REFEREE'S REPORT
on the HyperNIS project "Strangeness in nucleon and nuclei",
upgrade of the spectrometer in 2019-2021, proposal for experiments in 2022-2024
Theme 02-1-1086-2009/2024

The strangeness is one of the fundamental property of hadrons. The understanding of the origin of quark flavors is a priority task of particle and nuclear physics. This problem is related to the fundamental mysteries of Nature - the symmetry of space-time at small scales.

The experimental program of the HyperNIS project is aimed to investigate the role which strangeness plays in nucleon and nuclei.

The first part of the Project - the upgrade of the spectrometer – has been successfully completed in 2019-2021. The upgrade includes new readout electronics, new power supply modules for proportional chambers, RPC wall for TOF measurement, modules of VME crates for TQDC, trigger modules, high voltage, and gas supply systems. Thus, the spectrometer is ready for experiments.

The second part – experimental hypernuclear research program, is planned to perform in 2022-2024.

The first part of the experimental program is aimed to search for and study properties of the lightest neutron-rich hypernuclei. The search for ${}^{6}_{\Lambda}H$ and ${}^{8}_{\Lambda}H$ is a highly priority task. If the existence of these nuclei will be confirmed the next step is to determine the lifetime and production cross section. Authors noted that the controversial and inconclusive data on the existence of ${}^{6}_{\Lambda}H$ were obtained at Frascati and J-PARC.

Other goals are the determination of the binding energy of the loosely bound of ${}^{3}_{\Lambda}H$, the lifetime and production cross section of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ hypernuclei. The reaction

$$^{7}Li + C \to {}^{A}_{\Lambda}H + K + p(d,t,n) + \cdots \to {}^{A}He + \pi^{-} + \cdots (A = 3,4,6)$$

for production of hydrogen hypernuclei isotopes will be used in the experiment. The study of poorly investigated hypernucleus of ${}^{6}_{\Lambda}H$ with ^{6}Li beam will be a natural continuation of Li beam experiments. Determination of potential of $\Lambda N \to NN$ weak interaction in nonmesonic decays of the ${}^{10}_{\Lambda}Be$ and ${}^{10}_{\Lambda}B$ is interesting way to extend the project.

Let us note that original and attractive idea for the experimental estimation of the binding energy of the loosely bound ${}^{3}_{\Lambda}H$ suggested in the Laboratory of High Energies (JINR, Dubna) will be used. The hypernuclei are being produced by the excitation of the beam nuclei and the hypernuclei decay is being observed at a distance of tens of centimeters behind the production target. Passage of the hypernuclei "beam" through materials with different Z can be investigated to obtain experimental estimation of the binding energy. Authors suggest using the primary ^{4}He beam as a best one to determine the ${}^{3}_{\Lambda}H$ binding energy in future experiment.

The Hypernuclear program at Dubna started in 1988 is a highly theoretical motivated. The program of the Project is based on the obtained results of the investigation of the light hypernuclei production and decay of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$. In the original approach, the momentum of hypernuclei produced in the beams of relativistic ions is close to the momentum of the projectiles, is quite effective for measurements of hypernuclei lifetimes and production cross sections. The hypernuclei lifetime in the laboratory reference frame is increased by the Lorentz factor 3-7, and significant part of hypernuclei decays far behind the production target. Thus, the location of the decay vertices can be used for identification of the hypernuclei decay and for determination of the lifetime of the observed hypernuclei by measurements of their flight path distribution. The choice of the dedicated and very selective trigger on two body hypernuclei decays with negative pion is the key point of this approach. The accuracy of lifetime measurements is restricted only by statistical errors. The results of the cross-section calculations performed in the framework of the coalescence model are also in a good agreement with experimental data.

Results of measurements on ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ lifetimes obtained by other Collaborations at GSI, BNL and CERN confirm a great interest of physical community in such investigations.

The HyperNIS program is focused on properties of neutron rich hypernuclei. The results are highly anticipated to find equation of state (EoS) of neutron stars and determine portion of Lambdas in the baryon energy distribution in neutron stars and their masses.

Authors justify the advantage of the proposed approach (use fragmentation of ${}^{7}Li$ relativistic beam) for study of ${}^{6}_{\Lambda}H$ over the double charge exchange (DCX) mechanism used by the J-PARC and FINUDA Collaborations.

It is concluded that a crucial experiment can be carried out at the VBLHEP of JINR. Search for ${}^{6}_{\Lambda}H$ over with HyperNIS spectrometer to obtain high enough statistics (few hundreds of detected events) can be done to measure lifetime, production cross sections, mass and possibly to clarify the role of hyperons as a "glue" in the vicinity of the neutron rich drip line.

Three isotopes of hydrogen hypernuclei (${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, ${}^{6}_{\Lambda}H$) can be produced in the same experiment. It is possible to determine lifetimes of all these isotopes in the Dubna experiment. Authors of the Project propose to use ${}^{9}Li$ beam created as a secondary beam of fragmented carbon in the chain of possible processes

$$^{12}C + Al \to {}^{9}Li + C \to {}^{8}_{\Lambda}H + p \to {}^{8}He + \pi^- + p$$

to search for ${}^{8}_{\Lambda}H$. Lifetimes of ${}^{9}Li$ and ${}^{8}He$ beams are of the order of hundred milliseconds and to be enough that the experiment could be successfully carried out.

It is planned to study ${}^{6}_{\Lambda}He$ hypernuclei with ${}^{6}Li$ beam. The hypernuclei will be produced in peripheral Li interactions with carbon target. Trigger will be tuned to select pionic decays with negative pion and the daughter lithium nucleus emitted from the decay region

$$^{9}Li + C \to {}^{6}_{\Lambda}He + \cdots \to {}^{6}Li + \pi^-.$$

It is expected that new data from the present project will significantly improve the description of the hypernuclei production process. It was established that ${}^{6}_{\Lambda}He$ hypernucleus is loosely bound but its lifetime and production cross section were not measured up to now. It is the first task of the ${}^{6}_{\Lambda}He$ experiment.

The method of the Coulomb dissociation will be exploited for the experimental estimation of the ${}^{3}_{\Lambda}He$ and ${}^{6}_{\Lambda}He$ binding energy. This method is interesting from experimental point of view because interactions of hypernuclei "beam" should be investigated.

Study of nonmesonic decays of the ${}^{10}_{\Lambda}Be$ and ${}^{10}_{\Lambda}B$ hypernuclei is planned in the present project as well. This study is aimed on determination of the $\Lambda N \to NN$ weak interaction matrix elements and the branching ratio for the exclusive decays of these nuclei emitted two α's within a very small angle. The additional high resolution GEM detectors should be installed to detect the twin alpha particles. Additional trigger counter with thin (1 mm) quartz radiator can suppress by factor of 30-50 the background, coming from the beam nuclei fragmentation in the trigger detectors. A possibility to install few high-resolution trackers was analyzed.

Configuration of the HyperNIS spectrometer is described in Project. It includes target, beam monitors, trigger counters; vacuum decay vessel, the analyzing magnet, proportional chambers, RPC-TOF stations, scintillation counter to confirm registration of He nuclei.

Main features of experimental method elaborated at JINR and planned to use in the experiment are noted. These are an idea to investigate high energy hypernucleus produced by beam nucleus excitation, hypernucleus decays outside the target, trigger on pionic decays, the high spectrometer acceptance for forward collimated decay products, hypernucleus decay vertex in vacuum without background interaction, large gap in momentum distribution of different hypernuclei isotopes.

Simulation results of momentum distribution shown that in the case of realistic possible momentum measurement errors at 2% level peaks of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, ${}^{6}_{\Lambda}H$ can are clearly separated.

Efficiency for reconstruction of relatively slow pion momenta at the 30% level, efficiency of vertex reconstruction at a level of 90% were estimated. All MC calculations have been done to choose optimal geometry of target and proportional chambers to register more than 90% of decay pions.

Results obtained in 2017-2021:

Note last years (2017-2021) results: The ${}^{7}Li$ beam was used for tests and tuning of the modernized trigger system (background suppression factor higher than 10^4). New tracking upgrade was performed. MC test of generated events were tested. The deuteron beam was used to calibrate the spectrometer and test new equipment. Data for proportional chambers alignment were taken, few alignment program codes were developed and investigated. The extracted nuclear beam kinetic energy was increased up to 4 GeV/nucleon, transported to the spectrometer and the beam line to the HyperNIS by Nuclotron staff thus spectrometer was tested.

The significant upgrade of spectrometer includes - installation and testing of the time-of-flight detector (RPC wall), installation of new electronic gas supply system for proportional chambers, new front-end electronics for proportional chambers, new electronic modules of the trigger system, new server of DAQ system. Systems of on-line service (the beam control, monitoring of the chamber efficiencies, slow control for the high voltage supply units and others) were elaborated, tested and used. A new High Voltage supply system was put into operation for trigger photomultiplier tubes. A block of four Čerenkov trigger counters was produced and tested. Carbon target is situated inside of the block.

Goals of the planned experiments in 2022-2024:

1. Start of Hypernuclear research program with use of the ${}^{7}Li$ beam.
2. Production and installation of two GEM detectors to improve decay vertex localization.
3. The search for and study of hypernucleus ${}^{6}_{\Lambda}H$ (measurements of the lifetime, production cross section, mass).
4. The check predictions of two lifetimes of isomeric states of the ${}^{6}_{\Lambda}H$ or to search for ${}^{8}_{\Lambda}H$ or hypernucleus using ${}^{9}Li$ beam, if the first ${}^{6}_{\Lambda}H$ measurements are successful.
5. The study of poorly investigated ${}^{6}_{\Lambda}He$ (measurements of the lifetime and production cross section).
6. Search for hypernucleus ${}^{8}_{\Lambda}H$ and study of nonmesonic decay of medium hypernuclei ${}^{10}Be$ and ${}^{10}B$ and measurement of the Coulomb dissociation of ${}^{3}_{\Lambda}H$.

Now magnetic spectrometer with modern detectors and electronics is upgraded and commissioned and ready for hypernuclear experiments using extracted Nuclotron beams. Experimental program presented in the Project are of great interest, the planned results are physically motivated. The collaboration has extensive experimental experience, good theoretical justification, and clearly formulated high-priority tasks of fundamental importance. The resources required for the HyperNIS project "Strangeness in nucleon and nuclei" in 2019-2021 and 2022-2024 (theme 02-1-1086-2009/2024) are justified. I recommend supporting and prolong this work with the first priority and present the Project at the JINR PAC.

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