**APPROVED**

**JINR DIRECTOR**

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**“\_\_\_\_“\_\_\_\_\_\_ 2023 г.**

**SCIENTIFIC AND TECHNICAL REASONING FOR THE RENEWAL OF**

**PROJECT IN RESEARCH AREA WITHIN THE TOPICAL**

**PLAN FOR JINR RESEARCH**

**1. General information on the project**

**1.1. Project code 02-1-1087-2009**

**1.2. Veksler and Baldin Laboratory of High Energy Physics**

**1.3. Scientific field "Physics of elementary particles and relativistic nuclear physics (02)"**

**1.4. The name of the Project "** **Creation of a precision magnetic spectrometer SCAN-3 and research of non nucleon degrees of freedom in nuclei, nucleon correlations and**

**nuclear fragmentation at the internal target of the Nuclotron."**

**1.5. Project Leader Afanasiev S.V.**

**1.6. Project Deputy Leader Dryablov D.K.**

**2. Scientific rationale and organizational structure**

**2.1. Annotation**

1. **General aims of the project**

This project is aimed at studies of highly excited nuclear matter created in nuclei by a high-energy deuteron beam. The matter is studied through observation of its particular decay products − pairs of energetic particles with a wide opening angle, close to 180o. A new precision hybrid magnetic spectrometer SCAN-3 is to be built for detecting charged (π±, *K*±, *p*) and neutral (*n*) particles produced at the Nuclotron internal target in *d*A collisions. Detection and spectrometry of such pairs will enable to fulfill

- studies of low-energy ηA interaction and a search for η-bound states (η-mesic nuclei);

- studies of the Δ-isobar produced and stopped inside the nuclear matter.

Beyond that detection of the pairs will enable to fulfill

- studies of *np* and *pp* correlations;

- studies of single and pair cumulative processes;

- studies of heavy nuclei fragmentation to low-energy fragments.

1. **Physics motivation**
   1. Studies of ηA interaction and η-mesic nuclei

Currently, studies of interactions of η- (and η′-) mesons with nucleons and nuclei attract a lot of interest (see, e.g., [1]). Due to a very short life time of these mesons, information on their elementary interactions can be inferred only indirectly − for example, from a coupled-channel analysis of the reactions π*N*→π*N*, π−*p*→η*n*, γ*p*→π*N*, γ*p*→η*p* assuming a multichannel resonance model and factorization. Results obtained in this way strongly depend on details of the model used, so that, for example, the *s*-wave η*N*-scattering length *a*η*N* inferred in different works varies from Re *a*η*N* = 0.27 fm to 0.98 fm [2]. The positive sign of Re *a*η*N* leads to ηA attraction and can result in formation of bound states ηA [3]. Depending on the strength of the η*N* and ηA interactions a whole range of the ηA bound states with different A have been predicted including very light states with A ≥ 2.

Very often properties of the ηA interaction are derived from the underlying η*N* interaction fixed from phenomenological analyses. Modification of the η*N* interaction in nuclei is essential ingredient of such derivations which have to take into account: 1) a strong energy dependence of the underlying η*N* scattering amplitude for moving nucleons in the nucleus; 2) modifications of self-energy effects in nuclei for involved intermediate mesons and baryons [2,4].

In a more fundamental approach, the η/η′-A interaction can be understood at the quark-gluon level as a result of interaction of light quarks in the mesons with the scalar-isoscalar mean field (the σ-field, apart from the ω-field). The effective masses of η/η′ in the nuclear matter and hence the η/η′-A attractive potential are affected by the SU(3)-singlet component in the mesons and therefore are affected by nonperturbative contributions of gluons related with the axial U(1) dynamics in the nuclear matter [5].

All that gives a very good reason for further theoretical and experimental studies of the η/η′-A interaction, including a determination of spectra and decay modes of the bound states. Also, data on the ηA interaction, including data on the binding energies, can essentially constrain the η*N-*interaction and the η*N*-scattering amplitude.

The very first attempt to observe η-mesic nuclei was done long ago in the missing mass experiment A(π+, *p*)X [6]. No peak of the then predicted [3] strength and width was found. Soon a better strategy for searches for ηA was proposed [7]. It was based on detecting decay products of ηA: correlated π*N* pairs ejected in the process of one-nucleon annihilation

η*N*→π*N*

of the captured (stopped) η-meson, transversely to the beam. Thus, a signature of formation and decay of ηA can be a π*N* pair with an opening angle close to 180o and characteristic kinetic energies

*T*π ≈ 313 MeV, *TN* ≈ 94 MeV

(up to effects of Fermi motion and elastic rescattering of particles in the nucleus). Annihilation of the captured η-mesons in the nucleus can result in a peak in the distribution of the total energy *E*π + *EN* of the pair that lies below threshold of the η*N* channel (see Fig. 1). A signature of η-mesic nucleus just consists in the presence of a peak in the total energy of the pair that lies at *E*π + *EN*  < *m*η + *mN* = 1486 MeV. Precise measurements of the position and the width of the peak would allow one to establish the very existence of the bound state and to determine its properties.

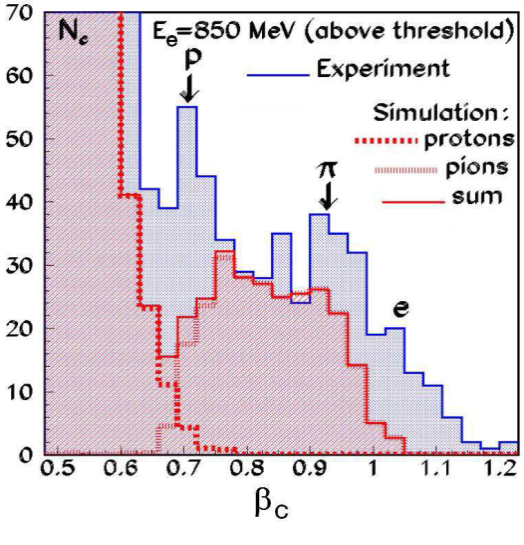
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| Fig. 1. Schematic distribution of π*N* pairs over their total energy. |

Following this scheme, two similar experiments have been done (with participation of some members of the present project). In experiment at the LPI electron synchrotron [7], together with the channel π±*n* also *pn* pairs have been detected. Such *pn* pairs having the kinetic energies

*Tp* ≈ *Tn* ≈ 270 MeV

can arise due to two-nucleon annihilation η*NN*→*NN* of η*.* Important finding of the experiment [7] was that the yield of the *pn* pairs was approximately equal to the yield of the π±*n* pairs while the background in the *pn* channel was essentially less (see Fig. 2 that shows distribution of charged components of the detected pairs over velocity; two peaks of approximately equal strength correspond to *pn* and π*n* pairs). Therefore, a search for η-mesic nuclei through the *pn* decay channel was proved to be a very attractive option. Energy resolution of the built setup [7] was not sufficient to determine whether the observed peak lies under threshold and is indeed related with formation of a bound state, the η-mesic nucleus. Further, more precise experiments are evidently needed along this line.

Fig. 2. Distribution of protons and charged pions over velocity in the experiment [7].



In the second experiment [8] performed at the Nuclotron, a deuteron beam, an internal target, and scintillator TOF and Δ*E*-*E* detectors have been used. The achieved energy resolution was also not sufficient to draw a firm conclusion on formation of η-mesic nuclei. Important finding of that experiment was that the yield of the correlated π*N* pairs was clearly seen on the top of background existing in *d*A collisions (see Fig. 3 where some results are shown). This finding allows us to plan a new version of the experiment, in which the energy resolution is seriously improved due to using a magnetic spectrometer.

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| Fig.3. Total energies of the correlated π−*р* pairs [8]. Background is subtracted. |

Recently a search for η-mesic nuclei had been performed at the COSY-GEM setup [9] using the reaction

*p* + 27Al → 3He + 25ηMg → 3He + *p* + π− + X.

A peak was found in the missing mass spectrum of (p, 3He) that corresponds to formation of the state with the binding energy of about 13 MeV and the width of about 10 MeV. Since the cross section of the chosen reaction channel with formation of the 3He fragment is extremely small (about 0.5 nb), the obtained data had rather low statistics. In our proposal we suggest to explore reactions

*d*  + 12С → η-mesic nucleus + *X* → π + *N + X,*

*d* + 12С → η-mesic nucleus + *X* → *N + N + X*

that have larger cross sections by 3 orders of magnitude.

* 1. Studies of Δ in nuclei

One of practically unsettled aspects of the behavior of the Δ in nuclei concerns a hypothetic quasi-bound Δ-nucleus state. The Δ*N* interaction as well as the *NN* one is attractive. Therefore, the Δ-isobar and the residual of the nucleus can form a highly excited short-living state, the Δ-nucleus, provided the momentum of the isobar is not large in comparison with a characteristic nucleon momentum. If the width of the quasi-bound Δ-nucleus is much less than the width of the free Δ, there must be relatively narrow peaks in the energy spectra of decay products of the Δ in nuclei: correlated π*N* and *NN* pairs emerging in subprocesses

Δ → π*N* and Δ*N* → *NN.*

A possible existence of the Δ-nucleus states had been predicted in some theoretical works. In particular, a quasi-bound Δ*N*-state with the quantum numbers T=2, JP=2+ was predicted in [10]. Today experimental situation here is not unambiguous. Experiments with photon and electron beams [11-15] and their analysis [16] do indicate the existence of Δ-nucleus states. On the other hand, the dedicated experiment [17] done with the pion beam did not find Δ-nucleus states provided their width is more than 20 MeV. In order to elucidate the question of existence of Δ-nuclei and their properties further experimental work is certainly needed.

In the framework of the present project we propose to study, with the same setup, the reactions

*d*  + 12С → ∆-nucleus + *X* → π + *N + X,*

*d* + 12С → ∆-nucleus + *X* → *N + N + X*

on the internal carbon target in the kinematic region where Δ-nuclei can be formed most efficiently. Decay products of the Δ-nuclei, π*N* and *NN* pairs, will mostly have the opening angle close to 180o. Like in the experiment on studying η-mesic nuclei, the *NN* decay channel can also be studied. It has the advantage of having a lower background in comparison with that in the π*N* channel.

1. **Layout of the setup**

We propose to extent a setup used at the Nuclotron in our previous studies in order to achieve the energy resolution for both charged and neutral components of the correlated π*N* and *NN* pairs of σ ≈ 5 MeV. To this aim we plan to construct a magnetic spectrometer (M arm) and two sectioned neutron detectors with a TOF base up to 6 m (P and K arms), see Fig. 4.

Technical parameters of the detectors, including their space and time resolution, have been specified using GEANT simulations [18].

Data acquisition system is to be built using VME modules produced in JINR.

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| Fig. 4. Layout of the SCAN-3 setup. |
| Fr, Fl, Br, Bl – scintillator monitor counters;  P1-P3, K1-K3, M1-M3 – trigger time-of-flight scintillator detectors;  Pch, Kch, Mch – threshold Cherenkov detectors;  Мс1, Мс2 – drift chambers;  Мс3 – multiwire proportional chamber;  M4 –scintillator total absorption detector;  Р4, K4 – two sets of scintillator neutron counters;  Р5, K5, М5 – veto detectors. |

1. **Yield estimates**

Our yield estimates are based on the following parameters of the Nuclotron and the setup:

* ∅8 µm internal carbon target (a filament);
* the number of inelastic *d*12С collisions *Ninel* ~ 108 s−1 (this gives the luminosity

*L* = *Ninel* / σ*inel* = 2.5·1032 cm−2 s−1 if the total *d*12С inelastic cross section σ*inel* = 0.4 barn);

* the solid angle of the M arm ΩM ~ 2 ⋅ 10−2 sr;
* the solid angle of the P and K arms ΩP ~ 3 ⋅ 10−2 sr.

Using theoretical estimates of the total cross section of η-nuclei formation based on one-pion-exchange model (ση ~ 2 µb), as well as estimates of angular distributions of the correlated π*N* and *NN* pairs, we expect the following yields of events with formation and decay of η-nuclei:

*Y*(π−*p*) ~ 40 hour−1, *Y*(π+*n*) ~ 12 hour−1, *Y*(*pn*) ~ 12 hour−1, *Y*(*pp*) ~ 2 hour−1.

at the deuteron-beam energy ≈ 2 GeV/u. The main backgrounds come from random coincidences. From the GEANT-4 simulations we expect that they are less than the above signal yields − in agreement with our previous results obtained at the Nuclotron [8].

Concerning events of the Δ-nuclei formation, our yield estimates are based on theoretical calculations of the differential cross section of Δ-nuclei formation followed by a decay to π*N*: d4σ/(d*E*π dΩπ d*EN* dΩ*N*) ≈ 50 nb/(MeV sr)2. Then we expect

*Y*(π±*p*) ~ 280 hour−1

for the deuteron energy of about 1 GeV/u.The yield of the *pN-*pairs is preliminary estimated to be ≥ 10% of the π±*p* yield, with the background being by the factor of ≈ 10 less. Using the GEANT-4 code, we estimated the background of random coincidences to be ~7 hour−1 for π±*p* pairs and ~2 hour−1 for *pN*.

1. **Conclusions**

The first main aims of the present project are:

- building of a magnetic spectrometer for detection of charged components of the correlated pairs with the energy resolution of 4-5 MeV;

- building of a precision time-of-flight neutron detector with a similar energy resolution;

- studies of correlated hadron pairs ejected from the target in *d*A collisions;

- studies of the S11(1535) and Δ(1232) resonances in the nuclear matter;

- a search for η-nuclei and Δ-nuclei in *d*A-collisions through narrow resonance peaks in the total energy spectra of the correlated pairs;

- determination of binding energies and widths of η in nuclei;

- measurements of the cross section σ(ηA) of η-nuclei formation in *d*A collisions; measurements of the A-dependence of σ(ηA);

- measurements of relative rates of π−*p* и *pN* events;

- measurements of the cross section of Δ-nuclei formation in *d*A collisions;

- determination of binding energies and widths of quasi-bound states of Δ in nuclei;

- measurements of relative rates of π+*p*, π−*p* and *pN* events.

**References**

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**2.3. Estimated completion date**

**2024 – 2029**

**2.4. Participating JINR Laboratories**

**Veksler and Baldin Laboratory of High Energy Physics (VBLHEP)**

**2.5. Participating countries, scientific and scientific-educational organizations:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organisation** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| Lebedev Physical Institute | Russia | Moscow | **V.A. Baskov,**  **A.I. L’vov,**  **V.V. Polyansky, S.S. Sidorin.** | Cooperation  Protocol |
| PTI | Tomsk | Moscow | **I.V. Glavanakov, A.N. Tabachenko** |  |

**2.6. Co-executing organisations** *(those collaborating organisations/partners without whose financial, infrastructural participation the implementation of the research programme on the theme is impossible. Example - JINR participation in the LHC experiments at CERN).*

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**

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| --- | --- | --- | --- |
| **№№**  **n/a** | **Category**  **employee** | **Core staff,**  **FTE amount** | **Associated personnel**  **FTE amount** |
| 1. | scientific staff | 5 |  |
| 2. | engineers | 3 |  |
| 3. | professionals | 3 |  |
|  | **Total:** | **11** |  |

**3.2. Human resources available**

**3.2.1. JINR core staff** (total number of participants)

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| --- | --- | --- | --- | --- |
| **№№**  **n/a** | **Category of employees** | **Division** | **Position** | **Amount**  **FTE** |
| 1. | scientific staff | LHEP | Head of Sector  Senior Researcher  Researcher | 1  2  2 |
| 2. | engineers | LHEP |  | 3 |
| 3. | professionals | LHEP |  | 3 |
|  | **Total:** |  |  | **11** |

**3.2.2. JINR associated personnel**

**4. Financial support**

**4.1.** **The full estimated cost of the project 138k$**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **№№**  **n/a** | **Name of work** | **Cost** | **Expenditure per year**  **(thousands of United States dollars)** | | | | |
| 1st  year | 2nd  year | 3rd  year | 4rd  year | 5rd  year |
| 1. | International cooperation (IC) | 20 | 4 | 4 | 4 | 4 | 4 |
| 2. | Materials | 103 | 23 | 20 | 20 | 20 | 20 |
| 3. | Equipment and third-party services |  |  |  |  |  |  |
| 4. | Commissioning work |  |  |  |  |  |  |
| 5. | Services of research organisations | 15 | 15 |  |  |  |  |
| 6. | Acquisition of software |  |  |  |  |  |  |
| 7. | Design/construction |  |  |  |  |  |  |
| 8. | Service costs (*planned in case of direct project affiliation)* |  |  |  |  |  |  |
| **TOTAL:** | | **138** |  |  |  |  |  |

**4.2. Extrabudgetary funding sources**

Estimated funding from co-executors/customers - the total amount.

**Project leader** \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/Afanasiev S.V.

Date of project submission to DNOD:\_\_\_\_\_\_\_\_\_

Date of decision of the STC laboratory:\_\_\_\_\_\_\_\_\_ Document Number: \_\_\_\_\_\_\_\_\_

Project start year: **2023**

(for renewable projects) ––: project start year **2023**

**APPROVAL SHEET FOR PROJECT**

**Creation of a precision magnetic spectrometer SCAN-3 and research of non nucleon degrees of freedom in nuclei, nucleon correlations and nuclear fragmentation at the internal target of the Nuclotron.**

PROJECT IDENTIFICATION: SCAN-3

PROJECT CODE: 02-1-1087-2009

TOPIC CODE: 02-1-1087-2009

NAME OF THE PROJECT LEADER: Afanasiev S.V.

AGREED

JINR VICE-DIRECTOR \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

SIGNATURE NAME DATE

CHIEF SCIENTIFIC SECRETARY \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

SIGNATURE NAME DATE

CHIEF ENGINEER \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

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LABORATORY DIRECTOR \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

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LABORATORY SCIENTIFIC \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

SECRETARY SIGNATURE NAME DATE

THEME / MIP LEADER \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

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PROJECT / SUBPROJECT OF THE LRIP \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

LEADER SIGNATURE NAME DATE

APPROVED BY THE PAC \_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_

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