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| **Work package number** | WP16 | **Start date** | 01/06/2019 |
| **Activity Type** | Networking activity | | |
| **Work package acronym** | NA5-THEIA | | |
| **Work package title** | Strange Hadrons and the Equation-of-State of Compact Stars | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

In a neutron star, the occurrence of hyperons emerges rather naturally at nuclear densities larger than about two times the nuclear density. The difficult reconciliation of the recent observations of neutron stars having about twice the solar mass with the presence of hyperons is referred to as the “hyperon puzzle”.

The cooperation of world-leading experimentalists and theoreticians in the field of strangeness nuclear physics with experts of the neutron star community is the aim of the networking activity THEIA, which will allow to critically assess the status of our present understanding and to determine the impact of terrestrial observations on the hadronic Equation of State (EOS).

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2 Progress made during the reporting period for each task***

|  |
| --- |
| ***Task 1: A=3 hypernuclei: The hypertriton puzzle and its implication for fragment formation in heavy ion reactions. Does a neutral A=3 hypernucleus exist?*** |
| The two experimentally established lightest hypernuclei 3ΛH and 4ΛH are important cornerstones in the field of strangeness nuclear physics. On one hand, the production of these nuclei in relativistic heavy ion collisions allows new insight in the production mechanism of complex clusters. On the other hand, the detailed structure of particularly the hypertriton is an important benchmark for our understand of the strong hyperon-nucleon and multibaryon interaction with strange baryons (hypertriton puzzle). It thus can impact our understanding of more complicated systems involving hyperons, such as the interior of neutron stars. The existence or non-existence of a neutral A=3 hypernucleus nn is another open issue.  During the last 2 years, new data on the hypertriton became available from ALICE and STAR. A new precision experiment was successfully performed at MAMI. Also, the theoretical understanding of these systems continuously improves. Indeed, in the coming years, several experiments are planned, which will produce even more precise and accurate lifetime and binding energy data. These data are expected to serve as benchmarks for any hypernuclear structure calculation.  A few highlights are summarized in the following:  *Hypertriton puzzle: binding energy vs. Lifetime (experimental results):*  In a three body system, when any pair of particles is close together, the third particle is, on  the average, relatively far away from them. Therefore, a small total Λ binding energy of the hypertriton 3ΛH implies that the Λ-hyperon has an extended wave function with respect to the deuteron core with a typical size of about 10fm. As a consequence of the extremeΛ-halo, the Λ particle in 3ΛH should have properties similar to the free L. In fact, all available calculations of the hypertriton lifeti predict values which deviate no more than about 10% from the free Λ decay. Indeed, bubble chamber and emulsion data from the 60s and 70s were – albeit with large uncertainties - consistent with these expectations. However, the first series of heavy ion collision experiments before 2019 at STAR@RHIC, HypHI@GSI and ALICE@LHC b found consistent with each other a lifetime which is about 30—40% shorter than the free Λ-hyperon, which was significantly below all present theoretical expectations. The combination of its unexpected short lifetime and its small Λ binding energy was one of the most intriguing puzzles in hypernuclear physics when STRONG2020 started and was referred to as the *hypertriton puzzle*. Indeed, this puzzle was in the center of many experimental and theoretical activities of THEIA.  Concerning the hypertriton production in heavy ion reactions, the ALICE collaboration at CERN presented new data <https://doi.org/10.1103/PhysRevLett.128.202301> on the production of 3H in Pb–Pb collisions at = 5.02 TeV. They found for in this new lifetime measurement a value of 253 ± 11 (stat.) ± 6 (syst.) ps which is still compatible with the latest lifetime measurement of STAR of 221±15(stat.)±19(syst.) ps. However, the deduced binding energy of 0.102 ± 0.063 (stat.) ± 0.067 (syst.) MeV found by ALICE are in tension with the STAR data from 2020, which was remarkably high 0.406 ± 0.120 (stat.) ± 0.110 (syst.) MeV <https://www.nature.com/articles/s41567-020-0799-7>. It is, however, interesting, that the latest (still preliminary) analysis of d-L correlation functions by STAR in 3GeV Au+Au collisions suggest a low hypertriton binding energy of 0.185 ± 0.145 MeV (95%CL), corresponding to 0.185 ± 0.075 MeV <https://doi.org/10.48550/arXiv.2401.00319>.  [Frankfurt]  At the Mainz Mikrotron (MAMI), a new high precision and accuracy pion spectroscopy experiment aims at a measurement with a systematic uncertainty which is comparable to the statistical error  of ≤ 20 keV <https://pos.sissa.it/380/201/>. The high accuracy will be made possible by measuring the absolute value of the beam energy with a novel undulator light interference method. The method is based on the analysis of the intensity oscillation length in the synchrotron spectrum from two collinear sources, which are realized by two undulators and the electron beam of MAMI <https://doi.org/10.1088/1742-6596/2482/1/012016>. The time delay between the two wave packets can be controlled by changing the distance between the two undulators. This new decay-pion spectroscopy experiment was delayed because of the Covid pandemic and was performed in summer 2022. The detailed calibration of all three spectrometers of the A1 setup by the undulator technique was performed in spring 2024. The analysis is still ongoing. The present status of the analysis has been presented at the SPICE workshop of THEIA <https://indico.ectstar.eu/event/203/>.  [Mainz]  *Hypertriton puzzle: binding energy vs. Lifetime (theoretical results):*  A comparison of light hypernuclei production, from UrQMD+coalescence and the thermal model, in heavy ion collisions over a wide range of beam energies and system sizes was performed in  <https://doi.org/10.1103/PhysRevC.107.014912>. It was found that both approaches provide generally similar results, with differences in specific details. Especially the ratios of hypertriton to Λ are affected by both the source radius Δr of the coalescence procedure as well as canonical effects. On the other hand, the double ratio called S3 is almost independent of canonical effects, which is in contrast to coalescence. Thus, both the beam energy dependence and centrality dependence of S3 can be used to constrain the hypertriton source radius. The predictions further suggest that the existence of the H-dibaryon (ΛΛ) seems to be ruled out by ALICE data.  [Frankfurt]  In <https://doi.org/10.1103/PhysRevC.109.044913>, the Ultra-relativistic Quantum Molecular Dynamics model is employed to simulate p-+C and p-+W collisions at plab =1.7 GeV motivated by the recent HADES results. By comparing the proton and L transverse momentum spectra, it was observed that the data and transport model calculation show a good agreement, if cluster formation is included to obtain the free proton spectra. Predictions of light cluster (d, t 3He, 4He, as well as 3ΛH and XN) multiplicities and spectra are made using a coalescence mechanism. The resulting multiplicities suggest that the pion beam experiment can produce a substantial amount of 3ΛH, especially in p-+W collisions due to the stopping of the L inside the large tungsten nucleus. The findings are supplemented by a statistical multi-fragmentation analysis suggesting that even larger hyper-fragments are produced copiously. It is suggested that even double strange hypernuclei are in reach and might be studied in more detail using a slightly higher pion beam momentum.  [Frankfurt]  In <https://doi.org/10.1051/epjconf/202227101002> the hypertriton puzzle was revisited theoretically, using 3ΛH and 3He wave functions computed within the abinitio no-core shell model employing interactions derived from chiral effective field theory to calculate the two-body decay rate Γ(3ΛH→3He+*π*−). Significant but opposing contributions arising from Σ*NN* admixtures in 3ΛH and from *π*−−3He final-state interaction were found. To derive *τ*(3ΛH), the inclusive *π*− decay rate Γ*π*−(3ΛH) was evaluated by using the measured branching ratio Γ(3ΛH→3He+*π*−)/Γ*π*−(3ΛH) and added the *π*0 contributions through the Δ*I*=1/2 rule. The resulting *τ*(3ΛH) varies strongly with the rather poorly known Λ separation energy *E*sep(3ΛH) and it is thus possible to associate each one of the distinct heavy ion *τ*(3ΛH) measurements with its own underlying value of *E*sep(3ΛH).  In <https://doi.org/10.1103/PhysRevC.109.024001> the same group noted the good agreement between the lifetime value *τ*(3ΛH)=238(27) ps computed at the lowest value *B*Λ=66 keV reached by us and the very recent ALICE measured lifetime value *τ*ALICE(3ΛH)=253(11)(6) ps associated with the ALICE measured *B*Λ value *B*ALICE=102(63)(67) keV.  [Barcelona, Jerusalem, Prague]  A hyperon-nucleon potential for the strangeness *S*=−1 sector (Λ*N*, Σ*N*) up to third order in the chiral expansion is presented <https://doi.org/10.1140/epja/s10050-023-00960-6>. SU(3) flavor symmetry is imposed for constructing the interaction, however, the explicit SU(3) symmetry breaking by the physical masses of the pseudoscalar mesons and in the leading-order contact terms is taken into account. A novel regularization scheme is employed which has already been successfully used in studies of the nucleon-nucleon interaction within chiral effective field theory up to high orders. An excellent description of the low-energy Λ*p*, Σ−*p* and Σ+*p* scattering data is achieved. New data from J-PARC on angular distributions for the Σ*N* channels are analyzed. Results for the hypertriton and *A*=4 hyper-nuclear separation energies are presented. An uncertainty estimate for the chiral expansion is performed for selected hyperon-nucleon observables.  [Bonn, Jülich]  Separation energies of light Λ hypernuclei (*A*≤5) and their theoretical uncertainties are investigated in <https://doi.org/10.48550/arXiv.2308.01756>. Few-body calculations are performed within the Faddeev-Yakubovsky scheme and the no-core shell model. Thereby, modern and up-to-date *NN* and *YN* potentials derived within chiral effective field theory are employed. It is found that the numerical uncertainties of the few-body methods are well under control and an accuracy of around 1 keV for the hypertriton and of less than 20 keV for the separation energies of the 4ΛHe and 5ΛHe hypernuclei can be achieved. Variations caused by differences in the *NN* interaction are in the order of 10 keV for 3ΛH and no more than 110 keV for *A*=4,5 Λ hypernuclei, when recent high-precision potentials up to fifth order in the chiral expansion are employed. The variations are smaller than expected contributions from chiral *YNN* three-body forces (3BFs) which arise at the chiral order of state-of-the-art *YN* potentials. Estimates for those 3BFs are deduced from a study of the truncation uncertainties in the chiral expansion.  [Bonn, Jülich]  In <https://doi.org/10.48550/arXiv.2309.12822>, the contribution of pionic final state interactions (FSI) in the weak decay of the hypertriton is investigated. Focusing on the 3He channel, we find a contribution of the pionic FSI of the order of 18%. Assuming a fixed value for the branching ratio *R*3 for the decay width into 3He over the decay width into 3He and *pd* final states, values were found for the hypertriton lifetime that are consistent with the world average as well as recent measurements by the ALICE Collaboration.  [Darmstadt, FAIR, Jülich]  Zu summarize, several new data on the A=3 hypertriton were presented during the duration of the THEIA networking activity of STRONG2020. With the most recent heavy ion data, the best estimate of the lifetime has moved closer to the freeΛ lifetime. At the same time our theoretical understanding of this system has significantly improved. Thus, the hypertriton puzzle has turned into a quantitative problem, calling for precision studies, on the experimental as well as on the theoretical side.  *Does a neutral hypernucleus nn exist?*  The small binding energy of the hypertrition leads to predictions of the non-existence of bound hypernuclei for isotriplet three-body systems such as nnΛ. However, invariant mass spectroscopy at GSI has reported events that may be interpreted as the bound nnΛ state (Phys. Rev. C 88, 041001(R)). Theoretically, this nucleus is likely to be unbound, though no firm predictions of its stability can be made. Clearly, an experimental clarification is required. At J-Lab, the nnΛ state was sought by missing-mass spectroscopy via the (e,e′K+) reaction at Jefferson Lab's experimental Hall A. No significant structures were observed with the acceptance cuts, and only upper limits of the production cross-section of the nnΛ state were obtained (Prog. Theor. Exp. Phys. 2022, 013D01 (2022)). Following the tentative observation at GSI, the search for the nn system in the 6Li+12C reaction was repeated with an improved setup at the GSI, making use of the fragment separator facility and the WASA detector. The experiment was successfully performed between March 9th and March 19th, 2022 (see MS20). The analysis has started. A first - still preliminary - status report on the experiment was delivered during the HYP22 conference in Prague in June 2022. During the 2024 THEIA meeting at ECT\* the ongoing progress of the analysis was shown, but unfortunately no final results have been released by the WASA Collaboration as yet.  *[Gießen, GSI, Mainz and others].* |
| ***Task 2: Study of antihyperons in nuclei at PHASE-1 of PANDA*** |
| The first measurement of the antihyperon potential in complex nuclei is part of the PANDA Phase-one program, which has been published in European Physics Journal A57, 44 (2021) <https://doi.org/10.1140/epja/s10050-021-00475-y>. During the Phase-1 of PANDA we plan to study antiproton-20Ne → interactions close to threshold. The development of the reconstruction software has been continued. Major effort was devoted to the reconstruction of very low-momentum decay products within the PANDA framework, which until now was only treated under so-called ideal conditions. We also study of the pA → +X and the pA → +X reactions. In nuclear targets, these reactions probe the proton and neutron distributions, respectively, and may allow to determine both the - potential but also the neutron variation of the skin thickness in different isotopes of e.g. Kr or Xe.  During this reporting period, extensive simulations with a modern transport model for the reaction p +20Ne →LL were performed. Besides the reconstruction of the true LL pairs within the customized PANDA analysis framework, the efficient background suppression was a major task. Since a suppression by a factor 107 is required, in total about 4 billion inclusive events had to be generated for our study, making use of the High Power Computing Cluster HIMster located at  the Helmholtz-Institute Mainz. By applying conventional successive cuts, the goal can already be reached. Modern machine learning methods (multilayer perceptron neural network or boosted decision tree method), lead to a further significant improvement of the signal to background ratio. A report on that work was submitted in February 2024 (see deliverable D16.2 and MS21)  *[Mainz]* |
| ***Task 3: Theoretical and experimental studies of bound mesonic systems*** |
| SIDDHARTA-2 represents a state-of-the-art experiment designed to perform dedicated measurements of kaonic atoms, which are particular exotic atom configurations composed of a negatively charged kaon and a nucleus. Investigating these atoms provides an exceptional tool to comprehend the strong interactions in the non-perturbative regime involving strangeness.  The experiment is installed at the DAΦNE electron-positron collider, of the INFN National Laboratory of Frascati (INFN-LNF) in Italy. His prime goal is to perform the first-ever measurement of the 2p → 1s X-ray transitions in kaonic deuterium, a crucial step towards determining the isospin-dependent antikaon-nucleon scattering lengths. Based on the experience gained with the previous SIDDHARTA experiment, which performed the most precise measurement of the kaonic hydrogen 2p → 1s X-ray transitions, the present apparatus has been upgraded with innovative Silicon Drift Detectors (SDDs), distributed  around a cryogenic gaseous target placed in a vacuum chamber at a short distance above the interaction region of the collider. A comprehensive description of the SIDDHARTA-2 setup including the optimization of its various components during the commissioning phase of the collider is presented in <https://doi.org/10.48550/arXiv.2311.16144>.  During summer 2021, the installation of the SIDDHARTA-2 apparatus has successfully been concluded during the commissioning phase of the DAFNE collider. Data taking was resumed in spring 2022 with a kaonic helium run <https://doi.org/10.48550/arXiv.2310.20584> for optimization of final degrader. In 2023 and 2024, the SIDDHARTA-2 experiment was taking data for the measurement of kaonic deuterium, aiming to collect 800 pb−1 of data. The experiment will provide a kaonic deuterium measurement at the same level of precision as the kaonic hydrogen one. First, very preliminary results for K-d at SIDDHARTA-2 were presented by Francesco Sgaramella during the THEIA workshop SPICE at ECT\* https://indico.ectstar.eu/event/203/.  *[Frascati, Krakow, Munich, Roma, Palermo, Vienna, Zagreb]* |
| ***Task 4: What role can a mini antiproton-proton collider at FAIR play for strangeness nuclear physics?*** |
| Considering the present situation at FAIR and in Europe, a antiproton-protn collider can only be a long term perspective. Concerning the physics addressed by THEIA, the low energy regime with √s up to about 5 GeV is relevant. The physics program at such a collider is based on hyperon-antihyperon pair production, which may provide tagged low-momentum hyperons and antihyperons. Possible physics topics are   * Hyperatom and antihyperatom production * Low momentum scattering of hyperons or antihyperons in a secondary target. * Production of doubly strange systems   The advantage of an antiproton-proton collider is the lower background and the controlled (anti)hyperon momenta, the major problem is the lower luminosity. Still insecure is a possible detection system for such low momentum particles.  Since the PANDA detector at FAIR is significantly delayed, it became clear that work on such future project can not reach the necessary attention in the present situation. We hope that once a firm timescale for the realization of the antiproton storage ring at FAIR has been established, the possibility of such a collider at FAIR will gain new momentum.  *[Mainz, Frankfurt, Jülich]* |
| ***Task 5: Annual workshops organized by THEIA will bring together scientists and students with complementary expertise*** |
| * The first THEIA workshop was held at Speyer, Germany. <https://indico.gsi.de/event/8950/> end of 2019 just before the corona crisis started. * The second workshop was planned to take place in October 2020 in Greece. Due to the Corona pandemic, this workshop had to be canceled. Also throughout 2021 and until spring of 2022 no meeting in person could be held. Instead, we organize two web-seminars with weekly talks: * Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar 2020/2021   October 2020 – May 2021; 46 talks  <https://indico.gsi.de/category/513/>   * Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar 2021/2022   October 2021 – March 2022; 18 talks  <https://indico.gsi.de/category/571/>   * The HYP22 conference, which is the major periodic conference of our community, took place in hybrid from in Prague in June 2022 and was to a large extent supported by THEIA   [http ://rafael.ujf.cas.cz/hyp2022/](http://rafael.ujf.cas.cz/hyp2022/)   * Finally, THEIA organized a workshop in May 13-17, 2024 at ECT\*   SPICE – Strange hadrons as a Precision tool for strongly InteraCting systEms.  https://indico.ectstar.eu/event/203/  These workshops turned out to be the most important and fruitful meetings for the scientific community of THEIA in the past years. Particularly the international web seminars during the corona crises were important to keep up the coherence of the community and to foster the continuous collaborations. In all these meetings, young scientists and students played a dominant role, giving on average more than 50% of the presentations  At the final workshop at ECT\* in 2024 there was an unanimous consensus, that the community will try to continue with these annual meetings also beyond STRONG2020.  [*All participating institutions*] |
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## **1.3 Highlights of significant results**

*[Include an overview of the project results towards the objective of the action in line with the structure of the Annex 1 to the Grant Agreement*.*]*

In the following we summarize three main achievements by THEIA:

*The lightest hypernucleus* 3ΛH

A profound understanding of the lightest hypernuclei is a cornerstone for any strong interaction theory dealing with strange baryons. Indeed, the hypertriton consisting of a proton, a neutron and a Λ hyperon, was addressed in several activities of THEIA:

* New data of ALICE and STAR were presented, suggesting a binding energy only slightly above the old emulsion data.
* A new and accurate measurements of the 3ΛH binding energy was successfully performed at the Mainz Mikrotron (MAMI).
* Measured lifetimes of the hypertriton by ALICE indicate a lifetime closer to the free L lifetime.

Thus, the hypertriton puzzle as it existed at the start of THEIA 5 years ago, has turned into a quantitative problem, calling for precision studies, on the experimental as well as on the theoretical side. Members of the networking activity THEIA made substantial contributions to this progress.

*Kaonic atoms*

Among strange exotic atoms the kaonic ones play a special role, since they permit linking the isospin-dependent scattering lengths to the kaon-nucleus potential below threshold. At the DAFNE collider at INFN-LNF the SIDDHARTA-2 collaboration performed the first measurement of the kaonic deuterium transitions, which will help to separate the isoscalar and isovector parts of the antikaon-nucleon scattering length. Future measurements, along the whole periodic table, going from light to heavy exotic strange atoms will be possible by using a series of complementary radiation detector systems recently developed. The new data base of kaonic atoms will thus become a bedrock for low-energy QCD

Thirdly, an important highlight was the final workshop organized by THEIA in May 13-17, 2024 at ECT\* SPICE – Strange hadrons as a Precision tool for strongly InteraCting systEms. https://indico.ectstar.eu/event/203/

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Part of the experiments delayed (low)

Whether the risk has materialized? (Yes)

The MAMI experiment was delayed, but could be performed still within the extended STRONG2020 period.

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. Concentrate on development of theoretical aspects

Whether the risk-mitigation plan was applied? (No)

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

During the first funding period this, the administration of the Networking activity NA5 was managed by local personnel. This has changed in 2021. Furthermore, in view of the situation of the travel budget caused by covid restrictions and the amount of work required to setup the hypernucleus database, we requested already to transfer of 25% of the travel budget to personnel cost. The preparation of the hypernucleus database was indeed ideal to bridge the peak phase of the corona pandemic in 2021/2022 because it could be performed without major person-to-person contacts.

Mainly for setting up the hypernucleus database during the second funding period, we actually used 9.75 person-months. To be able to continuously support the database throughout the last funding period, we ask already for the second funding period to increase the total person-months of this work package from 10 to 11.5.

In the seconds half of 2022, the transfer of the database to Japan required an additional 1.25 person-month for 2022, totaling 12.75 person-months. As a consequence, the cost for personnel increased from the envisaged 70.000€ by about 10% to a total of 77.538,61€. Since the spent travel budget for THEIA amounts to only 80.472,13€, the total budget of WP5 still remains slightly below the assigned sum of 160.000€.

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D16.2 | Antihyperons in nuclei, PANDA sofware tools | 9 - JGU MAINZ | Demonstrator | PU | 49 | yes | 56 | Uploaded to PANDA software repository;  üploaded report see MS21 |
| D16.3 | Bound mesonic systems | 9 - JGU MAINZ | Report | PU | 42 | yes | 42 | Uploaded report |
| D16.4 | Hypernuclear database | 9 - JGU MAINZ | data sets,  microdata, etc. | PU | 54 | yes | 54 | Web page  Continuously updated |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

D16.4: Due to the delays of planned experiments caused by the full or at least partial shut downs of experimental facilities like MAMI, we started to setup a hypernuclear database at MAMI. This interactive database allows the community to quickly evaluate the impact of new data and will thus help in the planning of new experiments. Furthermore, it provides standardized numbers and plots to the community, which will lay out the basis for all theoretical discussions. An international group of specialists representing the various experimental methods will assist in gathering and coherently treating all existing and future strangeness nuclear data.

The database is hosted by the Mainz University in the meantime on-line available for the scientific community at <https://hypernuclei.kph.uni-mainz.de/> It will continuously be updated when new data are published. In order to guarantee a continuous maintenance of the web page for the community, we are preparing a mirror of the webpage at the Tohoku University in Japan <https://lambda.phys.tohoku.ac.jp/HypernuclearDatabase/>

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
| MS21 | Design report for antihyperons in nuclei ready | 9 - JGU MAINZ | 42 | yes | 56 | Uploaded report |
| MS22 | SIDDHARTA-2 progress report | 9 - JGU MAINZ | 42 | yes | 39 | Uploaded report |

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

**D16.2: Antihyperons in nuclei**

Antiproton-nucleon annihilations represent the most effective way to produce low momentu hyperons and antihyperons under controlled kinematic conditions which is a prerequisite for the formation of bound hyperonic systems. Combined with large cross sections for the production of associated hyperon-antihyperon pairs , antiprotons circulating in an storage ring are ideally suited for exploring strange baryonic systems.

Antihyperons annihilate quickly in nuclei and conventional spectroscopic studies of bound systems

are not feasible. Quantitative information about the antihyperon potentials may be obtained via exclusive antihyperon-hyperon pair production close to threshold in antiproton-nucleus interactions. In such reactions, the transverse momenta of the baryon and antibaryon should be opposite and equal at the point of their production inside the nucleus. Once these hyperons leave the nucleus and are detected, their asymptotic momentum distributions will reflect the depth of the respective potentials. A deep potential for one species could result in a momentum distribution of antihyperons which differs

from that of the coincident hyperon.

The main task of the present project is the development of the ΛΛ reconstruction software for

the PANDA setup. This is a prerequisite to explore how the finite acceptance and resolution of

the experimental PANDA apparatus affects the experimental observables. The second objective

is development of the software tools which allow the required suppression of background

events.

The PANDA Collaboration is developing the PandaRoot framework based on Root as part of the FairRoot project. It is used both for the physics simulation and data analysis. Root is an object-oriented software framework developed at CERN since 1995 and is one of the premier software for particle physics analysis. Root is capable of handling large amounts of data and can be used either as compiled code or using interpreted C++ macros. The presented results used ROOT in version 6.22/08.



*Fig. 1: Workflow of the PandaRoot simulation stages. In green: simulation of the Panda detector in*

*operation. The output corresponds to the same data format that would be recorded in an experimental*

*measurement (blue). In yellow, the analysis by PandaRoot, which is identical for both measurement and simulation.*

PandaRoot is an extension of FairRoot, developed for the needs of the PANDA experiment. It is used both for the simulation of the complete pp annihilation inside the PANDA detector and the subsequent data analysis of both simulated and future experimental data. The software works in a modular way, where each detector subsystem has its own software

routines, handling digitization, hit or cluster generation. The data from all subsystem is then

combined in the analysis routines where the detector responses are used for track reconstruction

and particle identification. A flow diagram of the event generation, reconstruction and

analysis software is shown in Figure 1. Each PandaRoot simulation follows a chain of five

stages in which the stage specific tasks are completed:

1. Simulation (green part): The simulation stage works in several steps. In the firs step physical events either for a signal channel or generic background are generated. For this purpose, PandaRoot usually has several event generators implemented. However, in this work none of the original generators are used, instead the event generation is done externally using GiBUU. A custom written generator then adds the GiBUU tracks into PandaRoot.

The second step is the particle transport through the PANDA geometries and materials using the GEANT package. The GEANT toolkit is used for the simulation of particle propagation through matter. It can handle a large set of long-lived particles over a wide energy range from keV up to TeV and their interaction with matter in complex geometries taking into account a comprehensive range of physical processes.

In the digitization stage, the Monte Carlo information from the simulation stage is used to reproduce the signals that can be measured at the detector in reality. The data stored in this way are in the same format as experimental data measured later at the PANDA detector.

1. Reconstruction (yellow part in Figure 1): In the reconstruction step, the particle tracks, with their positions and momentum, are determined from the physical detector data. Once the tracks have been reconstructed, the particle species that gave rise to the tracks have to be identified. To achieve this, the information from the particle identification detectors

(PID) is correlated with the reconstructed tracks to form charged candidates.

1. Event reconstruction (red part in Figure 1): In the last step, the composite particles, in this

case Λ or Λ which decayed during the simulation and whose daughter particles could be

reconstructed, are calculated. PandaRoot contains all necessary tools for further analysis by supporting combinatorial calculations, mass selection and kinematic fitting.

In the present study, more than 4 billion events were generated with the high-performance computing cluster HIMster at the Helmholtz Institute Mainz.

The major task of this project was the background suppression to reach a high signal:background ratio. Besides conventional sequential cuts, we also applied machine learning algorithms. Indeed,

the so called boosted decision tree method significantly improves the number of true events by more than 50% for the same signal to background ratio. It could be shown that after filtering the generated ΛΛ pairs with the developed software, the sensitivity of e.g. the transverse momentum asymmetry to the antihyperon potential persists, thus proving the feasibility of the proposed measurement.

The analysis software has been uploaded to the PandaRoot software repository at FAIR and

can be applied by other PANDA users.

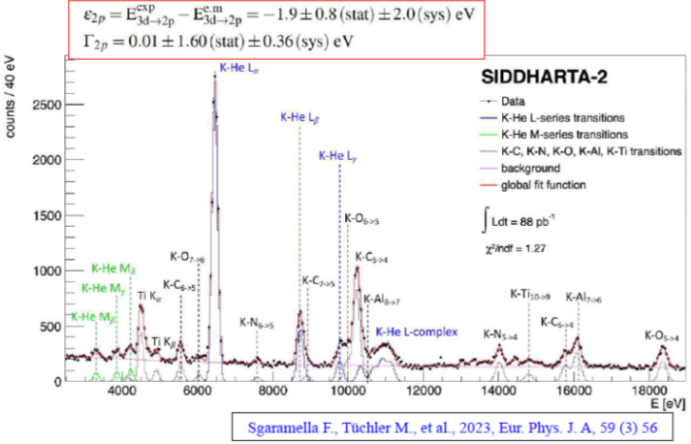
A detailed review was uploaded; see MS21.

**D16.3: Bound mesonic systems**

High precision light kaonic atoms X-ray spectroscopy is a unique tool for performing experiments equivalent to scattering at vanishing relative energies, to determine the antikaon–nucleus interaction at threshold without the need of extrapolation to zero energy. The SIDDHARTA-2 collaboration is going to perform the first measurement of kaonic deuterium transitions to the fundamental level, which is mandatory to extract the isospin dependent antikaon–nucleon scattering lengths.

In the previous period (up to M22) the SIDDHARTA-2 setup in its Phase 1 version was installed and in operation on the DAFNE collider. Since January 2021 to July 2021 the beam was used for:

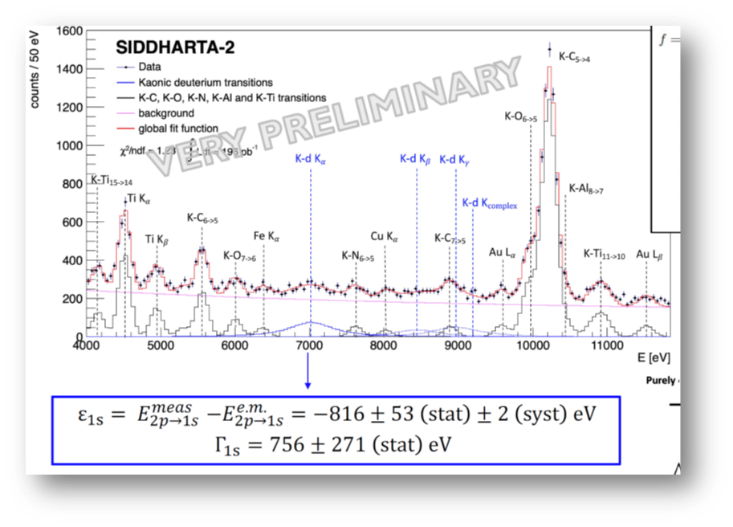
* + Measurement of machine luminosity with SIDDHARTA-2 luminometer
  + Background optimization by use of shielding
  + Kaonic helium measurements at 2 densities: 1.5% liquid and 0.75 % liquid densities which produces (papers in preparation) the most precise measurement of KHe transitions to 2p level in gas; see Fig. 2 for preliminary spectrum.



*Fig 2: Kaonic Helium spectrum measured by SIDDHARTA-2 with a gaseous target.*

The prime goal of SIDDHARTA-2 is to perform the first-ever measurement of the 2p → 1s X-ray transitions in kaonic deuterium, a crucial step towards determining the isospin-dependent antikaon-nucleon scattering lengths. Based on the experience gained with the previous SIDDHARTA experiment, which performed the most precise measurement of the kaonic hydrogen 2p → 1s X-ray transitions, the present apparatus has been upgraded with innovative Silicon Drift Detectors (SDDs), distributed around a cryogenic gaseous target placed in a vacuum chamber at a short distance above the interaction region of the collider. A comprehensive description of the SIDDHARTA-2 setup including the optimization of its various components during the commissioning phase of the collider is presented in <https://doi.org/10.48550/arXiv.2311.16144>.

During summer 2021, the installation of the SIDDHARTA-2 apparatus has successfully been concluded during the commissioning phase of the DAFNE collider. Data taking was resumed in spring 2022 with a kaonic helium run <https://doi.org/10.48550/arXiv.2310.20584> for optimization of final degrader. In 2023 and 2024, the SIDDHARTA-2 experiment was taking data for the measurement of kaonic deuterium, aiming to collect 800 pb−1 of data. The experiment will provide a kaonic deuterium measurement at the same level of precision as the kaonic hydrogen one. First, very preliminary results for K-d at SIDDHARTA-2 were presented by Francesco Sgaramella (see Fig. 3) during the THEIA workshop SPICE at ECT\* <https://indico.ectstar.eu/event/203/>



*Fig 3: Preliminary Kaonic deuterium spectrum measured by SIDDHARTA-2*

A very detailed review about SIDDHARTA 2 experiment can be found at <https://doi.org/10.48550/arXiv.2311.16144>

**D16.4: Hypernuclear data base**

Due to the delays of planned experiments caused by the full or at least partial shut downs of experimental facilities like MAMI, we started to setup a hypernuclear database at MAMI. This interactive database allows the community to quickly evaluate the impact of new data and will thus help in the planning of new experiments. Furthermore, it provides standardized numbers and plots to the community, which will lay out the basis for all theoretical discussions.

Ein Bild, das Text, Screenshot, Diagramm, Zahl enthält.

Automatisch generierte Beschreibung

*Fig 4: Screenshot of the interactive webpage of the hypernuclear data.*

The database is hosted by the Mainz University in the meantime on-line available for the scientific community at <https://hypernuclei.kph.uni-mainz.de/> It will continuously be updated when new data are published. In order to guarantee a continuous maintenance of the web page for the community, we are preparing a mirror of the webpage at the Tohoku University in Japan <https://lambda.phys.tohoku.ac.jp/HypernuclearDatabase/>

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-1)