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Strangeness in nucleon and nuclei

The HyperNIS project

Report on 2016-2018 upgrade of the spectrometer, proposal for experiments in 2019-2021

V.D.Aksinenko[1], *A.Ya.Astakhov*[3], *N.V.Atanov*[2], *A.V.Averyanov*[1], *A.N.Baeva*[1], *A.E.Baskakov*[1], *S.N.Bazylev*[1], *V.F.Chumakov*[1], *D.Chren*[4], *D.V.Dementiyev*[1], *A.A.Fechtchenko*[1], *A.A.Fedyunin*[1], *I.A.Filippov*[1], *S.V.Gercenberger*[1], *T.Horazdovsky*[4], *P.I.Kharlamov*[6], *Z.Kohout*[4], *M.G.Korolev*[6], *A.M.Korotkova*[1], *D.O.Krivenkov*[1], *R.I.Kukushkina*[1], *J.Lukstins*[1], *A.I.Maksimchuk*[1], *P. Manek*[5], *M.M.Merkin*[6], *T.Nakano*[7], *O.V.Okhrimenko*[1], *A.N.Parfenov*[1], *N.G. Parfenova*[1], *S.Pospisil*[5], *S.N.Plyashkevich*[1], *B.A.Popov*[2], *P.A.Rukoyatkin*[1], *R.A.Salmin*[1], *A.Sheremetiev*[1], *A.V.Shipunov*[1], *M.Shitenkov*[1], *A.V.Shutov*[1], *I.V.Slepnev*[1], *V.M.Slepnev*[1], *J.Smejkal*[5], *B.Sopko*[4], *V.Sopko*[5], *E.A.Strokovsky*[1], *S.V.Tereschenko*[2], *V.V.Tereschenko*[2], *A.L.Voronin*[1], *M.Yosoi*[7]

(1) *VBLHEP JINR*

(2) *DLNP JINR*

(3) *LIT JINR*

(4) *Czech Technical University, Prague, Czech Republic*

(5) *Institute of Experimental and Applied Physics (IEAP), Czech Technical University Prague, Czech Republic*

(6) *SINP Lomonosov Moscow State University, Russia*

(7) *RCNP, Osaka University, Japan*

Project leaders E.A.Strokovsky[1], J.Lukstins

ABSTRACT

The experimental program of the HyperNIS project is aimed at investigation of the role which strangeness plays in nuclei, the first part of the program – the study of the lightest neutron-rich hypernuclei; in particular, it is necessary to establish firmly if the hypernucleus ${}^{6}_{\Lambda}$H really exists. It should be noted that in the same experiment the lifetimes and production cross sections of ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H will be investigated. If the existence of ${}^{6}_{\Lambda}$H confirmed it will be naturally to push forward investigation of ${}^{6}_{\Lambda}$H properties and the search for ${}^{8}_{\Lambda}$H, the most neutral nucleus among relatively heavy and complicated nuclei. The further experiment will be the study of ${}^{6}_{\Lambda}$He, previously observed only in emulsion experiments. The next step of this program is aimed to determine the binding energy of the loosely bound ${}^{3}_{\Lambda}$H hypernucleus.

Upgrade of the spectrometer is done: new readout electronics is elaborated and installed, as well as new power supply modules for proportional chambers. RPC wall installed for TOF measurements (slow pions), all modules of VME crate (TQDC, synchronization) are new as well as server, trigger modules, high voltage and gas supply systems. The spectrometer is ready for experiments.

Introduction

The very first task of the study of the neutron-rich hypernuclei is search for (study of) ${}^{6}_{\Lambda}$H. Simultaneously, the lifetimes and production cross sections of ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H will be studied in the same experiment. Moreover, production of ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H hypernuclei is the precise reference signal to make sure that ${}^{6}_{\Lambda}$H should be seen or that there are no stable forms of ${}^{6}_{\Lambda}$H if it is not observed in the same run. This task is regarded as the very first experiment because at Frascati experiment [1, 2, 3] evidence of only three events was reported and controversial data obtained at J-PARC [4], where no signal was detected (instead of expected 50 events). On the other hand, before the J-PARC experiment A.Gal predicted that the possibility to see ${}^{6}_{\Lambda}$H signal was low in this case because the

[1]strok@jinr.ru

spectrometer at J-PARC is not suited well for the task – the energy of recoil nuclei is too high and this would lead to low production probability for hypernuclei with low binding energy.

The result of ${}^{6}_{\Lambda}$H hypernucleus search should be a turning point of the program. If ${}^{6}_{\Lambda}$H production cross section is high enough and event yield is large one should choose between two ways – either to continue the study of ${}^{6}_{\Lambda}$H properties or to search for ${}^{8}_{\Lambda}$H hypernucleus. It seems the search for and possible discovery of ${}^{8}_{\Lambda}$H hypernucleus will be the best decision. Particularly since it is very difficult task to investigate ${}^{8}_{\Lambda}H$ using pion or kaon beams. The results of these two experiments will determine if it is useful to study properties of the new hypernuclei or to turn to ${}^{6}_{\Lambda}$He and ${}^{3}_{\Lambda}$H hypernucleus program.

The study of poorly investigated hypernucleus ${}^{6}_{\Lambda}$He will be a natural continuation of Li beam experiments. With carbon beams the program can be extended by study of nonmesonic decays of the ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B hypernuclei.

Original and attractive idea is the experimental estimation of the binding energy of the loosely bound ${}^{3}_{\Lambda}$H hypernucleus. Here the approach suggested in the Laboratory of High Energies (JINR, Dubna) will be used. In this approach the hypernuclei under study 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. Thus, passage of the hypernuclei "beam" through materials with different Z can be investigated in order to obtain experimental estimation of the ${}^{3}_{\Lambda}$H binding energy. However, the best source of ${}^{3}_{\Lambda}$H beam is primary ^{4}He beam. This experiment will be done in perspective but beyond the 2019-2021 time schedule.

Physics motivation

The Hypernuclear program at Dubna [5, 6] was started in 1988 with the setup based on 2-m streamer chamber. The investigation of the light hypernuclei production and decay was done, namely, the lifetime of ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H as well as their production cross sections were measured [7]. It was shown that the approach, in which the momentum of hypernuclei produced in the beams of relativistic ions is close to the momentum of the projectiles, was quite effective for measurements of hypernuclei lifetimes and production cross sections. The dedicated and very selective trigger on two body hypernuclei decays with negative pion was the key point of this approach. The accuracy of lifetime measurements was, therefore, restricted only by statistical errors. The values of the experimental cross section were in good agreement with the results of the calculations (refs. [8] of H.Bandō, M.Sano, J.Žofka and M.Wakai, see also review [9]) performed using the coalescence model. It should be noted that hypernucleus lifetime up to now remains an actual problem. At the last Conference on hypernuclear physics (Sendai, Japan, 2015) there was a special section organized to discuss light hypernuclei low lifetime puzzle. Most of the measurements [10, 11, 12] have shown ${}^{3}_{\Lambda}$H lifetime values of 140-200 ps (155 at STAR, 181 at ALICE) while theory predicts 240-260 ps (256 ps, H.Kamada [13], 233/244 ps, T.Motoba [14]).

In all the previous hypernuclei experiments (except the above mentioned Dubna experiments and the Heavy Ion Beam experiment at GSI, Darmstadt [15, 16]) the hypernuclei are produced in various processes of target excitation. Common feature of all such experiments is that momenta of the produced hypernuclei are low and they decay practically at the production point inside the target. On the contrary, in Dubna experiments [17] the energy of hypernuclei is only slightly lower than that of the beam nuclei. Therefore 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.

The HyperNIS program is focused on **properties of the neutron rich halo hypernuclei**.

First of all, study of the $^6_\Lambda$H hypernucleus will be carried out with the ^{7}Li beam: $^7\mathrm{Li} + C \rightarrow^A_\Lambda \mathrm{H} + \mathrm{p(d,t,n)} + \ldots \rightarrow^A\mathrm{He} + \pi^- + \ldots$ where A=3,4,6.

We have chosen the ^{7}Li beam because an extra proton from the ^{7}Li can be stripped by fragmentation while additional (doubble) charge exchange reaction (DCX) is necessary if a ^{6}Li beam or target are used to produce the $^6_\Lambda$H hypernucleus. Probability of fragmentation is much higher then that of charge exchange reaction. Some problems of double charge exchange considering $^6_\Lambda$H hypernucleus production is discussed, for example, by A.Sakaguchi [18].

As it was mentioned, controversial results were obtained at Frascati [1, 2] and at the E10 collaboration J-PARC experiment [4, 18]. Theoretical predictions are strongly model dependent and controversial. For example, E.Hiyama and others have calculated [19] that $^6_\Lambda$H is not bounded nucleus. At the same time other estimates [20, 21] show that the binding energy for $^6_\Lambda$H should be about a few MeV. So, it is necessary to carry out an experiment what can test $^6_\Lambda$H hypernucleus without doubt.

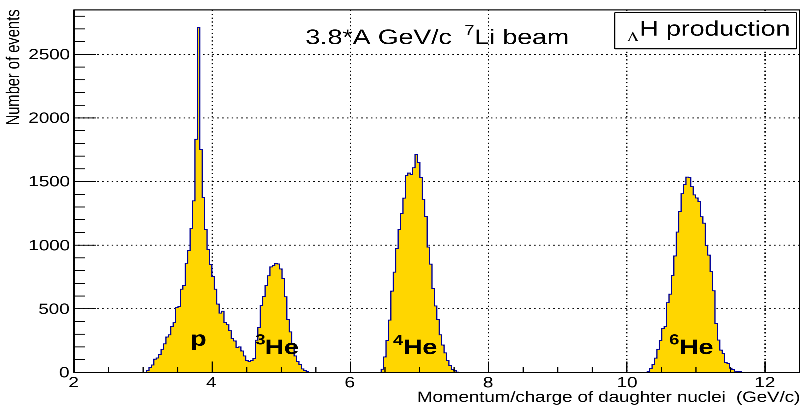

Figure 1: Expected distribution of He (hydrogen hypernuclei daughter nuclei) momenta values divided by their charge. P peak is the calculated momenta of protons produced in the Li fragmentation when $^6_\Lambda$H is produced. The peaks can be easy separated in order to identify different hyperhydrogen isotopes.

At this point one should note that in Frascati and J-PARC experiments no hypernuclei were directly observed, only secondary effects like negative pions assumed as products of $^6_\Lambda$H decay or missing mass of possible production reaction were determined. Because statistics at Frascati was very low (3 candidates), while no signal at J-PARC was observed, the situation is controversial. Therefore the experiment which can be carried out at the VBLHEP of JINR will provide crucial information. Search for $^6_\Lambda$H with HyperNIS spectrometer to obtain high enough statistics (few hundreds of detected events) should be done in order to measure lifetime and production cross sections. That will provide a basis to solve the problem: whether hyperons indeed are acting as a "glue" in the vicinity of the neutron rich drip line. Also, the mass of isotope $^6_\Lambda$H can be measured with use of our magnetic spectrometer and RPC blocks. $^4_\Lambda$H and $^3_\Lambda$H hypernuclei produced at the same experiment will directly show spectrometer efficiency and allow one to estimate $^6_\Lambda$H production cross section correctly. Identification of two isotopes is quite simple because their daughter momenta differ significantly. In Fig. 1 we present the calculated momentum distribution for ^{3}He, ^{4}He and ^{6}He - daughter nuclei of corresponding hypernuclei isotopes and momenta of stripping proton (production of $^6_\Lambda$H).

Production of hypernuclei with large neutron excess and neutron halo was discussed by L.Majling since 1994 [22, 23]. Possibility to study baryon-baryon interaction in system with extremely large value of N/Z=6 was pointed out. It was also emphasized that measurement of $^6_\Lambda$H

mass allows verification of the assumption that binding energy in neutron rich hypernuclei should be increased due to a specific "coherent $\Lambda - \Sigma$ mixing mechanism" [24, 25]. It should be noted that there is a chain of four nuclei with two neutron halo and different composition of the S-shell core: with and without Λ hyperon, namely the nuclei ^{5}H, $^6_\Lambda$H, ^{6}He, $^7_\Lambda$He. Thus, study of the $^6_\Lambda$H properties (as well as of $^6_\Lambda$He) will be significant for the theory. Also it was noted that $^8_\Lambda$H hypernucleus can be bounded. If the first experiment with $^6_\Lambda$H is successful, the following search for $^8_\Lambda$H hypernucleus will be the most natural aim. We propose to use ^{9}Li beam for such an experiment. Also it should be noted that search for $^8_\Lambda$H using pion or kaon beams is even more difficult than study of $^6_\Lambda$H. ^{9}Li beam will be created as a secondary beam when carbon is accelerated. Chain of possible processes is
$^{12}\mathrm{C} + \mathrm{Al} \rightarrow {}^9\mathrm{Li} + \mathrm{C} \rightarrow {}^8_\Lambda\mathrm{H} + \mathrm{p} + \ldots \rightarrow {}^8\mathrm{He} + \pi^- + \mathrm{p} \ldots$. Lifetimes of ^{9}Li and ^{8}He are of the order of hundred milliseconds what is long enough for the experiment.

Expected production cross sections of the lightest hypernuclei are given in Table 1. New data from the present project will significantly improve the description of the hypernuclei production process. Taking into account these values we have estimated possible counting rate for $^4_\Lambda$H pionic decays equal to 600 events per day [26] in case of ideal Nuclotron operation conditions (spill length 5 s, no intensity pulsations etc.). However, real tests have shown that this value should be reduced to 150-200 events per day because spill duration is shorter, we used lower beam intensity on the spectrometer because intensity pulsation causes overlapping of two beam particles inside a 50 ns time interval with overlapping of signal amplitudes and so on. Properties of the Nuclotron extracted beam are continuously improved but at this time the value of 150-200 events per day is the most realistic. If we suppose that binding energy of $^6_\Lambda$H is low we can expect that its production cross section is of the same order as that of $^3_\Lambda$H. Then, one can expect to register 30-40 events of $^6_\Lambda$H. But we should recognize that all estimates are based on the idea that coalescence is similar in all hydrogen hypernuclei production processes.

Table 1: Measured [7] and calculated [8] hypernuclei production cross sections. Beam kinetic energy: GeV per nucleon. In ^{7}Li beam on C target we have measured [31] cross section of charge change (at least stripping of a proton) $\sigma_{cc} = 650 \pm 20 mb$, this value is close to σ_{in}.

Beam	Hyper-nuclei	Energy (GeV)	Cross sec. (μb) Theory	Exp.
^3He	$^3_\Lambda$H	5.14	0.03	$0.05^{+0.05}_{-0.02}$
^4He	$^3_\Lambda$H	3.7	0.06	< 0.1
	$^4_\Lambda$H	2.2	0.08	< 0.08
		3.7	0.29	$0.4^{+0.4}_{-0.2}$
^6Li	$^3_\Lambda$H	3.7	0.09	$0.2^{+0.3}_{-0.15}$
	$^4_\Lambda$H	3.7	0.2	$0.3^{+0.3}_{-0.15}$
^7Li	$^7_\Lambda Li$	3.0	0.11	< 1
	$^6_\Lambda He$	3.0	0.25	< 0.5

At the next stage of the experiment, **the $^6_\Lambda$He hypernuclei** will be investigated with ^{6}Li beam: $^6\mathrm{Li} + \mathrm{C} \rightarrow {}^6_\Lambda\mathrm{He} + \ldots \rightarrow {}^6\mathrm{Li} + \pi^-$. The study of the $^6_\Lambda$He was stopped after emulsion experiments because it cannot be produced using kaon or pion beams. Therefore the lifetime of this hypernucleus is not measured up to now.

The method of the Coulomb dissociation suggested in refs. [26, 27, 28, 29] will be exploited for the **experimental estimation of the $^3_\Lambda$H 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** ΛN $\rightarrow$ NN **weak interaction matrix elements** and implies measurements of the branching ratios $\Gamma^{n\,(p)}_{\alpha\alpha\,i}$ for the exclusive decays of the ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B hypernuclei [17, 30].

Spectrometer scheme

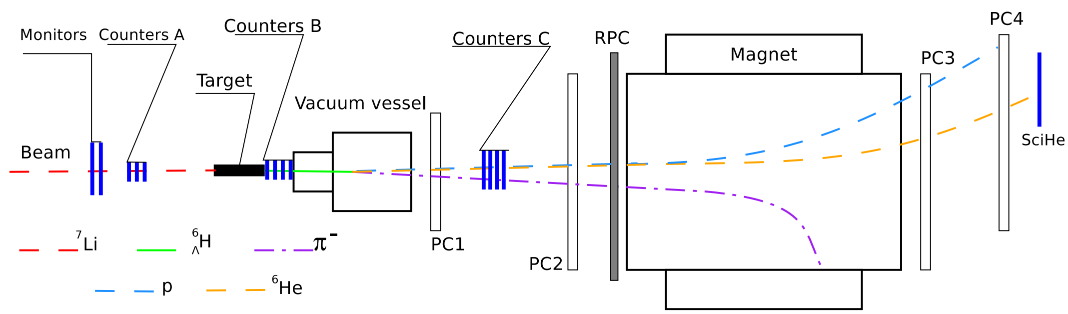

Figure 2: Configuration of the HyperNIS spectrometer. In particular for the search of ${}^{6}_{\Lambda}$H hypernuclei with the ^{7}Li beam (not in scale). Target – carbon 12 × 3×3 cm, 20.4 g/cm^2; beam monitors; A,B,C – trigger counters; vacuum decay vessel of 55 cm length; the analyzing magnet of 0.6T; PC_{1-4} – proportional chambers, RPC – TOF stations, SciHe – Scintillation counter to confirm registration of He nuclei.

Configuration of the spectrometer is presented in Fig. 2. Pionic decays ${}^{A}_{\Lambda}\mathrm{H} \rightarrow \pi^- + {}^{A}\mathrm{He}$ A=6,4,3 will occur inside the vacuum vessel with rather high probability (70%). The Čerenkov and scintillation counters (trigger detectors B,C correspondingly) are tuned to measure charge difference between hypernucleus and its decay products. Taking into account that resolution of Čerenkov counters is better, a block of four Čerenkov counters is used as B detector. Blocks of proportional chambers PC_1 (four chambers 38×38 cm^2) and PC_2 (three chambers 130×80 cm^2) register hits from pion and the daughter nucleus (He), allowing the reconstruction of the decay vertex. In addition, the set of all the proportional chambers (PC_{1-4}) is used to measure momentum of the He nucleus. The chambers PC_{3-4} are of the same size as the chambers PC_2. With the ^{7}Li beam the full set of the chambers allows detection of the secondary proton (p) or other fragments and the momentum separation of the hydrogen hypernuclei daughter nuclei – He isotopes. The scintillation counter SciHe is used to measure signal amplitude at the location where ^{6}He daughter nuclei are expected to separate them from tritium fragments produced together with ${}^{4}_{\Lambda}$H hypernuclei. Two GEM detectors will be installed to improve localization of decay vertex position. Such detectors are necessary in case of study of nonmesonic decays (${}^{10}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B).

The trigger aimed to detect the pionic decays of hypernuclei was developed and used successfully in the previous experiment in Dubna [5, 7, 17, 32, 33]. The idea of the trigger is as follows. *When the* ${}^{6}_{\Lambda}$H *hypernucleus is produced*, the Li nucleus should emit spectator proton while remaining core ^{6}He nucleus is being changed into the ${}^{6}_{\Lambda}$H. Each of these two particles have charge equal to 1 (total $Z = 1 + 1$) and hit block B of the Čerenkov counters (see Fig. 2). Since the counter response is proportional to Z^2 of interacting particle, both particles will create in the Čerenkov B counters the signals proportional to $U = 1^2 + 1^2 = 2$.

Mesonic decay ${}^{6}_{\Lambda}\mathrm{H} \rightarrow {}^{6}\mathrm{He} + \pi^-$ results into particles of $Z = 2$ (He) and $Z = 1$ (π^-). The scintillation counters C should register signal proportional to $U \geq 4$ *if the hydrogen hypernucleus decay takes place* but less than $U = 9$ created by Li beam nuclei. Finally, we should underline that in the case of pionic decays the signal registered in the counters C is higher than that of the B while for the majority of the background events the signal in the C is lower than in B.

We underline six main features of the method elaborated at JINR. 1. It is based on an idea to investigate high energy hypernucleus produced by beam nucleus excitation. 2. Hypernucleus decays outside the target what allows one to organize selective trigger and to obtain lifetime from distribution of decay points. 3. Trigger is tuned to find pionic decays of hypernuclei when charge of the daughter nucleus is higher than that of hypernucleus. 4. High acceptance of decay products. 5. We analyze events when hypernucleus decay vertex is observed in vacuum where no background interaction can simulate the decay. 6. Momenta of different hypernuclei isotopes are well separated by large gaps therefore it is easy to identify isotopes ^{3}He, ^{4}He and ^{6}He. In Fig. 1 we present the calculated ^{3}He, ^{4}He and ^{6}He momentum distribution for reactions
$^7\mathrm{Li} + \mathrm{C} \rightarrow ^A_\Lambda\mathrm{H} + p(d,t,n) + \ldots \rightarrow ^A\mathrm{He} + \pi^- + \mathrm{p(d,t,n)}$ where A=6,4,3.

In order to measure momenta of relatively slow pions, emitted at relatively large angles, the time-of-flight method will be used. MC calculations show that our RPC detector is effective for approximately 30% of the full pion spectrum and will be used to determine mass of hypernucleus.

Calculations and also experiments show that the decay vertices can be found safely if the decay opening angle is not too narrow, namely estimated efficiency of vertex reconstruction will be at a level of 90%. because opening angles are concentrated at higher values. To increase accuracy of vertex reconstruction in 2020 two GEM 50×50 cm detectors will be installed.

Measured response of a Čerenkov counter is presented in Fig. 3. Since counter blocks B and C contain four detectors their selectivity to different values of charge of measured particles are high enough to reject background triggers by a factor of 10^4.

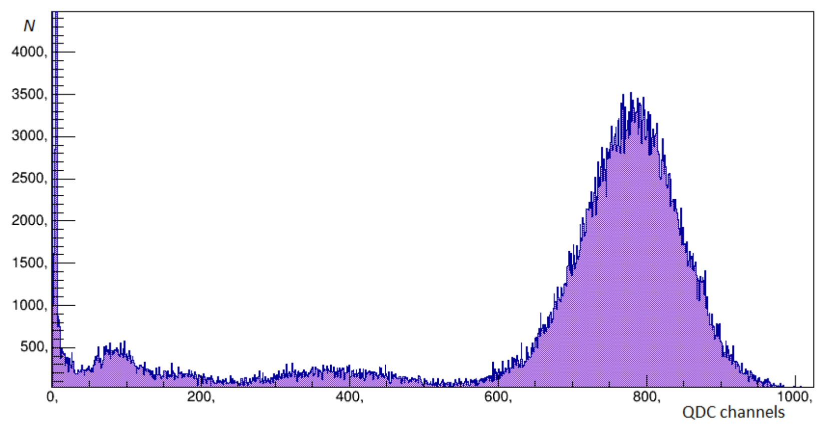

Figure 3: Pulse hight distribution of Li beam fragments measured with one of the Čerenkov counters. Clean separation of p, He and Li particles is obtained.

Last years results and plan for the coming 3 years

The HyperNIS spectrometer was significantly upgraded during the last years. Installation and testing of the time-of-flight detector (RPC wall) before the analyzing magnet in order to determine momentum of pions from decays of hypernuclei (by measuring the time of flight) was a serious step aimed to enhance capability of the spectrometer. New electronic gas supply system allows one to improve time resolution. It should be mentioned that similar gas supply was installed for proportional chambers too.

The most important improvement consisted of R&D and production of new front-end electronics for proportional chambers. 200 analog signal cards (32 inputs in each card) were produced in Minsk. The digital part of the FEE cards was designed and tested in JINR. Electronic modules of the trigger system were replaced with new ones too. All modules in VME crate (TQDC modules, data acquisition and service modules as well) and the main DAQ server are new. A new High Voltage supply system was introduced for trigger photomultiplier tubes. It has up to 64 high stability outputs driven by WIENER MPOD crate controller and programs adapted by HyperNIS personal. Proportional chambers are driven using CAEN high voltage supply modules. Recently, a block of four Čerenkov trigger counters was installed (block B, see Fig. 2). To reject possible background of nuclear fragments produced in the trigger counters (tritium first of all) several additional scintillation counters were produced and tested.

Systems of on-line service – the beam control, monitoring of the chamber efficiencies, slow control for the high voltage supply units and other systems were elaborated, tested and used. Since the beam intensity in the hypernuclei experiments is relatively low ($10^5 - 10^6 s^{-1}$), it was necessary to organize Internet access to the beam control data for the Nuclotron staff. Taking into account experience of test runs, this system is beeing upgraded from run to run. All data from trigger counters are available in the Nuclotron control room and can be used by the staff to improve the beam tuning.

In 2017-2018 ^{7}Li beam was available only for a short (63 hours) test run, which was used to synchronize readout systems of proportional chambers and to tune the trigger for hypernuclei detection. This run was too short to start data taking. Background trigger rejection at the level of 10^4 was firmly checked.

Planned experiments and upgrade:

- Focused on the hypernuclear program of the HyperNIS project with use of the d and ^{7}Li beams (the deuteron beam is needed for methodical purposes). In 2019 - two GEM detectors will be installed to improve decay vertex localization.

- The study of hypernucleus $^6_\Lambda$H (years 2020-2021): Search for $^6_\Lambda$H, measurements of the lifetime with accuracy of 10-15 ps, production cross section, mass value with accuracy of 1-2 MeV (if the isotope exists). Minimal necessary statistics for these goals is about 500 detected events of the $^6_\Lambda$H production. If production cross section is as low as in case of $^3_\Lambda$H approximately 200 hours of Li beam are necessary.

  If the first $^6_\Lambda$H experiments are successful, we will choose the next task: either to take 2000 detected events of the $^6_\Lambda$H to check predictions of two lifetimes of isomeric states of the $^6_\Lambda$H or to search for $^8_\Lambda$H hypernucleus using ^{9}Li beam.

- In 2021-2022: study of poorly investigated $^6_\Lambda$He (measurements of the lifetime and production cross section): at least 500 detected events of the $^6_\Lambda$He production are expected.

- In 2022-2023: measurement of the Coulomb dissociation of $^3_\Lambda$H; search for $^8_\Lambda$H hypernucleus; study of nonmesonic decay of medium hypernuclei $^{10}_\Lambda$Be and $^{10}_\Lambda$B.

The project should be ended in 2023 year. It is the most important technical result of the project that a new multipurpose magnetic spectrometer with modern detectors and electronics is commissioned and is ready for hypernuclear experiments using extracted Nuclotron beams. The spectrometer will be available for other experiments (or for tests of other detectors).

The study of properties of the lightest hypernuclei is relevant, has high importance and can be performed in JINR with beams from Nuclotron. Trigger of the HyperNIS spectrometer works with high suppression factor and efficiency. Installing and commissioning of the new FEE allow us to significantly improve tracking efficiency and to carry out the proposed hypernuclear experiments. This can give answers to open questions in hypernuclear physics which are very hard to answer using alternative methods and approaches. At present, the upgraded HyperNIS spectrometer was tested using beta sources and cosmic muons too.

It should be noted that the HyperNIS spectrometer and the beam line can easy be used to test detectors. HyperNIS test runs were used (and can be used in future) to test pixel detectors (TimePix) from Prague (IEAP), microstrip detectors for satellite experiment, etc. TimePix tetsts were carried out together with the Prague team. These tests provided good experience for young Czech researchers. Also several students for JINR were trained. A.Baeva has competed her master's degree work. A student from Belorussia now is training and in 2019 will be ready for his master's degree work at HyperNIS spectrometer. Upgrade of the spectrometer, tuning of new modules and counters, test runs have shown that the HyperNIS team is ready to achieve proposed aims.

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