CEνNS at the ESS

Progress Report to the ESS Fundamental and Particle Physics STAP

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The now nearly-complete European Spallation Source will soon provide the most intense neutron beams for fundamental and applied science. Simultaneously, the ESS will also generate the highest pulsed-flux of neutrinos suitable for the detection of coherent elastic neutrino-nucleus scattering (CEνNS) [1, 2]. This recently-demonstrated mechanism of neutrino interaction has generated much excitement, as it provides numerous new ways to study the properties of these elusive particles and of target nuclei. CEνNS also allows for a dramatic reduction in neutrino detector mass, enabling the construction of compact devices apt for a nonintrusive deployment at the ESS.

This document is intended to briefly delineate several fronts of considerable progress made in establishing a program for coherent elastic neutrino-nucleus scattering (CEνNS) studies at the ESS. As such, it is meant to update the attached Expression of Interest, which was originally submitted to the ESS Directorate in 2020. The reader is referred to this EoI for a general introduction to the subject and ESS potential in this area. The points previewed below, among others, will be further developed during our upcoming presentation to the Scientific and Technical Advisory Panel (STAP) for Fundamental and Particle Physics at the ESS.

- We are already well in the process of developing next-generation CEνNS detector technologies for future installation at the ESS. As emphasized in [1, 2] the timing of ESS construction is perfectly adapted to the construction of ambitious technologies aiming to provide the best possible CEνNS detectors for the best suitable neutrino source. We are focusing on providing the lowest achievable sub-keV threshold to large-mass (tens of kg) detectors, as new physics revealed by CEνNS arises preferentially at the smallest detectable energies. Another area of our concentration is in exploiting the synergy between complementary targets (e.g., CsI and Xe).
- In parallel, we are studying the quenching factor for low-energy recoils in target materials to be employed. This is a crucial aspect, as future CEνNS measurements at the ESS are expected to be limited by this knowledge only, and not by signal statistics, as is the case when using weaker neutrino sources.
- This activity has already obtained full support from the European Research Council and other agencies. In this respect, three of the detector technologies that we initially plan to utilize at the ESS (cryogenic undoped CsI, high-pressure noble gas detectors, and germanium point-contact diodes) are funded via an ERC-Advanced and an ERC-Starting grant (2.8 MEUR and 1.5 MEUR, respectively), with an additional ERC-Starting proposal (1.7 MEUR) presently in the final second phase of

the selection process. A US National Science Foundation award (0.5 MUSD) complements several aspects of germanium detector installation. In addition to this, the Basque government -heavily invested in ESS construction- has backed our activities with thus far 2.0 MEUR, via their IKUR program (“neutrionics”, i.e., the interface between neutron and neutrino science being one of its four strategic priorities [3]). Prompted by the Basque government and ESS Directorate, we have recently submitted a Memorandum of Understanding between the Donostia International Physics Center (DIPC) and the ESS, in order to finalize an agreement on the specifics of our collaboration in this area.

- Several nonintrusive locations for compact CEνNS detectors have been located in collaboration with ESS personnel. We will introduce these, as well as the good prospects for neutron background abatement derived from our previous experience at the SNS and from full simulations of neutron transport at the ESS facility [4]. Our plans to validate these predictions using a custom-designed neutron scattering camera, coinciding with first protons on target during the summer of 2025, will be presented. Advanced active veto concepts to be implemented around CEνNS detectors, able to produce an optimal signal-to-background ratio, will be discussed.
- While one of the advantages of the described activity is the ability to perform it without deviation from the ESS neutron mandate, i.e., in an entirely passive manner, we will present a short list of minor requests from the ESS, for their consideration. Chief among those is access to the (presently unused) areas identified for detector installation. Given the proximity in time of our first on-site activities we would like to request minimal office and staging space, as well as access to ESS engineering personnel for necessary consultations. A final request is the formalization of our MoU. This document specifies our responsibility for the financial overburden that might arise from certain activities, to be discussed.
- During our presentation we will also briefly touch upon several spin-offs already generated from our ongoing work. Specifically, opportunities to collaborate with European industry on the development of advanced light sensors, and potential detector applications in areas outside of particle physics.

CEνNS is to broaden our ability to investigate physics beyond the Standard Model at the interface of particle and nuclear physics. The compact nature of CEνNS detectors, together with the potential of the ESS as a high-intensity pulsed neutrino source, provide a singular opportunity to expand the physics reach of the facility with essentially no deviation from its program, nor a significant impact on finances and resources. We are positioned to initiate CEνNS-related activities coinciding with first protons on target, and to deploy first CEνNS detectors in time for regular ESS operation around 2027. However, in view of the interest in this area, we expect that the activities to be described during our presentation will be just the beginning of a rich neutrino physics program at this European facility, one that will expand its breadth as detector technologies and beam delivery continue to improve.

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Coherent Elastic Neutrino-Nucleus Scattering at the ESS

Expression of Interest

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ABSTRACT:

The European Spallation Source will soon provide the most intense neutron beams for multidisciplinary science. Conveniently, it will also generate the largest pulsed neutrino production rate suitable for the detection and study of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS), a process recently measured for the first time at ORNL's Spallation Neutron Source. CEνNS holds the potential for significant advances in sensitivity to numerous aspects of particle and nuclear phenomenology, providing a new, long-sought tool in the search for physics beyond the Standard Model.

We propose to use innovative nuclear-recoil detector technologies, optimized to profit from the order-of-magnitude increase in neutrino production that is expected from the ESS when compared to all other existing or planned spallation sources. These low-cost, compact, unintrusive devices profit from previous R&D aimed at other particle physics applications. They can be deployed coincident with the start of the ESS user program, without any significant impact or deviation from the ESS neutron mandate. The combination of a state-of-the-art performance from these advanced detectors, together with the uniqueness of the ESS as a high-yield pulsed neutrino source, will return high-statistics, precision CEνNS measurements at the limit of the sensitivity to new physics reachable through this novel neutrino interaction mechanism.

Exploiting the exciting new development and opportunity that CEνNS represents, the program described here will significantly expand the physics reach of the ESS to a new area, that of neutrino physics, at the expense of just a minimal investment of resources.

1 Science Case and Opportunity

Neutrinos with energies below few tens of MeV undergo a large enhancement to their cross-section for elastic scattering off nuclei [1, 2]. This mechanism is typically referred to as coherent elastic neutrino-nucleus scattering (CEνNS). During this neutral-current interaction, all nucleons participate coherently in the scattering process. The contribution from protons is markedly diminished by the numerical value of the weak mixing angle, resulting in a coupling effectively proportional to the square of the number of neutrons in the target nucleus [2]. This large enhancement to the scattering cross-section makes of CEνNS the most probable mechanism for low-energy neutrino interaction, resulting in a substantial detector miniaturization. Despite this marked advantage, the process remained undetected until 2017, more than four decades after its theoretical description. This counterintuitive delay resulted from the modest energy of the nuclear recoils induced -the single observable from this process-, and from the limited intensity of available neutrino sources in this energy range. First evidence for CEνNS [3, 4] was obtained using a 14.6 kg low-background sodium-doped cesium iodide detector [5] exposed to the neutrino emissions from ORNL's Spallation Neutron Source (SNS), a precursor facility to the European Spallation Source (ESS).

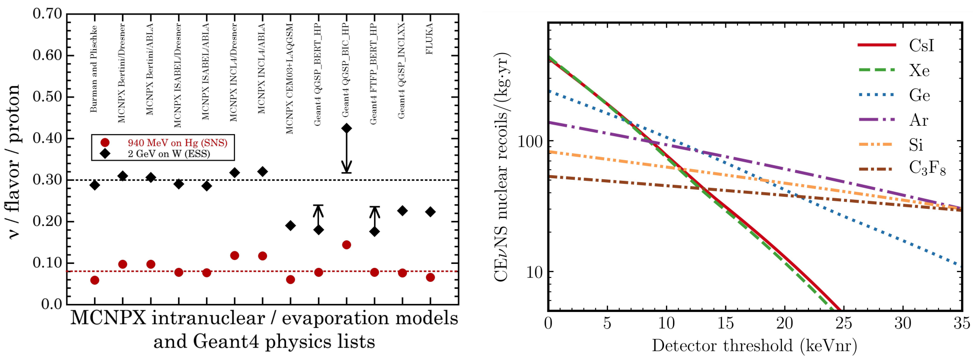

Figure 1. *Left:* neutrino yields for the SNS mercury and ESS tungsten targets, obtained from different simulation packages. The first column shows predictions from a dedicated calculation [6, 7], validated against neutrino cross section measurements [8]. The combination of increased neutrino yield per proton and larger proton current on target of the ESS generates an increase in neutrino production rate by a factor 9.2 with respect to the SNS [9]. *Right:* Expected integrated CEνNS rate above nuclear recoil threshold, 20 m away from the ESS target, for detector materials examined in [9]. All technologies considered for use at the ESS have state-of-the-art thresholds at or below 1 keV$_{nr}$. This maximizes sensitivity to new physics, which becomes most evident at the lowest recoil energies [9].

A number of tests for new physics are possible using CEνNS-sensitive neutrino detectors. For instance, a neutral-current detector responds almost identically to all known neutrino types [10]: observation of neutrino oscillations in such a device would provide unequivocal direct evidence for sterile neutrino(s) [2]. In addition to this, the differential cross section for this process is strongly dependent on the value of the neutrino magnetic moment [11]. Numerous studies have described the sensitivity of CEνNS to non-standard neutrino interactions with quarks [12, 13], to the effective neutrino charge radius [14], to neutron density distributions [15–17], and to accelerator-produced dark matter candidates [18]. Precise measurements of the CEνNS cross section can provide a sensitive appraisal of the weak nuclear charge [19], and constraints on new gauge bosons [20]. A more extensive review of the rich particle phenomenology that can be investigated through CEνNS is available from [9].

In a seminal paper [2], Drukier and Stodolsky described the prospects for CEνNS detection from a variety of low-energy neutrino sources (solar, terrestrial, supernova, reactor, and spallation source). Of these, spallation sources were highlighted as the most convenient, due to higher recoil energies -easier to detect- and pulsed operation -leading to a more favorable signal-to-background ratio-. While the main use for these facilities is as intense neutron sources, their protons-on-target (POT) produce positive pions, which preferentially decay at rest (DAR), generating a monochromatic flash of 30 MeV prompt ν_μ. This is followed by delayed ν_e and $\bar{\nu}_\mu$ emissions with a broad energy (Michel spectrum, up to few tens of MeV), over the ~2.2 μs timescale characteristic of μ decay. Specifically, the instantaneous neutrino flux 20 m away from the ESS spallation target is expected to be $\sim 1.4 \times 10^{10}$ cm^{-2} s^{-1} [9].

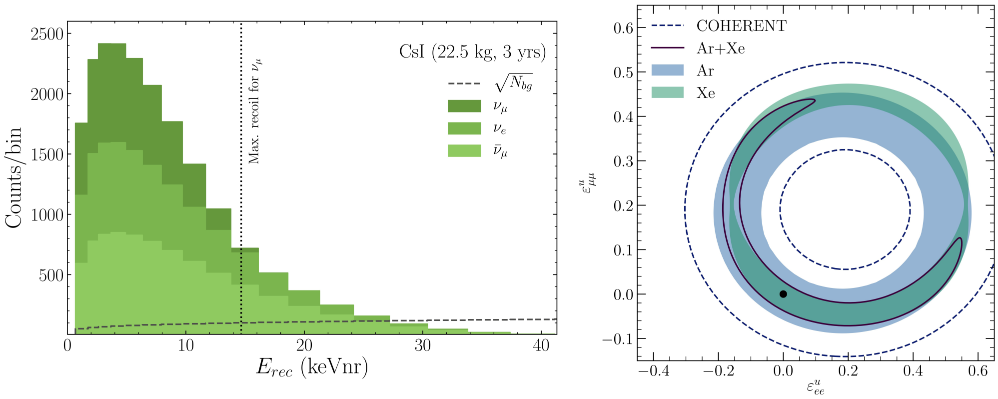

Figure 2. *Left:* Large CEνNS signal statistics expected from a 22.5 kg cryogenic CsI detector installed 20 m from the ESS target [9]. Improvements in neutrino production and detector performance provide a ~ ×100 increase in CEνNS signal throughput with respect to the room-temperature CsI[Na] originally employed at the SNS [9]. The ability to distinguish prompt ν_μ from delayed ν_e, $\bar{\nu}_\mu$ neutrino emissions using recoil energy information can be exploited towards a sensitive search for sterile neutrinos [21]. *Right:* increase in sensitivity to a parametrization of non-standard neutrino interactions with quarks, obtained by combining several target materials at the ESS (in this example different gases within a NEXT chamber), compared to the SNS. A similar advantage in all other areas of interest is expected (Table I, [9]), a result of the order of magnitude increase in neutrino production at the ESS, and of technological advances in the nuclear recoil detectors being considered.

The physics potential of CEνNS studies at the ESS has been examined in a recent publication [9]. To avoid repetition, in this document we only summarize and condense the arguments presented there in more detail. The ESS is on schedule to provide first protons on target during 2021, generating by 2023 an order of magnitude increase in neutrino production with respect to the SNS (Fig. 1). Compact, low-cost detectors (few kg to few tens of kg) operated at the ESS, have the opportunity to produce CEνNS measurements not limited in sensitivity by signal statistics (Fig. 2), but instead only by the irreducible O(10)% systematic error associated to uncertainties in detector response and neutrino flux. Differences in beam timing profile between the SNS and ESS were included in the analysis in [9], concluding that the increase in neutrino production more than compensates for their impact on background reduction. The outcome is that the ESS will provide the very best sensitivity to neutrino properties and other areas of phenomenology that can be achieved via CEνNS, from any foreseeable future neutrino source (Fig. 2, Table I). The large CEνNS signal throughput expected at the ESS allows to keep the detectors small (Fig. 3), and therefore unintrusive to ESS neutron operations.

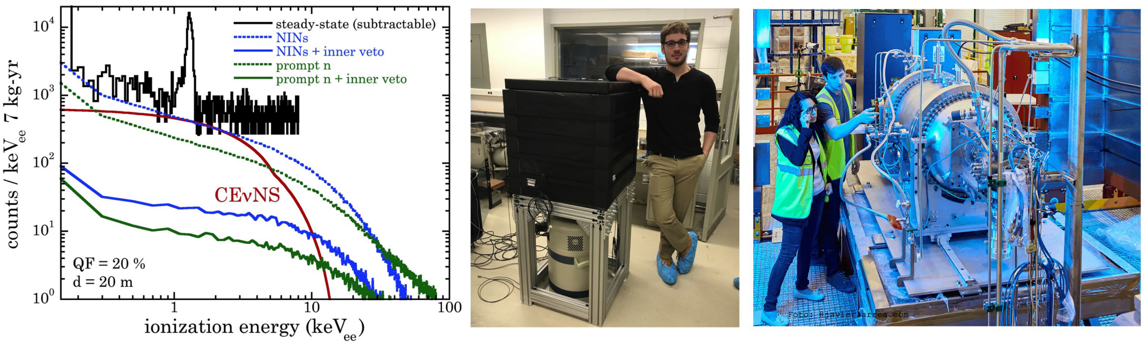

Figure 3. *Left, center:* innovative, compact nuclear recoil detectors such as PPC germanium diodes [22] are ready for an early ESS deployment. The plot shows a favorable comparison between simulated beam-related and measured steady-state (subtractable) backgrounds from the compact 3 kg PPC in the picture, against the expected CEνNS signal at the ESS. An overly conservative increase in beam-related backgrounds by a factor of ten with respect to our own measurements at the SNS was adopted in the simulations [9]. At an early stage of this project we envision a full characterization of ESS backgrounds via simulation and neutron measurements (Sec. 3). *Right:* The NEXT-White detector at the Canfranc underground laboratory (LSC). An envisioned chamber at the ESS will be similar in size, and will share many technical solutions already developed for this apparatus.

	Ar	C_3F_8	CsI	Ge	Si	Xe	Xe+Ar	COH-SNS
$\sin^2\theta_W$	$0.239^{+0.028}_{-0.022}$	$0.239^{+0.025}_{-0.020}$	$0.239^{+0.032}_{-0.026}$	$0.239^{+0.029}_{-0.024}$	$0.239^{+0.032}_{-0.029}$	$0.239^{+0.033}_{-0.026}$	$0.239^{+0.020}_{-0.029}$	0.248 ± 0.094
$\langle r^2_{ee}\rangle$	[-65, 20]	[-58, 18]	[-67, 16]	[-67, 20]	[-54, 18]	[-70, 17]	[-55, 20]	[-65, 6]
$\langle r^2_{\mu\mu}\rangle$	[-51, 7]	[-46, 6]	-[59, 7]	[-54, 7]	[-43, 6.5]	[-60, 7.5]	[-28, 7]	[-60, 10]
$\lvert\langle r^2_{e\mu}\rangle\rvert$	< 15	< 12	< 21	< 17	< 11	< 21	< 17	<35
μ_{ν_μ}	< 9	< 11	< 9	< 7	< 6	< 9	< 10	<31

Table I: Allowed ranges at 90% C.L. for the weak mixing angle (given as best fit ±1.64σ), neutrino charge radii for three flavour projections (in units of 10^{-32} cm^2, and after marginalizing over the other two flavour projections), and the ν_μ magnetic moment (90% CL upper bound in units of $10^{-10}\mu_B$) at the ESS, compared to the SNS (right column). The pion DAR neutrino production at the ESS is the largest of any present or planned spallation source, providing the best sensitivity to the many phenomenological applications of CEνNS [9].

In the same publication we have described the opportunity to reinvest state-of-the-art nuclear recoil detectors already developed for other uses (e.g., DAMIC-M CCDs [23–26] and scintillating bubble chambers [27] for WIMP detection, NEXT gaseous TPCs for double-beta decay [28–30]), for this purpose of CEνNS exploration (Fig. 3). Our publication also describes novel technologies such as undoped cryogenic (80 K) CsI scintillators. This material, in combination with advanced light sensors and waveshifters, increases the CEνNS signal rate per detector mass by a factor of eight, with respect to the room-temperature CsI[Na] that was employed for the first CEνNS detection at the SNS. To provide some perspective, a compact 22 kg CsI detector will register ~8,000 CEνNS events per year at the ESS [9]. This can be contrasted with the ~3,000 events per year that a massive 750 kg liquid argon detector would achieve at the SNS [31]. Similarly-large signal rates are expected from other compact technologies proposed for use at the ESS [9]. What is more, they are all able to reach nuclear recoil energies of $\lesssim 1$ keV$_{nr}$. This maximizes their sensitivity to new physics, which appears preferentially at the lowest energies [9]. This is again in contrast with the 20 keV$_{nr}$ threshold that can be expected from LAr scintillation [18, 31]. While some of the detector technologies we have proposed excel in specific areas (e.g., DAMIC silicon CCDs for neutrino magnetic moment studies, Table I), their combination is synergistic, both for improving sensitivity, and for the investigation of possible anomalies (Fig. 2, [9]).

2 Timeline

The time required to secure funding, design, and construct CEνNS detectors suitable for deployment at the ESS is an excellent match to the start of a neutron program in 2023. In some instances (e.g., ongoing DAMIC-M silicon CCD deployment at Modane), this is also well-aligned with completion of detector use at other locations. The interim period can also be utilized to perform neutron transport simulations aiming to validate the suitability of locations within the ESS facility, already identified as potential sites for unintrusive CEνNS experimentation (Fig. 4). Neutron background measurements able to validate these simulations, similar to those already performed by us at the SNS (Fig. 5, [3, 4]), can commence as early as first ESS protons-on-target are produced. Over this early period, the possibility of developing a conventional (i.e., not CEνNS-sensitive) ~1-ton charged-current neutrino detector [32] can also be studied. This additional activity would be beneficial for the whole program, as such a device holds the potential to reduce a systematic uncertainty in the neutrino flux that can impact CEνNS sensitivity to new physics (Fig. 1, [9]). Calibrations of detector response to low-energy nuclear recoils, of crucial importance for the interpretation of results [33], can also be performed during this preparatory period.

From the present perspective, a rough timeline can be sketched:

- **Phase I (2020-2021):** applications for seed funding, background simulations for site selection, detector design, detector response calibrations. Preparation of a Technical Design Report.
- **Phase II (2022-2023):** neutron background measurements. Following confirmation of site suitability, deployment of first-ready technologies (e.g., germanium PPCs, Fig. 3), detector construction and installation.

- **Phase III (2024-2026):** CEνNS studies (sensitivity estimates [9] assume 3-years of data-taking).
- **Phase IV (2027-...):** in the event of detection of potential signatures of new physics, or if a large increase in sensitivity is foreseen by extrapolating a best-performing technology, concentration on the design of a single larger detector can be contemplated at this point.

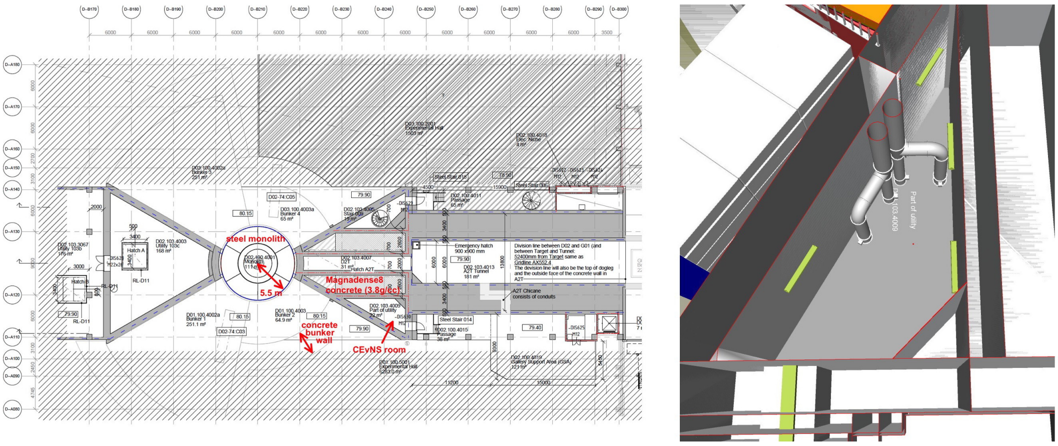

Figure 4. ESS building layout indicating an unallocated room identified as a possible site for CEνNS detectors, and NAVISWORKS 3-D visualization of this room. Two promising locations have already been identified, in collaboration with ESS personnel. The first is this room (15-23 m to target), featuring 5.5 meters of steel monolith and a minimum of 6 meters of magnetite-loaded heavy concrete (3.8 g/cm^3) in the line-of-sight to target. A second are underground galleries as close as 23 m to target, with compacted soil and concrete pylons separating them from the monolith. Based on our previous experience in characterizing and simulating neutron backgrounds at the SNS, both locations hold great potential, to be confirmed via MCNPX simulations and neutron measurements.

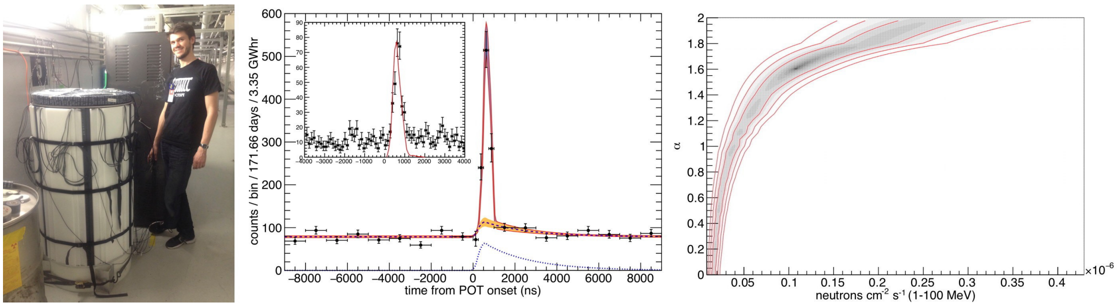

Figure 5. *Left:* former University of Chicago graduate student B. Scholz next to neutron detectors and dedicated shielding used for background studies at the SNS, prior to the first CEνNS measurement. This equipment exists and is available for similar studies at the ESS. *Center:* (from [3, 4]) beam-related background studies at the SNS. Both prompt neutron (central spike) and neutrino-induced neutron (NIN) backgrounds (yellow best fit) were measured or constrained using neutron-sensitive scintillator cells. Similar studies are envisioned at the ESS once proton production has been initiated. *Right:* best-fit spectral hardness and flux for the small component of prompt neutrons detected at the CsI[Na] detector site during SNS background studies [3, 4]. This is used to predict beam-associated backgrounds, allowing to select locations within the facility suitable for CEνNS experimentation.

3 The νESS collaboration

The proponents of this physics program are in the process of organizing an international νESS collaboration. Given the envisioned multi-detector nature of the experiment, the νESS is conceived as a *Federation* which initially would include at least four major lines of experimental effort:

1. **Cryogenic scintillators**
2. **Low-background CCD arrays**
3. **High-pressure gaseous noble gas chambers**
4. **Neutrino and Neutron flux measurement detectors**

Each line is led by a co-spokesperson (CSP) in charge of advancing his or her specific front. At the same time, the collaboration will organise a number of global working groups (GWG) which will include:

1. **Background characterisation of the site**
2. **Infrastructures**
3. **Monte Carlo simulation tools**
4. **Phenomenology and physics analysis**

Lastly, the collaboration will perform R&D towards a second generation of CEνNS neutrino experiments, which include scintillating bubble chambers and ultra-low threshold gaseous detectors, among other possibilities.

The scientific management of the collaboration will be the responsibility of the Federation Steering Committee (FSC), that will include the CSPs and the PIs of the GWGs. The FSC will be chaired by a coordination-spokesperson (XSP). The institutional management of the collaboration will be managed by the Federation Institutional Board (FIB), which will consist of the XSP, the CSPs (ex-officio members), one representative of the ESS and one representative of each of the institutions involved in the collaboration.

4 Costing & Expected ESS Support

The development of a World-Class CEνNS program at the ESS requires, on one side, appropiate funding for the detectors, and on the other, a minimum of local support from the ESS. Detector funding is to be sought during the first two phases, from EU and US sources, at no ESS cost. However, an early and firm commitment from the ESS to this activity would facilitate the obtention of this external funding. From the present perspective, and in view of the compact nature of the devices being considered, and of the maturity of the technologies involved, the funding necessary for detector construction should be <20 MEUR. This rough upper limit includes the mentioned possibility of building a $\sim$1-ton charged-current detector for an accurate neutrino flux characterization.

Early access to the ESS, as soon as protons-on-target are generated, would be necessary to perform the neutron background studies delineated in Sec. 3. In this respect of potential site identification, a dynamic collaboration with ESS personnel is already taking place. Besides a suitable location(s) for the detectors, the minimal support envisioned from the ESS once CEνNS activities have started would include the allocation of some infrastructure, similar to what is provided to neutron instruments (local collaborators, power, POT trigger signals, supplies such as cryogens, data storage, safety supervision, on-site office space, etc.).

5 Conclusion

CEνNS provides a new tool in the search for new physics beyond the Standard Model, one that spans both particle and nuclear realms. The technological maturity, small footprint, and low-cost of CEνNS-sensitive detectors, together with the unique intensity of the ESS as a pion DAR pulsed neutrino source, invite us to consider the development of a neutrino physics program at the ESS, with concentration on minimizing interference with neutron activities. However, we emphasize that the sensitivity of CEνNS investigations at the ESS depends critically on the neutrino production rate achieved, and therefore on reaching full design specifications of 5 MW power and 2 GeV proton energy, both in a timely fashion. While the expectations presented here and in [9] do not require a departure from those established goals, it is worth mentioning that the further improvements (e.g., pulse compression) involved in the ESSnuSB extension [34, 35] would be beneficial to this program of activities.

Given the opportunity, we intend to apply our accumulated experience in developing low-background nuclear recoil detectors, which includes the first CEνNS detection at the SNS, to create this new program of ESS activities. The net result will be a significant expansion of the ESS physics potential, in exchange for a modest investment of resources.

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