Letter of Intent

Acronym and title: STRANGE-MATTER, Advanced Studies on **Strange** Hadronic **Matter**
Project leader: *Dr. Raffaele Del Grande (Czech Technical University in Prague)*

1. Research objectives. The objective of the STRANGE-MATTER project is to advance our understanding of the strong interactions involving strange hadrons, such as kaons and hyperons, with nuclear systems. These studies are essential for addressing fundamental open questions in hadron physics and nuclear astrophysics, including: *the nature of the interaction between nucleons and strange hadrons; the formation mechanisms and structure of hypernuclei and of exotic bound systems; the role of strange hadrons in dense nuclear matter, such as in the core of neutron stars.* The project builds on the substantial progress achieved by the THEIA NA within STRONG-2020, which established close scientific collaborations between the theoretical and experimental communities across Europe and partner countries. Progress has been achieved, but still many of the properties and of the dynamics of strange hadron systems remain only partially understood or not yet uncovered. Also new challenges appeared.
STRANGE-MATTER aims to accelerate the progress in the field. This will be possible by coordinating activities, including theoretical interpretations, at the Transnational Access (TA) infrastructures working in the field, by sharing data repositories and analysis tools, and harmonizing theoretical interpretation frameworks. A significant goal is also the training of a new generation of scientists and mentoring networks. This will help to ensure the long-term sustainability and innovation capacity of the European community in the field. For details of the scientific objectives in relation to the TA see section below.
2. Connection to Transnational Access infrastructures (TAs). The STRANGE-MATTER project is built around and strongly connected to programs ongoing at the major TA facilities and infrastructures that host complementary experimental programs relevant to the physics of strange hadrons: FAIR@GSI (Germany), MAMI/MESA (Germany), INFN-LNF (Italy), LHC@CERN (Switzerland), J-PARC (Japan), RHIC@BNL (USA) and JLab (USA).
The activities are organized around four scientific pillars, connected to the TAs as follows: *(1)* *Strangeness in Nuclei with Extreme Isospin*. In neutron stars, nucleons and hyperons are expected to coexist in a highly neutron-rich environment. To gain insight into how hadrons interact in such systems, the STRANGE-MATTER project will promote a combined study of neutron-rich nuclei and hypernuclei. The MAMI-A1 experiment has recently measured the energy and width of the ground state of the neutron-rich ^{6}H isotope, revealing that the neutron-neutron interactions in ^{6}H may be stronger than expected. This result opens new avenues for exploring extreme isospin nuclei, with upcoming experiments aiming to clarify the structure of the observed tetra-neutron (nnnn) signal, search for the trineutron (nnn) and the decay of the doubly strange partner nnΛΛ via a missing mass study in relativistic heavy-ion reactions. At the same time, precise hypernuclear spectroscopy experiments are planned at JLab, targeting neutron-rich hypernuclei such as $^{48}{}_{\Lambda}$K and $^{208}{}_{\Lambda}$Tl. The former is ideally suited to explore major properties of ΛNN three-body interactions in Λ-hypernuclei. Additionally, high-resolution spectroscopy studies on Λ- and Ξ-hypernuclei, aiming at providing novel insights into three-body interactions involving Λ and Ξ hyperons, have been completed (E70, E73, E96) or planned (E63, E75, E94) at J-PARC. A new single-Λ hypernuclei program, HYPER, is planned at the Antimatter Factory of CERN.
(2) *Nucleosynthesis of Hypernuclei in High-Energy Nuclear Collisions*. Relativistic heavy-ion collisions offer a unique laboratory to study the still unclear formation process of light and

multi-strange hypernuclei in a rapidly expanding and cooling environment. This phenomenon can be modelled by using a hybrid approach which includes the dynamical description of the strangeness formation and the statistical description of the nucleation process. The production of hyperons and other baryons and the fragment formation in local parts of nuclear matter can be modelled by means of transport codes (e.g. UrQMD) and a recently developed statistical approach. The latter can describe the available experimental data on the production of light hypernuclei and predict new species. This hybrid approach, to be developed within this project, will serve to interpret new measurements on (multi-)hypernuclei production, expected by experiments at FAIR@GSI, RHIC@BNL, and LHC@CERN heavy-ion accelerators.
(3) Two- and three-body interaction studies using femtoscopy. The femtoscopy technique has become a powerful tool to explore low-energy interactions involving strange hadrons. The p-Ξ and p-Λ correlations analyses by ALICE@LHC have, for the first time, validated lattice QCD predictions and constrained effective field theory interactions. These results allowed the construction of an equations of state (EOS) for neutron stars, by using more realistic two-body interaction models. A central objective of the STRANGE-MATTER project is to include realistic three-body interactions in the hypernuclear EOS. This will be achieved through an ambitious experimental and theoretical program that leverages large-statistics datasets from LHC Run 3, recorded with the ALICE detector. Dedicated femtoscopic analyses will be performed to understand the poorly known nucleon-Σ interaction and the interactions in three-particle systems such as p-p-Λ, p-p-Σ and p-p-Ξ. In parallel, hyperon-deuteron correlations (Λ-d, Σ-d, Ξ-d) will be studied to probe the isospin and spin dependence of the three-body interactions. Complementary measurements are ongoing or planned at STAR@RHIC and ALICE@LHC in heavy-ion collisions. Additionally, information from femtoscopic data for non-strange p-p-p and p-d systems will be important in the search for a possible trineutron state in n-n-n correlation measurements at RIKEN and/or R3B@FAIR.
(4) Kaon-nucleon interaction and Kaonic bound state properties. Among strange exotic bound states, the kaonic ones play a unique role in determining the kaon-nucleus optical potential. In 2023-2024, the SIDDHARTA-2 collaboration performed the first measurement of X-rays from the kaonic deuterium atom, employing stopped kaons at DAΦNE. This measurement will allow to disentangle for the first time ever the isospin components of the antikaon-nucleon scattering lengths. At the J-PARC facility, complementary high precision studies will be performed (E57) by using an energetic K^- beam and employing novel Transition Edge Sensors. Moreover, an intensive campaign for the study of exotic kaonic nuclei has been initiated at J-PARC (E80 and E89), motivated by the observation of a KbarNN state by the E15 experiment. The cooperation between the experimental groups at LNF and J-PARC infrastructures, together with theoreticians in STRANGE-MATTER will be crucial.
3. Estimated budget request. The estimated budget covers outreach and training activities (20k Euro/year), the organization of an annual workshop and support for travel (40k Euro/year) and indirect cost (15k Euro/year). The total cost for a funding period of 4 years amounts to 300k Euro.
4. Participating and partner institutions. U. Barcelona, U. Bochum, U. Bonn, Chalmers U. of Technology, Czech Technical U. in Prague, GSI Darmstadt, TU Darmstadt, U. Frankfurt, Fudan U., U. Gießen, U. Hampton, U. Heidelberg, INFN (Catania, LNF, Pisa, Torino, Trieste), Japan Atomic Energy Agency, Hebrew U. Jerusalem, FZ Jülich, Instituto de Estructura de la Materia Madrid, U. Mainz, TU Munich, Nucl. Phys. Institute Rez/Prague, Inst. for Physical and Chemical Research RIKEN, U. of Southampton, Aristotle U. Thessaloniki, U. Tohoku, U. Tokyo, U. Valencia, U. Washington.