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NA61/SHINE Experiment—Program beyond 2020

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Abstract: The fixed-target NA61/SHINE experiment (SPS CERN) looks for the critical point (CP) of strongly interacting matter and the properties of the onset of deconfinement. It is a scan of measurements of particle spectra and fluctuations in proton–proton, proton–nucleus, and nucleus–nucleus interactions as a function of collision energy and system size. This gives unique possibilities to researching critical properties of the dense hot hadronic matter created in the collision process. New measurements and their objectives, related to the third stage of the experiment after 2020, are presented and discussed here.

Keywords: QCD matter; phase transition; critical point

1. Introduction

The NA61/SHINE, **S**uper Proton Synchrotron (SPS) **H**eavy **I**on and **N**eutrino **E**xperiment, is the continuation and extension of the NA49 [1,2] measurements of hadron and nuclear fragment production properties in fixed-target reactions induced by hadron and ion beams. It has used a similar experimental fixed-target setup as NA49 (Figure 1), but with an extended research program. Beyond an enhanced strong interactions program, there are the measurements of hadron production for neutrino and cosmic ray experiments realized. NA61/SHINE is a collaboration, with about 150 physicists, 33 institutions, and 14 countries being involved.

The strong interaction program of NA61/SHINE is devoted to studying the onset of deconfinement and search for the critical point (CP) of hadronic matter, related to the phase transition between hadron gas (HG) and quark-gluon plasma (QGP). The first order phase boundary between the HG and QGP phase is expected to end at the CP, as seen in Figure 2. At the CP, the sharp first-order phase transition turns into a rapid crossover, resulting in the appearance of large fluctuations of various observables, which are sensitive to the vicinity of the CP. The CP has long been predicted for thermal quantum chromodynamics (QCD) at finite μ_B/T [3–5]. Lattice QCD calculations, which are becoming more and more accurate, have led to the present conclusions that the cross-over region occurs at $T_c(\mu_B = 0) = 154 \pm 9$ MeV [6] and the location of the CP is not expected for $\mu_B/T \leqslant 2$ and $T/T_c(\mu_B = 0) > 0.9$ [7]. A more detailed exploration of the QCD phase diagram would need both new experimental data with extended detection capabilities and improved theoretical models [8].

The NA49 experiment studied hadron production in Pb + Pb interactions, while the NA61/SHINE collects data varying collision energy (13A–158A GeV) and the size of the colliding systems, as shown in Figure 3. This is, in a sense, equivalent to the two-dimensional scan of the NA61/SHINE piece of the hadronic phase diagram in the (T, μ_B) plane, as depicted in Figure 2. Changes in the collision energy lead to different values of the net baryon number chemical potential μ_B and temperature T. Different sizes of colliding systems allow to identify the minimum hadronic volume, which can be excited to the state where statistical physics concepts of HG/QGP phase transition are still meaningful. The research program was initiated in 2009, with the p + p collisions used later on as reference measurements for heavy-ion collisions.

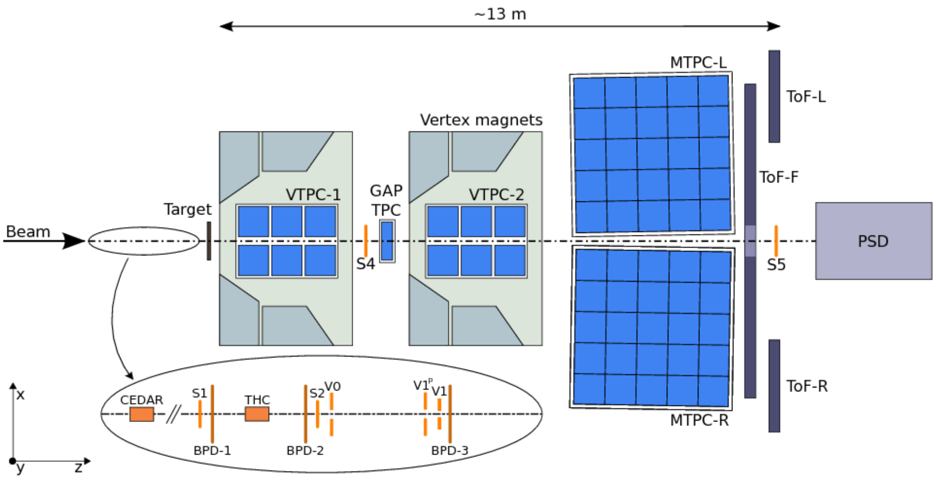

Figure 1. The present NA61/SHINE detector consists of a large acceptance hadron spectrometer, followed by a set of six Time Projection Chambers (TPCs), as well as time-of-flight (ToF) detectors. The high resolution forward calorimeter, the projectile spectator detector (PSD), measures energy flow around the beam direction. For hadron–nucleus interactions, the collision volume is determined by counting the low momentum particles emitted from the nuclear target with the low momentum particle detector (a small TPC) surrounding the target. An array of beam detectors identifies beam particles, secondary hadrons, and nuclei, as well as primary nuclei, and measures precisely their trajectories.

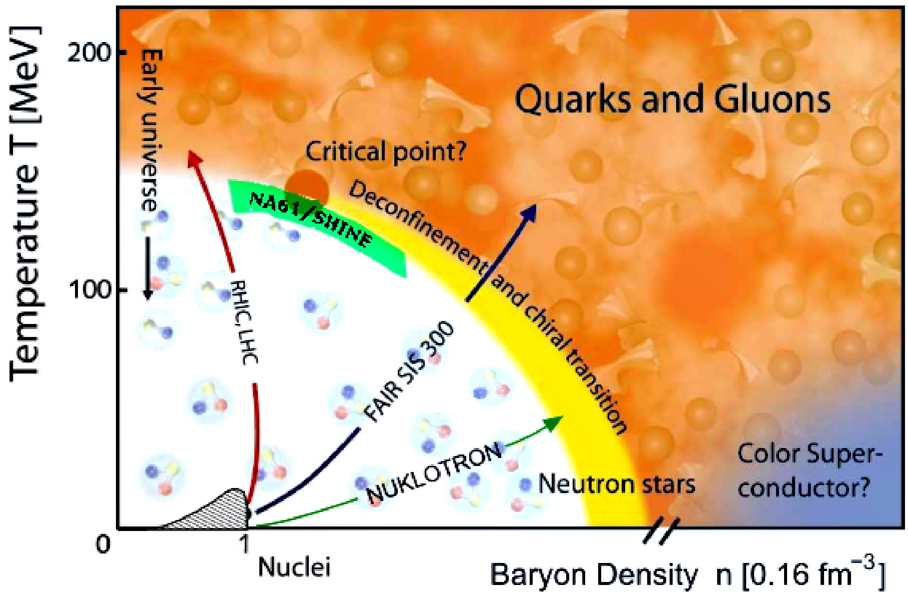

Figure 2. Phase structure of hadronic matter covered by NA61/SHINE (green), compared to present and future heavy ion experiments.

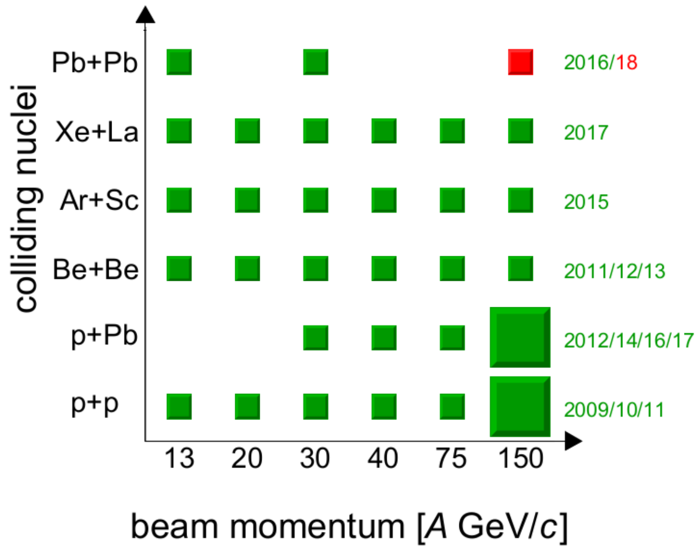

Figure 3. For the program on strong interactions NA61/SHINE scans in the system size and beam momentum. In the plot, the recorded data are indicated in green and the approved future data in red.

Hadron production measurements for neutrino experiments are just reference measurements of p + C interactions for the T2K experiment, since they are necessary for computing initial neutrino fluxes at J-PARC. These measurements have been extended to the production of charged pions and kaons in interactions with thin carbon targets and replicas of the T2K target, to test accelerator neutrino beams [9]. The collection of data began in 2007.

Collected p + C data also allow to better understand nuclear cascades in the cosmic air showers—necessary in the Pierre Auger and KASCADE experiments [10,11]. These are reference measurements of p + C, p + p, π + C, and K + C interactions for cosmic ray physics. The cosmic ray collisions with the Earth's atmosphere produce air shower secondary radiation. Some of the particles produced in such collisions subsequently decay into muons, which are able to reach the surface of the Earth. Cosmic ray induced muon production would allow to reproduce primary cosmic ray composition if the related hadronic interactions are known [12].

As seen in Figure 2, the phase structure of hadronic matter is involved. Progress in the theoretical understanding of the subject and collecting more experimental data will allow to delve into the subject. While the highest energies achieved at LHC and RHIC colliders provide data related to the crossover HG/QGP regions, the SPS fixed-target NA61/SHINE experiment is particularly suited to explore the phase transition line HG/QGP with the CP included.

Results of Initial NA61/SHINE Research

The production properties of light and medium mass hadrons, in particular pions and kaons, have been measured [13] according to the NA61/SHINE proposal [1]. The Be + Be results are close to p + p independently of collision energy. Moreover, the data show a jump between light (p + p, Be + Be) and intermediate, heavy (Ar + Sc, Pb + Pb) systems [14]. The observed rapid change of hadron production properties that starts when moving from Be + Be to Ar + Sc collisions can be interpreted as the beginning of the creation of large clusters of strongly interacting matter—the onset of fireball. One notes that non-equilibrium clusters produced in p + p and Be + Be collisions seem to have similar properties at all beam momenta studied here.

The K^+/π^+ ratio in p + p interactions is below the predictions of statistical models. However, the ratio in central Pb + Pb collisions is close to statistical model predictions for large volume systems [15].

In p + p interactions, and thus also in Be + Be collisions, multiplicity fluctuations are larger than predicted by statistical models. However, they are close to statistical model predictions for large volume systems in central Ar + Sc and Pb + Pb collisions [16].

The two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production separated by two thresholds: The onset of deconfinement and the onset of fireball [17]. The sketch presented in Figure 4 illustrates this preliminary conclusion. Collected Ar + Sc and Xe + La data are being analyzed to provide further information.

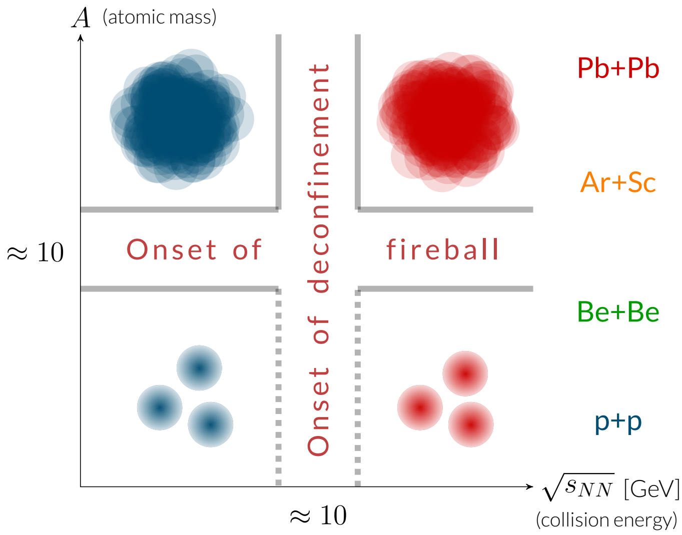

Figure 4. The onset of deconfinement and the onset of fireball. The onset of deconfinement is well established in central Pb + Pb (Au + Au) collisions. Its presence in collisions of low mass nuclei, inelastic p + p interactions in particular, is questionable.

Total production cross-sections and total inelastic cross-sections for reactions π^++C,Al and K^++C,Al at 60 GeV/c and π^++C,Al at 31 GeV/c were measured. These measurements are a key ingredient for neutrino flux prediction from the reinteractions of secondary hadrons in current and future accelerator-based long-baseline neutrino experiments [18].

2. New Measurements Requested

The third stage of the experiment, starting after the Long Shutdown 2 (LS-2) of the CERN accelerator system, would include:

- Measurements of charm hadron production in Pb + Pb collisions for heavy ion physics;
- measurements of nuclear fragmentation cross-section for cosmic ray physics;
- measurements of hadron production in hadron–nucleus interactions for neutrino physics.

The proposed measurements and analysis are requested by heavy ion, cosmic ray, and neutrino communities. A careful analysis of fluctuations and intermittency phenomena in NA61/SHINE data collected so far is necessary to look for the CP [19].

The objective of **charm hadron production measurements** in Pb + Pb collisions is to obtain the first data on the mean number of $\bar{c}c$ pairs produced in the full phase space in heavy ion collisions. Moreover, further new results on the collision energy and system size dependence will be provided. This will help to answer the questions about the mechanism of open charm production, about the relation between the onset of deconfinement and open charm production, and about the behavior of J/ψ in quark-gluon plasma.

The objective of **nuclear fragmentation cross-section measurements** is to provide high-precision data needed for the interpretation of results from current-generation cosmic ray experiments. The proposed measurements are of crucial importance to extract the characteristics of the diffuse propagation of cosmic rays in the Galaxy.

The objectives of **new hadron production measurements for neutrino physics** are to further improve the precision of hadron production measurements for the currently used T2K replica target, to perform measurements for a new target material, both for T2K-II and Hyper-Kamiokande experiments, and to study the possibility of measurements at low incoming beam momenta (below 12 GeV/c), relevant for improved predictions of both atmospheric and accelerator neutrino fluxes.

NA61/SHINE is the only experiment which will conduct such measurements in the near future. Together with other HIC experiments, it creates a full-tone physical picture of QCD in dense medium. Especially concerning the strong interaction heavy-ion program, the NA61/SHINE has unique capabilities in comparison with the other experiments (see Figure 2):

The limitations of other experiments are related to: (i) Limited acceptance, (ii) measurement of open charm not considered in the current program, or (iii) very low cross-section at SIS-100.

Concerning other experiments' capabilities shown at Figure 5:

- LHC and RHIC measurements of open charm at high energies are performed in a limited acceptance due to the collider kinematics and the detector geometry. The NA61/SHINE measurement will not be subject to these limitations [20–23];
- RHIC BES collider ($\sqrt{s_{NN}} = 7.7 - 39$ GeV): Measurement not considered in the current program [24–26];
- RHIC BES fixed-target ($\sqrt{s_{NN}} = 3 - 7.7$ GeV): Measurement not considered in the current program [27];
- NICA ($\sqrt{s_{NN}} < 11$ GeV): Measurements during stage 2 (after 2023) are under consideration [28];
- J-PARC-HI ($\sqrt{s_{NN}} \lesssim 6$ GeV): Under consideration, may be possible after 2025 [29];
- FAIR SIS-100 ($\sqrt{s_{NN}} \lesssim 5$): Not possible due to the very low cross-section at SIS-100, charm measurements are planned with SIS-300 ($\sqrt{s_{NN}} \lesssim 7$ GeV), but not with the start version (timeline is unclear).

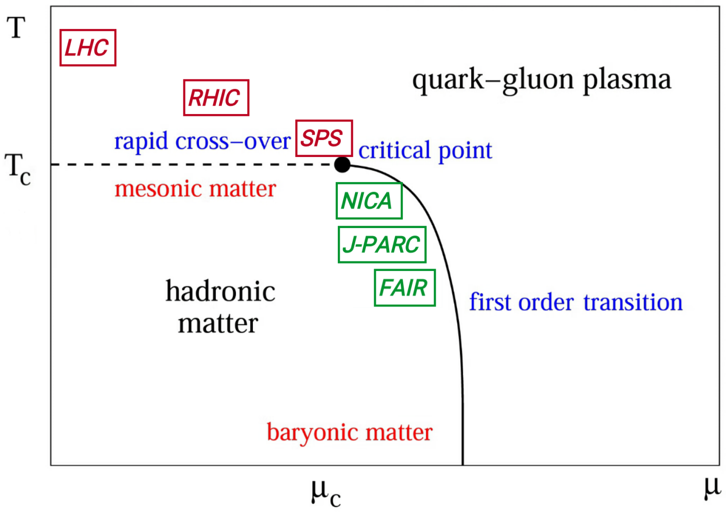

Figure 5. Recent (red) and future (green) heavy ion facilities in the phase diagram of strongly interacting matter.

The beam momentum range provided to NA61/SHINE by the SPS and the H2 beam line is highly important for the heavy ion, neutrino, and cosmic ray communities. It covers:

- Energies at which the transition from confined hadrons to quark gluon plasma in heavy ion collisions takes place—the onset of deconfinement [30];
- proton beams of momenta used to produce neutrino beams at J-PARC, Japan and Fermilab, US [31];
- light nuclei at momenta > 10 A GeV/c, important for the understanding of the propagation of cosmic rays in the Galaxy [32].

Specific Research Goals

The NA61/SHINE charm program addresses questions about the validity and the limits of statistical and dynamical models of high energy collisions in the new domain of quark mass, $m_c \approx 1300$ MeV $\gg T_C \approx 150$ MeV [33]. To answer these questions, knowledge is needed on the mean number of charm–anticharm quark pairs $\langle c\bar{c}\rangle$ produced in the full phase space of heavy ion collisions.

Such data do not exist yet and NA61/SHINE aims to provide them within the coming years. The related preparations have started already. In 2015 and 2016, a Small Acceptance Vertex Detector (SAVD) was constructed and first measurements of open charm production started in 2016—Figure 6. Vertex resolution has appeared precisely enough (30 µm) to distinguish D^0 decay. That was possible due to the fixed-target experiment-specific property, where the Lorenz factor $\beta\gamma \approx 10$ makes short-living D^0 an observable particle, even in such a small acceptance vertex detector.

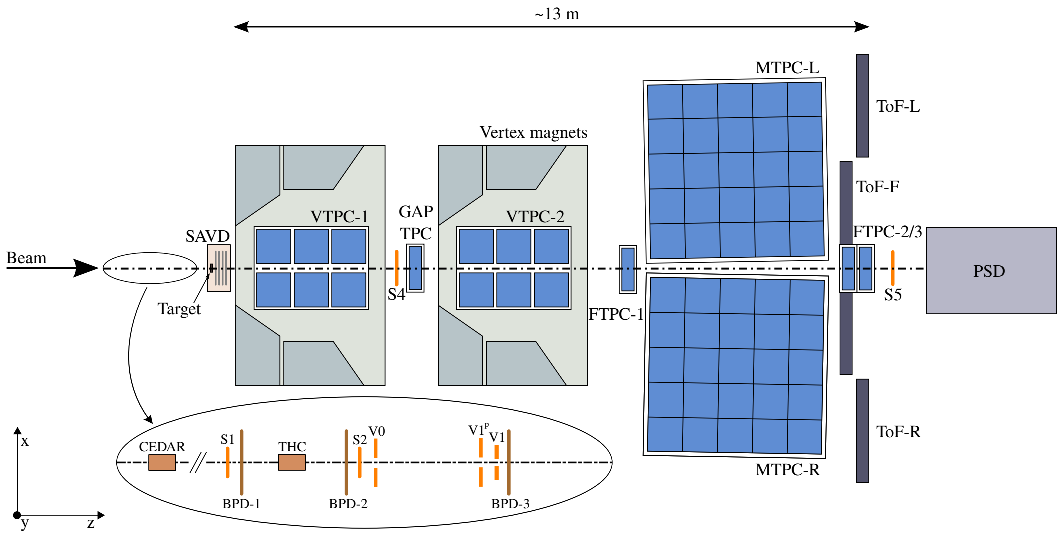

Figure 6. Present NA61/SHINE setup with the SAVD included.

Successful performance of the SAVD in 2016 led to the decision to also use it during the collection of Xe + La data in 2017. About $5 * 10^6$ events of central Xe + La collisions at 150A GeV/c were collected. The Xe + La data are currently under analysis and are expected to lead to physics results in the coming months. One expects to reconstruct several hundreds of D^0 and $\bar{D}^0$ decays. Beyond this, about 4000 D^0 and $\bar{D}^0$ decays can be expected to be reconstructed from the collection of Pb + Pb data in 2018. Further data collection on Pb + Pb collisions and the reconstruction of decays of various open charm mesons are planned by NA61/SHINE for the years 2022–2024. This would be combined with the required detector upgrades, including a full scale, large acceptance vertex detector—now under construction.

Another domain of NA61/SHINE activity will be to measure fragmentation cross-sections relevant for the production of Li, Be, B, C, and N nuclei. These elements are of particular importance for the physics of cosmic rays in the Galaxy. The NA61/SHINE facility has already successfully taken data with light ion beams [34] and can be used with practically no modifications to perform the needed cross-section measurements at isotope level. The ability to separate different isotopes from fragmentation interactions for a given charge was validated with simulations [35].

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Conflicts of Interest: The author declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CERN	Conseil Europén pour la Recherche Nucléaire
CP	critical point
FAIR	Facility for Antiproton and Ion Research
HG	hadron gas
HIC	heavy-ion collision
J-PARC	Japan Proton Accelerator Research Complex
LHC	Large Hadron Collider
LS	long shutdown
NICA	Nuclotron-based Ion Collider fAcility
QCD	quantum chromodynamics
QGP	quark-gluon plasma
SAVD	small acceptance vertex detector
RHIC	Relativistic Heavy Ion Collider
SPS	Super Proton Synchrotron

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