fission process, cross-section measurements), interferometry (measuring of scattering lengths, tests of the foundations of quantum mechanics), searches for short-range forces by neutron scattering, and technical developments (test and optimization of sources for ultracold neutrons (UCNs), polarization techniques, neutron optical devices, imaging).

(i) Neutron beta decay. Free neutrons decay into proton, electron and anti-electronneutrino. The distribution of the decay products in space and energy can be parameterized by correlation coefficients [5]. In this way, more than 20 observables can be defined [5, 6], for example the beta asymmetry coefficient A or the electron-neutrino correlation coefficient a. In the Standard Model of particle physics (SM), neutron decay is described as pure vector minus axialvector (V–A) interaction, by 2 parameters only. Physics beyond the SM predicts additional interactions, such as V+A, scalar or tensor interactions. Precision measurements of correlation coefficients allow testing the SM and searching for these additional interactions. The theoretical framework only assumes Lorentz invariance but no specific properties of the new physics. Therefore, neutron beta decay is a “broad band” probe for physics beyond the SM [7].

ANNI is optimized for measurements of correlation coefficients in neutron beta decay. Together with instrumentation developed by users, it will improve these measurements by one order of magnitude, unlocking the accuracy range of 10^{-4}. This accuracy tests new physics on a mass scale of 1-100 TeV, far beyond the threshold for direct production at existing or planned particle colliders. See [8, 9, 6] for recent reviews and [10, 11, 7] for theoretical prospects.

(ii) Hadronic parity violation. Weak interaction between quarks in the strangeness-conserving sector is difficult to access experimentally, because of the overwhelming strong interaction. Parity violation is specific to weak interaction. Therefore parity violating observables are used as filters to suppress strong interaction. Hadronic parity violation is traditionally parameterized by the meson exchange model of Desplanques, Donoghue, and Holstein (DDH) [12]. However, quantitative estimates are difficult and come with large uncertainties, due to the strong interaction. Since a few years, this situation is changing qualitatively: Effective field theories allow model-independent parameterizations and QCD on the lattice starts to be able to calculate parameters of the effective theories from fundamental QCD and weak interaction. New lattice gauge theory collaborations have been formed to calculate challenging non-perturbative QCD observables. This is a frontier of computational physics (“exascale computing”). These theoretical developments enable quantitative tests of the non-perturbative limit of QCD, provided that experiments become sufficiently sensitive. See [13, 14] for recent reviews. ANNI will unlock the sensitivity range needed to resolve the predicted tiny effects of hadronic weak interaction experimentally. This will allow a systematic experimental study of these effects which enables quantitative tests of the non-perturbative limit of QCD.

(iii) Electromagnetic properties of the neutron. Electromagnetic properties of the neutron are related to diverse questions of particle physics, see [6] for a review. The electrical neutrality of neutrons and of atoms is not required by the SM [15]. The existing experimental limits can be considered as experimental hint for grand unification [16]. The detection of a finite electric dipole moment (EDM) would indicate a violation of CP (charge conjugation-parity) symmetry beyond the SM, by processes at energy scales of 1 TeV to more than 1000 TeV [17]. If a neutron EDM is found above $10^{-28}e\cdot\text{cm}$, it would be a strong hint for baryogenesis near the electroweak scale; if not, other ways such as leptogenesis or processes close to the inflationary scale are more probable [6].

The pulse structure at ANNI enables novel concepts to measure electromagnetic properties of the neutron. This gives a systematically different access to these fundamental properties. As example, a measurement of the neutron EDM using a pulsed cold neutron beam has been proposed in [18], with an estimated sensitivity of $5\cdot10^{-28}e\cdot\text{cm}$ in 100 days of beam time. This would match the sensitivity envisaged by future experiments using stored UCN. We note that ANNI also provides a high flux of neutrons with 8.9 Å which could be used to produce UCN in superfluid He, similar to the planned SNS EDM experiment [19].

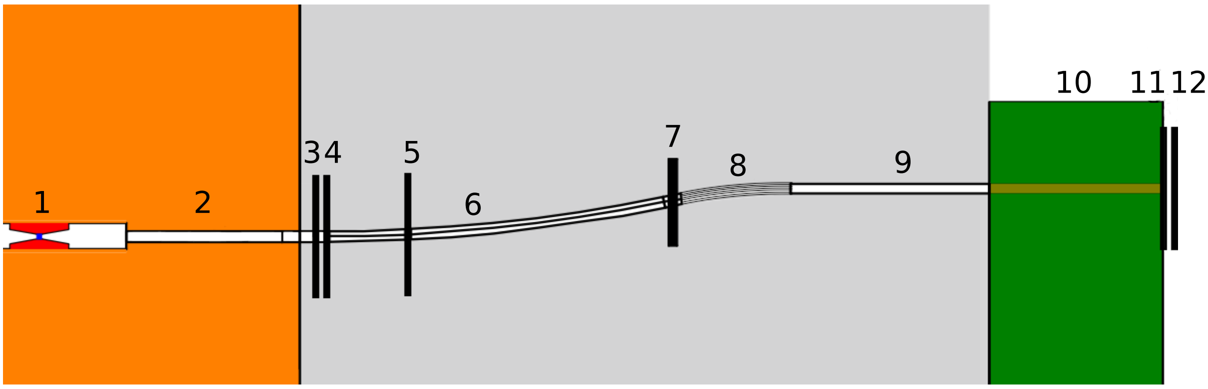

Figure 1: Design of the ANNI guide and chopper system: 1 Flat ESS moderator, 2 in-pile straight guide (horizontal trumpet), 3 first pulse defining chopper, 4 and 5 frame overlap choppers, 6 first bender, 7 shutter, 8 second bender (exchangeable by polarizing bender), 9 straight guide (anti-trumpet), 10 beam definition area, 11 second pulse defining chopper, 12 pulse suppressing chopper. Element 2 is located in the target monolith, 3-9 in the guide bunker, 10-11 in an instrument casemate, and the user experiment or the ep/n separator can be installed in the experimental area, starting at 12.

1.2. Design

The instrument ANNI (see Fig. 1 for guide and chopper system) is designed to provide maximum flux with wavelength information at moderate resolution. These fundamental requirements result in a short neutron guide with two frame overlap choppers. The guide uses the flat moderator (see also section 1.3) and is followed by an area for beam definition. The user experiment can be installed at a distance of 26 m from the moderator. The experimental area has a minimum width of 5 m (corresponding to 11° at 26 m from the moderator), a standard length of 25 m, and is extendable to a length of 50 m (i.e. to 76 m from the moderator) in order to provide sufficient space for specific experiments such as [18]. Several experiments will use the pulse structure in order to define the position of the neutron pulse in space (see example in [20]). For this purpose ANNI includes two pulse defining choppers that can rotate at 70 Hz (to provide short transition times) and a pulse suppression chopper. Pulse multiplication is planned for specific experiments.

Optimization was performed for a series of existing or proposed reference experiments. The best configuration is a guide with S-shape in the vertical plane and a ballistic geometry in the horizontal plane. The final cross-section is $11.2 \times 7\,\mathrm{cm}^2$. In order to go out of direct view twice, for this short guide with large cross-section, a strong curvature is needed. This is achieved by 2 benders, a first with 8 m length and a second with 2.5 m length. The second bender is interchangeable with a polarizing bender of the same geometry, providing moderate polarization (98%) at highest flux. For many precision measurements, a very high beam polarization is required. This is achieved by installing a second bender in the area for beam definition (X-SM geometry, see [21]). The instrument includes equipment for spin flipping, polarization analysis, and a ^{3}He spin filter polarizer.

The ep/n separator serves as a gate for charged neutron decay products for measurements of a large number of correlation coefficients. It delivers a beam of decay electrons and protons under precisely defined and variable conditions and spatially separated from the neutron beam. It also includes interfaces and basic infrastructure for user-supplied secondary spectrometers. The design of the ep/n separator is based on the concept of PERC [22] but features an upstream detector that will further reduce systematic effects and allows operation in a symmetric setup. A first secondary spectrometer is already under construction [23].

Parameter	Value	Comment
Capture flux full spectrum	$5.4 \cdot 10^{10}\,\mathrm{n/(cm^2s)}$	at guide exit
	$1.8 \cdot 10^{10}\,\mathrm{n/(cm^2s)}$	at start of experimental area
Capture flux 2–8 Å(FOCs)	$4.0 \cdot 10^{10}\,\mathrm{n/(cm^2s)}$	at guide exit
	$1.4 \cdot 10^{10}\,\mathrm{n/(cm^2s)}$	at start of experimental area
Particle flux @ 8.9 Å	$5.8 \cdot 10^{8}\,\mathrm{n/(cm^2s\text{Å})}$	at start of experimental area with guide bridging beam definition area
Divergence distribution	42 mrad (FWHM)	horizontal, full spectrum
	22 mrad (FWHM)	vertical, full spectrum

Table 1: Key performance numbers of ANNI [1]. (FOCs: With frame overlap choppers.)

Furthermore, ANNI includes all infrastructure needed for particle physics experiments, for example monitor detectors, background monitors, a He liquefier, shielding material, electricity and cooling water supply for large electromagnets etc.

1.3. Performance

Simulations of the instrument performance have been carried out using McStas [24] and the flat moderator component "2014" (with corrected solid angle calculation). The final ESS moderator configuration was not known at the time of instrument design. Minor adaptations of the design to one of the two butterfly moderators will be needed; however, no significant changes in the performance are expected.

Simulated key performance parameters are presented in Table 1. These parameters refer to the time average. In order to compare ANNI's performance with that of existing facilities, typical reference experiments have been simulated as benchmarks. Two classes of experiments can be distinguished: (i) Experiments that use pulsed beams in order to control systematic effects gain 1-2 orders of magnitude in event rate at ANNI: Compared to other pulsed sources such as the SNS, the flux at the ESS is one order of magnitude higher and the lower repetition rate allows for a larger wavelength frame at accessible distances from the moderator. At continuous sources, creating the pulse structure costs much more intensity than at ANNI where the peak flux of the ESS can be used. (ii) Experiments that do not use pulsed beams so far will not or only moderately gain in event rate (compared to the most intense continuous beams). However, these experiments may profit in systematics, for example in signal-to-background ratio. It should be noted that the European flagship experiments in particle physics with cold neutrons [22, 25] belong to class (i).

2. Search for $n\bar{n}$ oscillations

2.1. Physics motivation

The lack of discoveries at accelerators exploring the high energy frontier strengthens the motivation to search of new physics elsewhere. The unprecedented proton beam power of 5 MW expected at the ESS poses unique possibilities to search for new physics, including the search for neutron-anti-neutron oscillations.

Deviations from baryon number conservation have not been observed, but yet the Universe consists of baryons rather than anti-baryons. It is an intriguing question, to explain how the asymmetry came to be. Also, to explain the origin of the neutrino mass, interactions with baryon number violation (BNV) are theoretically favored [26]

Even within the SM baryon number is subject only to an approximate conservation law. At the perturbative level baryon number conservation arises due to the specific matter content in the

SM, and corresponds to a so-called *accidental* symmetry. In fact, the SM predicts BNV through rare non-perturbative electroweak instanton processes which violate B and L, but conserves $B - L$ [27, 28].
Furthermore, precision tests of the Equivalence Principle [29] offer no evidence for a long range force coupled to baryon number and thus a local gauge symmetry forbidding BNV. Consequently, BNV arises as a generic feature of many proposed extensions to the SM [30]. A promising means of searching for BNV is via the observation of the $\Delta B = 2$ process, neutron-anti-neutron oscillation [31, 32].

There exists a symbiosis between neutron-antineutron oscillations and neutrino physics via the quantum number $B - L$. A popular model explaining the origin of neutrino mass is the see-saw mechanism [33]. In this framework neutrinos possess a Majorana component and lepton number is violated by two units. Evidence for $\Delta L = 2$ processes are sought in double neutrinoless beta decay searches [34]. Since, howecer, $B - L$ (the true anomaly-free SM symmetry) is also violated by two units it would be natural to expect $\Delta B = 2$ processes. In addition to the complementarity with neutrino physics, neutron-anti-neutron oscillation features in a number other models of physics beyong the SM, for examples R-parity violating supersymmetry [30]. Values of the BNV mass scale for which observable oscillations take place exceed those attainable at colliders. Using a six-fermion BNV operator and dimensional reasoning mass scales of $10 - 1000$ TeV are obtained while other approaches (also leading to an observable signature) predict scales near the grand unified mass [31]. A further motivation for searching for oscillations was recently provided by the observation that such processes violate not only baryon number but also CP [37], thereby addressing two of the Sakharov conditions [36] for baryogenesis. In addition to the theoretical motivation given above a strictly experimentalist consideration of BNV hunting highlights the importance of neutron-anti-neutron oscillation searches. In an oscillation experiment only the violation of baryon number is sought, and not that of other hitherto conserved quantities. Single nucleon decay searches (eg, $p \to \pi^0 e^+$) require lepton number violation in order to ensure angular momentum conservation. Only searches for free neutron oscillation [38, 39] and anomalous nuclear decays, under the neutron oscillation [40] or dinucleon decay-hypothesis [41], offer high precision sensitivity to BNV-only processes.

2.2. Experimental setup

If neutrons can oscillate to anti-neutrons, the probability for the process to occur would be proportional to the free flight time squared, so an experiment to search for neutron-anti-neutron oscillations should aim for highest possible flight time. This requires an intense cold neutron beam and good vacuum. The flight path should be as long as possible and magnetically shielded in order to suppress energy splitting between neutron and anti-neutron energy states inflicted by the (anti)neutron magnetic moment ($\Delta E = \mu B$). To observe the anti-neutrons, an annihilation target (film) is needed and it should be surrounded by tracking detectors in a magnetic field to trace the produced charged pions and by calorimeters to perform energy measurement of the neutral pions. By this approach the invariant mass of the annihilating particle can be reconstructed offline and the experimental background can be severely suppressed. Since this would be a discovery type of experiment, background suppression is essential as any presence of background would reduce the sensitivity. The present limit: $\tau > 0.87 \times 10^8$ s was set by ILL experiment [39], using an approach according to lines of ideas discussed here.
There are a number of reasons to expect that a higher sensitivity can be reached at ESS than was the case for the ILL experiment. The fact that the neutron-anti-neutron oscillation search at the ESS is proposed before the construction of the facility gives rise to a number of advantages when outlining the experiment. Fig. 3 shows the preliminary engineering design of the beam extraction proposed for the neutron-anti-neutron experiment.

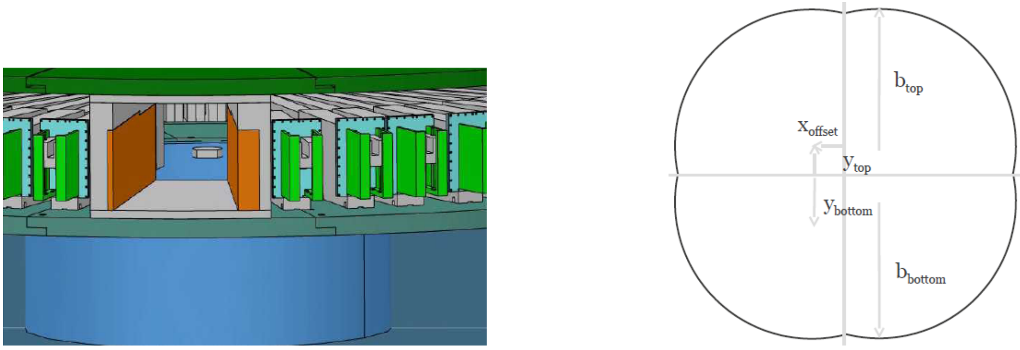

Figure 3: Left: Beam extraction of the neutron-anti-neutron oscillation experiment. Right: Cross-section of the *clover* reflector discussed in the text.

The experiment would temporarily[1] occupy ∼15 degree horizontally corresponding to three conventional ESS beam ports. The extended solid angle compared to the scattering instruments is beneficial for the neutron-anti-neutron oscillation experiment due to the loose requirements on beam collimation: any neutron that given one scatter on a focusing neutron optic can be aimed to the annihilation target is useful. Since the annihilation target film is expected to have a size in the order of one meter squared, this means that the acceptance in terms of divergence is far beyond that of conventional beam ports for neutron scattering instruments.
Since the figure of merit of the neutron-anti-neutron oscillation search is proportional to free flight time squared, the instrument is designed to have the longest possible flight path, which given the facility footprint dictates the orientation of the instrument to be perpendicular to the proton driver, where instruments up to 300 meters of length can be accommodated. The highest sensitivity is reached by optimizing for cold neutrons, which given the recent baseline change of the ESS moderator configuration from voluminous para-hydrogen moderators, to flat butterfly shaped ones, constitutes a significant challenge. The newly adapted moderator configuration can be seen in Fig. 4. In the right-hand figure insert the location of the four 'hot-spots' of cold neutron emission are seen to be separated by tens of centimeters. In order to extract as many

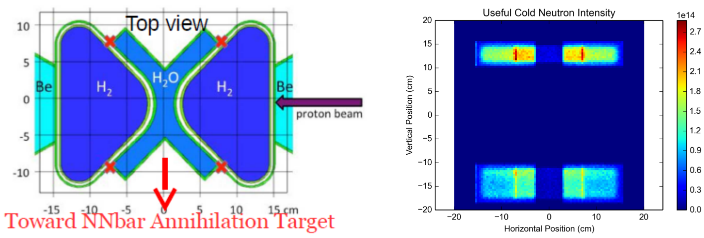

Figure 4: ESS moderator configuration as seen from above (left) and sidewise cold neutron emission map (right).

useful neutrons as possible several options are considered, including the double-cone reflector cut out shown in Fig. 5. To reflect neutrons from all four hot-spots into the annihilation film, a *clover* shaped reflector is proposed (see Fig. 3) and presently being optimized. Assuming a detection efficiency of 50% and that the experiment can be made completely background free, which was the case for the ILL experiment, Table 2 shows the preliminary sensitivity reach. In this table, the *unobstructed* case, refers to the situation where the limitation of the reflector and

[1] The duration of the neutron-anti-neutron experiment is undecided. Possibly 3-5 years.

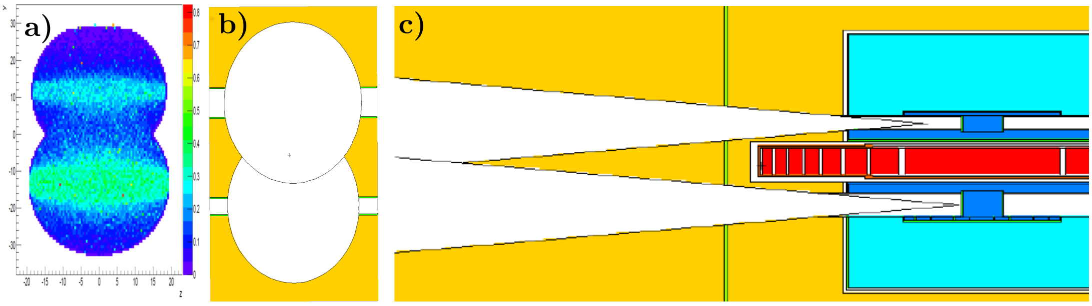

Figure 5: Double cone extraction, considered for the neutron-anti-neutron oscillation experiment, shown in side-view c) and perpendicular b). In a) the position of neutrons arriving at a radius of 2 m from the moderators is shown. The simulations are performed using MCNPX [42, 43], based on the recently adapted butterfly moderator geometry, modified to allow for extended neutron extraction through the double cone shown in the figure.

Source interface	Unobstructed	Beam port entrance	Beam port exit	Be Reflector
Available cold neutron intensity [n/s]	$2.2 \cdot 10^{17}$	$2.00 \cdot 10^{17}$	$1.43 \cdot 10^{17}$	$1.03 \cdot 10^{17}$
Baseline FOM (ILL/year)	211	209	106	64

Table 2: Experimental reach of the proposed neutron-anti-neutron oscillation experiment at ESS and a comparison to the corresponding ILL experiment [39].

beam port are completely neglected, whereas the *beam port entrance* and *beam port exit* refer to the situations taking into account the angular limitations inflicted by the entrance and exit of the beam port respectively (see Fig. 3). In addition to the limitations inflicted by the beam port, the *Be reflector* also takes into account the restrictions of the double cone collimator shown in Fig. 5. In neither case is any attempt made to mirror stray neutrons into useful trajectories - thus the sensitivities listed in the table can be considered conservative.

3. Conclusions and prospects

The ESS provides unique possibilities for experiments concerning fundamental physics. In this paper two such proposals are selected and the concepts of the proposed cold neutron beam facility for fundamental physics ANNI as well as the neutron-anti-neutron oscillation experiment are discussed. ANNI will outperform all existing cold neutron beam facilities for precision measurements of neutron decay, hadronic parity violation, and electromagnetic properties of the neutron, by up to 1-2 orders of magnitude in event rate. Preliminary investigations of a neutron-anti-neutron oscillation experiment suggest that a sensitivity which is 2-3 orders of magnitude better than the present limit should be within reach at the ESS. Recently a collaboration was formed with the intention to propose a neutron-anti-neutron oscillation experiment at ESS [44]. It is expected that a Technical Design Report will be finalized by 2017.

The list of possibilities for fundamental physics at the ESS, however, goes beyond these two examples. The reader is referred to Refs. [45, 46, 47, 48, 49] for additional examples, focussing, but not limited to, ultra cold neutron production and possible use for experiments.

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