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A neutron-antineutron oscillation experiment at the European Spallation Source

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Abstract

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. For instance, kaon oscillations provided us with our first insight into CP-violation, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation. The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with 2 orders of magnitude improvement in sensitivity to the neutron oscillation probability. Here, a general overview of the European Spallation Source will be given and the physics case for a neutron oscillation experiment will be discussed, together with the main experimental challenges and possible solutions.

Keywords: ESS; Neutrons; Antineutrons; Spallation; Oscillations; BAU.

1. Introduction to the ESS

The European Spallation Source (ESS) [1] is a multi-disciplinary research center based on the world's most powerful neutron source. It is a pan-European project gathering 17 partner countries for a total construction cost estimated at 1843 M€. Nearly half of the construction cost will come from the host countries (Sweden, Denmark), while the other half will come from partner countries.

The ESS will be built in Lund, Sweden. This new facility will provide to the scientific community new research opportunities using neutrons in the fields of life sciences, energy, chemistry, environmental technology, cultural heritage and fundamental physics. The unique capabilities of the ESS, namely the high peak flux of the neutron beam and the inherent time structure of the beam, will permit to push the frontiers of neutron sciences. Fig.1 presents the brightness at the ESS cold moderator compared to today's leading neutron science facilities.

Construction work has started this year on the site of Lund. First neutrons will be delivered in 2019. The ESS user program will start with 6 instruments in 2023. In 2025, the ESS construction will be complete with 22 operational instruments. ESS will operate as a user facility.

A unique feature of ESS neutron production will be that it is a long pulse spallation source; that is the length of the pulse is as long as 2.86 ms, with a repetition rate of 14 Hz. Neutron production will be described in the next section.

2. Neutron production at the ESS

A proton energy of 2 GeV requires an average macro-pulse current of 62.5 mA to reach a proton beam

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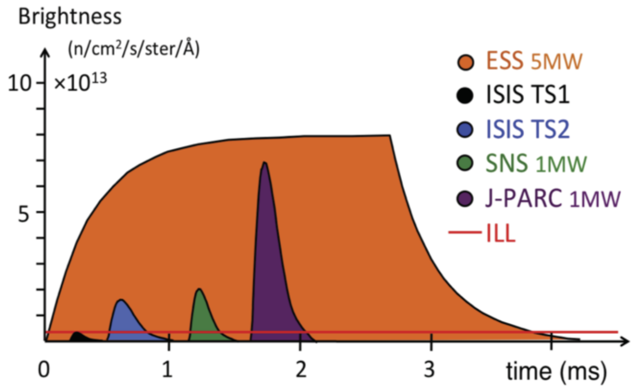

Figure 1: Single-pulse source brightness as a function of time at a wavelength of 5Å at the ESS compared to other leading neutron facilities [2].

power of 5 MW.

The ion source produces a proton beam that is transported through a Low Energy Beam Transport (LEBT) section to the Radio Frequency Quadrupole (RFQ) where it is bunched and accelerated up to 3.6 MeV. In the Medium Energy Beam Transport (MEBT) section the transverse and longitudinal beam characteristics are diagnosed and optimized for further acceleration in the Drift Tube Linac (DTL).

Then, the proton beam reaches the first superconducting section, which consists of 26 double spoke cavities with a geometric beta value of 0.50. The cavities are followed by 36 Medium Beta Linac cavities with $\beta = 0.67$ and 84 High Beta Linac elliptical cavities, with $\beta = 0.86$.

After acceleration, the beam is transported to the target through the High Energy Beam Transport (HEBT) section. Fig.2 shows the block diagram of the ESS accelerator.

With a velocity close to the speed of light, protons hit a heavy metal target made of tungsten to produce high-energy neutrons by the spallation process. The last step consists in slowing down these neutrons to suitable energies for the different ESS instruments thanks to a moderator-reflector arrangement surrounding the target. Then the thermal/cold neutrons produced are delivered to the instruments through beam ports leading to neutron guides. The key parameters of the ESS are summarised in Tab.1.

Figure 2: The general lay-out of the ESS linac [2].

Parameter	Unit	Value
Average beam power	MW	5
Nb of target station		1
Nb of instruments in construction budget		22
Nb of beam ports		48
Nb of moderators		2
Separation of ports	degrees	5
Proton kinetic energy	GeV	2
Average macro-pulse current	mA	62.5
Macro-pulse length	ms	2.86
Pulse repetition rate	Hz	14
Max accelerating cavity surface field	MV/m	40
Max linac length	m	482.5
Annual operating period	h	5000
Reliability	%	95

Table 1: ESS high-level parameters [2].

3. Fundamental physics at the ESS

Fundamental neutron physics concerns neutron experiments which have the aim to answer questions in cosmology, astrophysics, and particle physics. Neutrons offer an opportunity to improve our understanding of the Universe and its evolution.

The high neutron intensity at the ESS will permit to study the low-energy precision frontier [3] that consists in looking carefully at low-energy processes that can be accurately predicted by theory. The deviations (or their absence) from expectations in such processes would prove the existance (or non-existance) of new physics. In this manner, the precision frontier complements the studies done at the high-energy frontier as at the LHC at CERN [4] for instance.

One of the main challenges is to test the validity of the Standard Model of particle physics. This model has provided the framework for explaining phenomena involving the weak, the strong and the electromagnetic interaction. However the Standard Model seems to not be the complete theory. Indeed, it does not include gravitation.

This is a list of experiments that are expected to gain considerably at the ESS [5] :

- Observables in neutron decay [6] such as the neutron lifetime, decay correlations coefficients (a, A, B, C, D, R), the Fierz interference term (b) and internal Bremsstrahlung are sensitive to effects due to physics beyond the Standard Model. Those parameters that are not suppressed in the Standard Model can be calculated accurately. The goal is to look for non-zero values for the coefficients that are suppressed in the Standard Model or for small deviations from the non-zero Standard Model predictions that could signal the presence of virtual new particles that were more active as real particles in the early Universe [7].

- The observation of a non-zero electric dipole moment of the neutron (nEDM) could signal the presence of CP-violating interactions needed to produce the matter-antimatter asymmetry in the Universe. A nEDM can only exist if the negative and positive charge distributions inside the neutron do not coincide. So far, no nEDM has been seen. It may be that a future experiment at the ESS, with the significantly higher neutron flux, could push the neutron electric dipole moment program across the finish line in the search for cosmologically relevant CP-violation [8, 9].

- The neutron, as a massive particle, is sensitive to quantum effects. It can be used as a powerful tool to scan the quantum world for new discoveries. Entanglement, contextuality and quantum states of neutrons in the gravitational field would be interesting topics for related experiments at the ESS. Many of such experiments require ultra-cold neutrons (UCN), which can be efficiently produced at the ESS. For example, the newly established technique of gravity-resonance spectroscopy or many other experiments with gravitational quantum states of UCN would profit strongly from the increased UCN density at such a source [10, 11, 12].

- The case of neutron-antineutron oscillations will be treated more in details here.

4. Neutron-antineutron oscillations

4.1. Physics case

The matter-antimatter asymmetry of the Universe (BAU) still remains one of the most intriguing questions at the frontier of particle physics and cosmology. Producing different amounts of matter and antimatter requires a process that violates baryon number conservation. An observation of neutron-antineutron oscillations could help to understand the nature of this process [13].

Neutron-antineutron oscillation require a change in baryon number B by 2 units with no change in lepton number L. In the Standard Model, baryon number violation exists but is suppressed at low temperatures and (B-L) is conserved. Extensions to the Standard Model allow violating either B or L and may result in B violation by 2 units without changing the lepton number. Indeed, the observation of neutron-antineutron oscillations would be a discovery of primary importance because of its incontestable evidence for new physics beyond the Standard Model [14]. At the present level of sensitivity, neutron-antineutron oscillations probe intermediate energy scales, between the electroweak scale and grand unified theories.

4.2. Phenomenology

The transition probability to observe one neutron spontaneously converting to an antineutron can be extracted from the solution of the Schrödinger equation [14]:

$$i\hbar\frac{\delta\Psi}{\delta t} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}\Psi \tag{1}$$

With:

- Ψ: Neutron-antineutron state.
- E_n: Neutron energy.
- $E_{\bar{n}}$: Antineutron energy.
- α : Mixing parameter.

In presence of external fields (magnetic/nuclear), the transition probability for n → $\bar{n}$ is:

$$P_{n\to\bar{n}} = \frac{\alpha^2}{\alpha^2 + V^2} \times \sin^2\left(\frac{\sqrt{\alpha^2 + V^2}}{\hbar} \times t\right) \tag{2}$$

With:

$$V = \frac{1}{2}(E_n - E_{\bar{n}}) \tag{3}$$

For $\frac{\alpha}{\hbar}t << 1$ and in quasi-free condition (i.e $\frac{V}{\hbar}t << 1$), the transition probability becomes:

$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\to\bar{n}}}\right)^2 \tag{4}$$

With:

$\tau_{n\to\bar{n}} = \hbar/\alpha$, the free oscillation time.

4.3. Sensitivity

Two categories of experiments have already searched for neutron-antineutron transitions; experiments using neutrons bound inside nuclei and the ones using free neutrons. For experiments with free neutrons, the sensitivity is defined by the product of the number of neutrons per second, N, times the square of the free observation time, t^2, see eq. (4).

The reference experiment for oscillation searches using free neutrons was performed with the high flux reactor at the ILL (Grenoble, France) [15] in the 90s by the Heidelberg-ILL-Padova-Pavia collaboration [16]. Here, a sensitivity of 1.5×10^9 n.s has been obtained. This value is used as a reference such that the figure of merit = 1.5×10^9n.s = 1 ILL sensitivity unit. After one year of running at the H53 cold beam line of the ILL, a new limit for the free oscillation time was obtained: $\tau_{n\to\bar{n}} \geq 8.6\text{x}10^6$s.

According to the eq.(2), for the case of intranuclear transition, the transition probability is strongly suppressed by the nuclear potential. The corresponding intranuclear oscillation time is given by :

$$\tau_{intra} = R \times \tau^2_{free} \tag{5}$$

Where R represents the suppression factor estimated theoretically around $\sim 1\times10^{23}$ s^{-1} for most nuclei [17].

The best limit in the intranuclear transition search was provided by the Soudan 2 Collaboration [18]. The limit of $\tau_{Fe} \geq 7.2 \times 10^{31}$ years for the lifetime of the iron nucleus has been obtained. According to eq. (5) that corresponds to a free neutron oscillation time $\tau_{n\to\bar{n}} \geq 1.3 \times 10^8$ s.

Fig.3 presents a comparison of the sensitivity between neutron-antineutron oscillation searches with free and bound neutrons. An improvement of τ_{free} by one order of magnitude corresponds to an improvement of τ_{intra} by two orders.

The neutron-antineutron experiment proposed at the ESS promises a much-improved sensitivity and a considerable discovery potential. The aim of this experiment is to observe neutrons propagating in free space for a maximum time without wall collisions. In

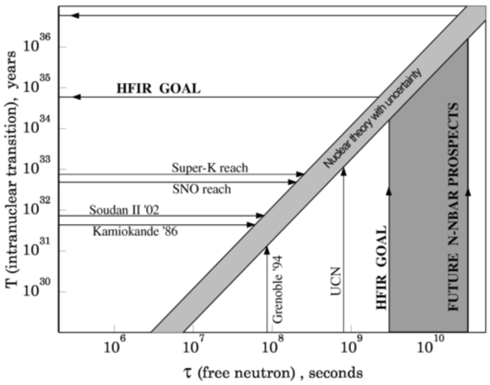

Figure 3: Comparison of free-neutron and bound-neutron methods for neutron-antineutron transition search. [14].

case of a transition to an antineutron, an annihilation event at the detector at the end of the flight path would be detected.

Recent developments in cold neutron optics technology combined with the specific advantages of the ESS may make possible an improvement of the sensitivity by a factor ~ 500 ILL units for the free neutron oscillation probability.

Even without the observation of such oscillations, the expected gain of up to 2 orders of magnitude in the exclusion limit would provide guidance for models aiming to explain the matter-antimatter asymmetry in the Universe.

4.4. Requirements for a future experiment at the ESS

In order to maximize the sensitivity, a horn-shaped super-mirror reflector must be installed in a wide beam port with direct view on a large moderator. The horn focuses the neutrons to a detector placed at > 200 m distance from the moderator to profit from a long flight time. Neutrons with very long wavelengths are particularly useful due to their low velocity. The flight tube must be maintained at high vacuum and the neutrons must be protected from magnetic fields at the nT-level. Fig.4 represents a schematic view of the experimental set-up for a neutron-antineutron experiment at the ESS. To maximise the beam divergence acceptance, and hence the flux, a target of several meters diameter is required. To make a discovery for one detected event, detection of antineutrons must be background free. GeV spallation neutrons from the ESS will be suppressed by using the time structure of the facility. Precise tracking, excellent timing resolution and a veto detector are needed to restrict candidate events to the target region and to suppress the overwhelming background of low-energy gammas from neutron capture as well as cosmic background.

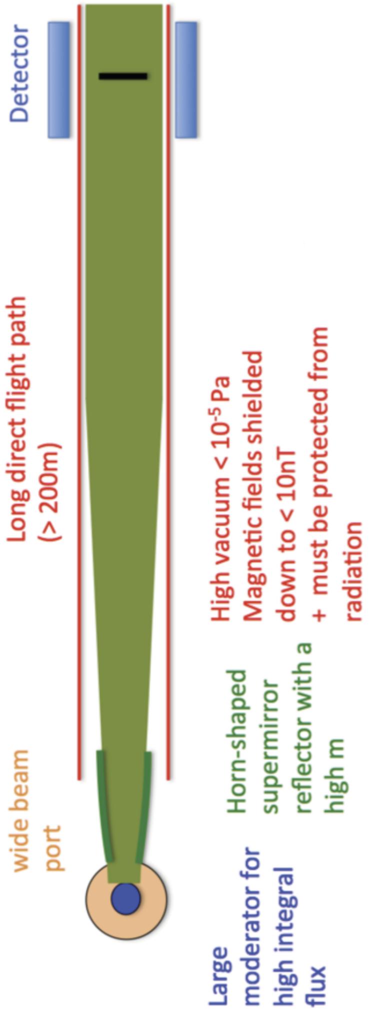

Figure 4: Set-up of a neutron-antineutron experiment at the ESS.

5. Outlook

Neutrons oscillating into antineutrons could offer a probe of baryon number violation. The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers a major opportunity to conduct an experiment with a real improvement in sensitivity to the neutron oscillation probability. In order to establish a collaboration about this topic, a first workshop took place at CERN in June 2014 [19] to identify the different working groups, find partners or institutions. Subject to funding, the goal is to submit a proposal to the ESS in approximately 2 years.

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