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Research program for the Nuclotron *

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Information is given about program of the experiments in relativistic nuclear physics at the accelerator complex of the Veksler and Baldin Laboratory of High Energies at the Joint Institute for Nuclear Research (JINR, Dubna) and about new projects for this facility.

1. INTRODUCTION

As an independent scientific trend of nuclear physics, relativistic nuclear physics (RNP) arose in the early 1970s after a successful acceleration of nuclei heavier than hydrogen at the Synchrophasotron in the Laboratory of High Energies (now V. Veksler and A. Baldin Laboratory of High Energies, VBLHE) [1].The studies of multiple particle production, the search for asymptotic regimes of hadron production carried out at the Synchrophasotron formed the basis for application of new theoretical approaches and experimental methods to the study of relativistic nuclei.

The beginning of fundamental studies on RNP dates back to the late 1960s, when beams of relativistic deuterons were obtained at the Synchrophasotron for the first time in world accelerator practice. The study of nucleus-nucleus collisions extended to the region of energies where the principles of relativity theory begin to play a dominant role. Long-term aims of research on RNP – a high-priority scientific direction at JINR arising at the interfaces of nuclear physics and elementary particle physics – were then determined. Its main purpose is to establish the limits of applicability of the proton-neutron model of atomic nucleus and to investigate nuclear matter at the level of subnucleon constituents – quarks and gluons (partons).

Thus, the RNP is founded on the achievements of quantum field theory, elementary particle physics, nuclear and accelerator physics. Following Dubna, RNP became a significant part of the programmes at the world largest accelerator centres. Orientation on the solution of present-day RNP problems helped to choose optimum ways for accelerator developments – development of ion sources, construction of experimental zones of accelerated beams. The project of the Nuclotron, a special-purpose accelerator of relativistic nuclei whose magnetic system is based on superconductivity, was proposed and completely realized [2].

Quantitatively new possibilities for studying the properties of atomic nuclei at the subnucleon level appear after the start-up and development of the Nuclotron in the 1990s.

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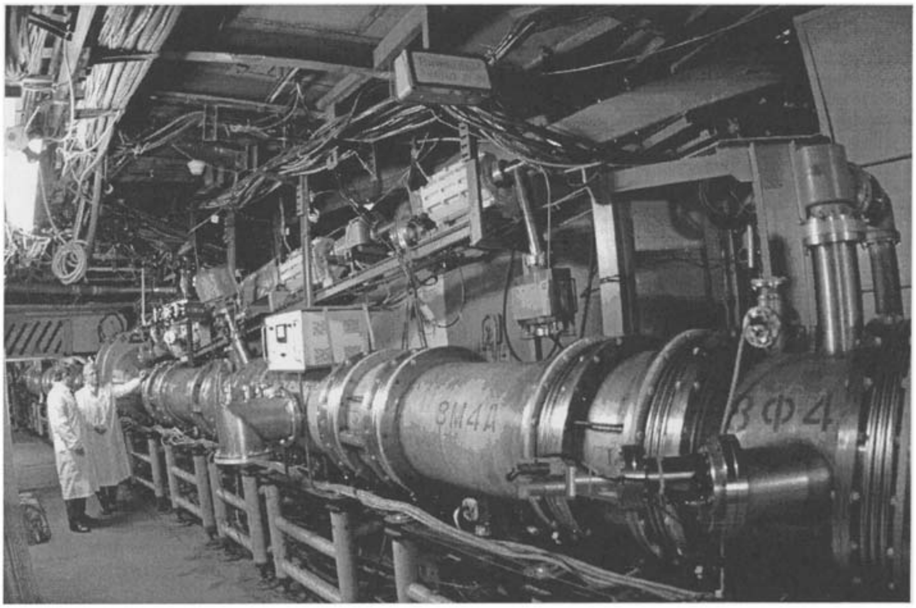

Figure 1. The view of the Nuclotron.

There are now lower limitations on the charge of accelerated ions and their intensity, on the extraction time from the accelerator ring and on the geometric beam size; the energy consumption of the accelerator decreases significantly. The availability of relativistic nuclear beams allows one to raise anew the questions related to more traditional directions of nuclear physics – clusterization, multifragmentation, non-nucleon (isobar) excitation, properties of hypernuclei. Investigations are also extended to the region of lower energies to several hundred million electron-volts. This allows the phenomena in the asymptotic and transition region to be bound up.

These achievements make it possible to formulate the priorities of future research: Effects of nonpertubative quantum chromodynamics (QCD) in nuclei; Spin effects in the deuteron; Interaction of polarized nucleons; Fundamental role of three-nucleon forces; Nuclei structure at relativistic energies.

2. THE NUCLOTRON ACCELERATOR COMPLEX

The Nuclotron provides for a wide supply of physics experiments with beams of relativistic and polarized nuclei up to 6 A GeV energy[3]. Obtaining an extracted beam of particles and ions from the Nuclotron has opened new prospects of research not only in RNP but also in applied fields. The view of the Nuclotron is shown in Figure 1.

Some parameters of the Nuclotron beams are listed in the Table 1.

The Nuclotron construction makes JINR the leading international scientific research

Table 1
The parameters of the Nuclotron beams

Beam	Intensity, paticle/spill	
	available	planned with booster
p	2.5×10^{10}	10^{13}
d	5×10^{10}	10^{13}
d↑	3×10^{8}	5×10^{10}
t	4×10^{5}	10^{10}
^{4}He	8×10^{8}	2×10^{12}
^{7}Li	2×10^{9}	5×10^{12}
^{10}B	2×10^{7}	10^{10}
^{12}C	6.5×10^{8}	2×10^{12}
^{24}Mg	1.2×10^{8}	5×10^{11}
^{40}Ar	10^{8}	10^{10}
^{56}Fe	10^{6}	10^{11}
^{84}Kr	10^{3}	5×10^{8}

centre in the field of RNP and QCD using hadron systems.

The planned programme of the development of the VBLHE accelerator complex in 2003-2009 will allow the Nuclotron to take one of the leading places as an accelerator of relativistic and polarized nuclei of intermediate relativistic energies and the required conditions to be created for performing investigations on high-priority problems of elementary particle physics and RNP by the physicists of the JINR Member States and other countries at a high level.

3. THE RESEARCH DIRECTIONS

We have the following main research directions at the Nuclotron [4].

Effects of nonpertubative QCD in nuclei. As the experiments at energies of several GeV have shown, the production of particle and nuclear fragments in nuclear collisions goes into the asymptotic regime – limiting nuclear fragmentation. This indicates a significant role of parton degrees of freedom. These investigations formed an empirical basis for the development of nuclear models at distances smaller than the nucleon size (the models of fluctons and short-lived nucleon correlations, multiquark states in nuclei and so on). It is planned to extend these studies at the Nuclotron to the region of subthreshold particle production in the collisions of nuclei and polarized deuterons. These investigations are of great interest for studying nonperturbative effects, vacuum structure and spin effects in nuclear matter.

Spin effects in the deuteron. In the research programme on RNP, the investigation of the deuteron structure with spin degrees of freedom is considered to be a high-priority direction due to the presence of polarized deuteron beams having a record energy to the distances equivalent to an internal momentum of up to 1 GeV/c. Investigations in the reactions with relativistic polarized deuterons are oriented on studying spin effects at meson fragmentation beyond the kinematic limits of the fragmentation of one nucleon (cumulative mesons).

This regime corresponds to the fragmentation of a strongly correlated pair of nucleons. Studies in this field allow one to obtain information on the spin structure of the deuteron core at small internucleon distances and to understand deeply the mechanisms of cumulative meson production.

Interaction of polarized nucleons. The unique beams of polarized neutrons have been produced using the break-up reaction of relativistic deuterons. The existing polarized targets on the Nuclotron beams allow one to expand the studies which are characteristic of the physics of nucleon-nucleon intermediate energy-interactions – measurement of the interaction cross sections of neutrons and protons in pure spin states at a record collision energy. The development of this direction of meson production is promising for studying the manifestation of the nucleon quark structure.

Fundamental role of three-nucleon forces. Three-nucleon forces play a fundamental role in nuclei beginning with tritium and ^{3}He. Even the value of tritium binding energy cannot be obtained only using pair nucleon-nucleon potentials. The study of deuteron-proton elastic scattering reactions and deuteron break-up in different kinematics has also shown that the obtained experimental data cannot be described within the solution of the Faddeev equation taking into account only nucleon-nucleon interactions. Taking three-nucleon forces into consideration allows one to reproduce both the binding energies of three-nucleon bound state and the data on the reaction cross sections of deuteron-proton interactions.

Nuclei structure at relativistic energies. The study of the nuclear structure at the level of nucleons and their clusters is deeply associated with astrophysics phenomena. Research progress on relativistic nuclear beams opens up new approaches to the solution of high-priority problems of nuclear structure from the lightest to the heaviest ones. Radioactive nuclei and resonance nuclear states are not simply a train of wastes from star burning reactions and explosion-type processes in cosmos, and they are intermediate stages ("stations of waiting") on the way to an effective generation of the world of stable nuclei. Observations of nuclear cosmos activity and investigations of nuclear structure at accelerators, including radioactive nuclei, may prompt new solutions in the region of thermonuclear energy synthesis.

4. SCIENTIFIC PROGRAM

The scientific program for the Nuclotron includes the following studies [4], [5] and [6].

4.1. Relativistic interactions of few-nucleon systems (A<5)

Studies of polarized effects in fragmentation of light nuclei will be carried out under the **PIKASO** project at the SPHERE set-up. The main aim of this project is to investigate the deuteron spin structure at short internucleon distances as well as spin effects correlated with meson- and quark-exchange mechanisms. This programme is directed to the use of deuteron beams with a momentum of up to 9 GeV/c which are available at the VBLHE accelerator complex. The first results of this experiment obtained at the Synchrophasotron is presented in Figure 2.

The project **DELTA-2** (Institute for Nuclear Research, Moscow) is intended for experiments on the VBLHE polarized proton target using extracted beams of the Nuclotron as

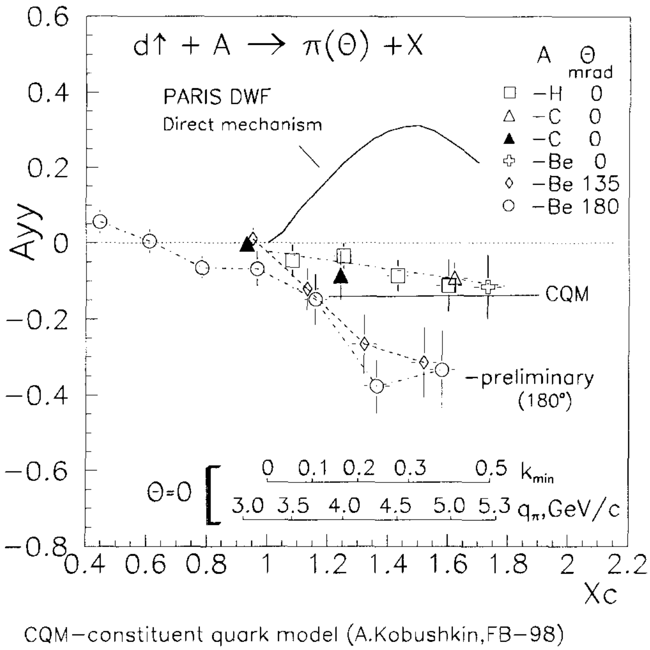

Figure 2. The tensor analyzing power A_{yy} vs x_c (the comulative variable) at fragmentation of 9 GeV deuterons into pions at $\theta = 0$, 135, and 180 mrad. For $\theta = 0°$ there are shown the scales of q_π, pion lab. momentum, and k_{min}. The solid curves show calculations with Paris DWF and the estimation according with the constituent quark model (CQM) of A.Kobushkin.

well as for experiments on the Nuclotron internal target. The set-up represents a two-arm free-magnet spectrometer used to register and measure the energy of neutral (gamma-quanta and mesons) and charged (mesons, protons, deuterons) particles. In the physics programme, it is planned to investigate in detail π^0 and η meson production in neutron-proton collisions of polarized beam and target nucleons at energies of 1.2 - 2.0 GeV in order to test theoretical assumptions of the meson production mechanism and also the hypothesis of the presence of a spin-polarized $s\bar{s}$-component of strange quarks inside the nucleon.

In the experiment **STRELA**, it is supposed to study a spin-dependent part of the nucleon scattering amplitude in the $np \to pn$ charge-exchange process on an extracted deuteron beam of the Nuclotron. It is planned to measure the production cross section of two protons at a small momentum transfer in dp interactions in the region of deuteron momenta from 3.0 to 4.0 GeV/c.

The principal object of the project **DELTA-SIGMA** is to study nucleon-nucleon interactions using a secondary beam of polarized high energy neutrons which we now have only at the VBLHE accelerating complex. It is proposed to make detailed measurements of the energy dependence of $\Delta\sigma_T(np)$ and $\Delta\sigma_L(np)$. These quantities represent the differences of the total neutron-proton cross sections for antiparallel and parallel spin orientation of beam neutrons and target protons polarized in the longitudinal (L) and transverse (T) directions. Results of measuring of $\Delta\sigma_L(np)$ is presented in Figure 3.

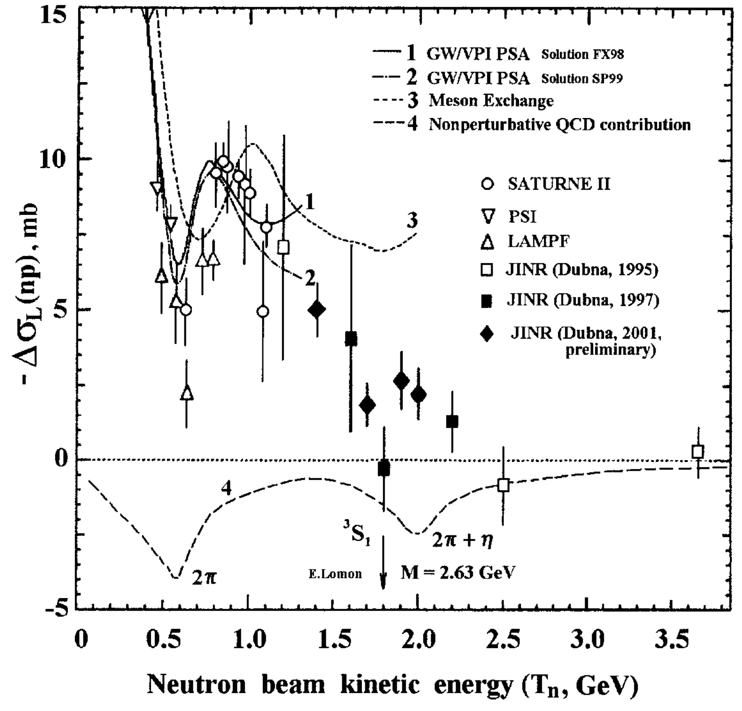

Figure 3. Energy dependence of the $\Delta\sigma_L(np)$ observables obtained with neutron polarized beam. The new 2001 points were measured at neutron beam kinetic energies 1.4, 1.7, 1.9 and 2.0 GeV.

The project **NIS** has been proposed by VBLHE and Laboratory of Particle Physics (LPP) of JINR. The project is aimed at searching for effects of polarized nucleon strangeness including violations of the OZI rule, in vector meson production in pp and np interactions near threshold. If this hypothesis has been confirmed, both the "spin crisis" problem and the seeming violation of the OZI rule will find their natural explanation. It is necessary to carry out measurements the ratio of the production cross sections of ϕ and ω mesons near their production threshold in nucleon interactions, i.e. at laboratory nucleon momenta above 2.7 GeV/c.

In the experimental programme of **LNS** project, it is assumed to investigate the deuteron and ^{3}He structure at small distances between nucleons. The programme includes a study of dp-elastic scattering and a deuteron break-up reaction in *dp* interactions using a nonpolarized and polarized deuteron beam, an internal target of the Nuclotron and a measurement of the tensor analyzing power of the $d+d \rightarrow\ ^3He+n$ and $d+d \rightarrow\ ^3H+p$ reactions as well as a polarized RIKEN deuteron beam (Japan).

The project **pHe3**. The main objective of the joint VBLHE-RIKEN experiment is to study the $^3He(^3H)$ structure at distances, unachievable now with the use of electromagnetic probes, by measuring the angle dependences of the tensor analyzing powers A_{yy}, A_{xx} and A_{xz} in the $d+d \rightarrow\ ^3He+n$ and $d+d \rightarrow\ ^3H+p$ reactions. These polarization observables are sensitive to the spin neutron (proton) distribution in $^3He(^3H)$ at small distances in the framework of one-nucleon data exchange. On the other hand, both ^3He and ^3H are mirror nuclei relative to the number of protons and neutrons, and the difference in their observed values can be interpreted in terms of charge symmetry violation.

In the project **SPIN**, it is planned to measure spin effects in nucleon-nucleon and nucleon-nucleus interactions (and in nuclear decays) and to get the main spin observables in the $np \rightarrow pp\pi^-$ reaction.

4.2. Manifestation of the structure and excited states of nuclei at relativistic energies

The project **SPHERE** includes the following programme of investigations at the Nuclotron in geometry close to 4π: study of multiple cumulative particle production (special attention will be given to the study of vector meson production in the cumulative region); investigation of resonance physics and search for exotic quark states; study (with the GIBS collaboration) of dynamic correlations of secondary particles and nuclear excitations in charge-exchange reactions, investigation of hypernuclei (measurement of the lifetime of $^3H_\Lambda$, $^4H_\Lambda$, $^6He_\Lambda$ hypernuclei and the binding energy of $^3H_\Lambda$, $^6He_\Lambda$ hypernuclei) and study of their Coulomb dissociation; investigation of η nucleus production. The set-up **GIBS** is a magnetic spectrometer based on a 2 m streamer chamber. It is proposed to upgrade the GIBS spectrometer for further experiments at the Nuclotron. The spectrometer is equipped with a new filmless information registration system from the streamer chamber and also with proportional chambers for ^3He momentum measurement. The streamer chamber will be used as a vertex detector.

The project **FAZA** is being performed by specialists of Dzhelepov Laboratory of Nuclear Problems (DLNP) of JINR and VBLHE. The scientific goal of the project is to investigate the nuclear equation of the state at reduced density and at temperature below the critical T_c for the "liquid-gas" and "liquid-fog" phase transitions. The study of "thermal" multifragmentation (with beams of light relativistic ions) is adequate to this task. This is a new, many-body type of decay of very hot nuclei ($E^* = 500--700\ MeV$) which is characterized by a copious emission of intermediate mass fragments ($2 < Z < 20$). It was shown by the FAZA collaboration for the first time that this type of disintegration takes place after an expansion of the excited nucleus due to thermal pressure.

In the project **BECQUEREL**, it is planned to expose nuclear emulsions to different beams of relativistic particles. The research programme is concentrated on a detailed study of relativistic fragmentation of light radioactive and stable nuclei. The expected results will allow one to answer some high-priority questions of the cluster structure of light nuclei. Event of 4.5 A GeV/c ^{24}Mg nucleus dissociation in emulsion into five ^{4}He and one ^{3}He nucuclei is presented in Figure 4. Due to the best space resolution, nuclear emulsions will permit unique and provable results to be obtained. The most important exposures will be performed on secondary beams of radioactive He, Be, B, C and N nuclei formed from the beams of stable nuclei at the Nuclotron.

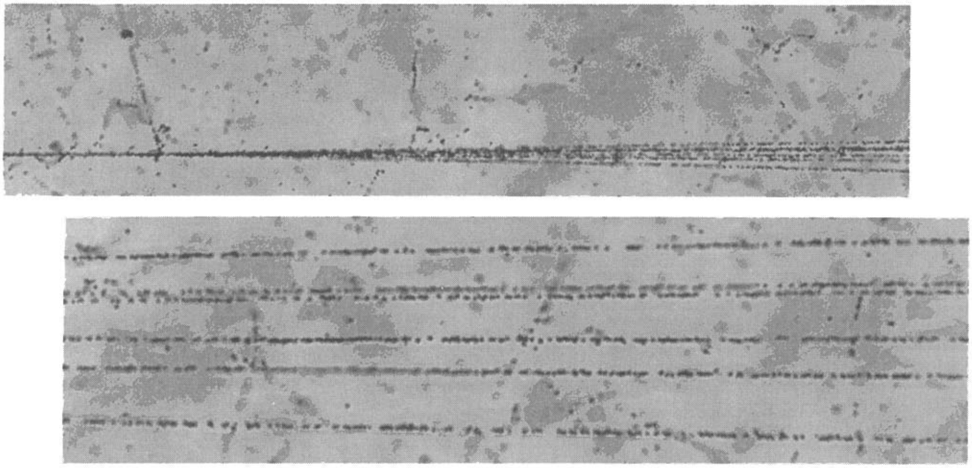

Figure 4. Event of 4.5A GeV/c ^{24}Mg nucleus dissociation in emulsion into five ^{4}He and one ^{3}He nuclei are shown on two consecutive sections of the tracks with an evident zoomed image (bottom). A three-dimensional image of the event is reconstructed as a plane projection by means of an automatic microscope (PAVICOM, Lebedev FIAN, Moscow).

4.3. Study of multiple production processes in collisions of relativistic nuclei from the lightest to heavy ones at energies of hundreds of MeV to TeV

The project **MARUSYA** is aimed at investigating the properties of the transition (from nucleon to quark-gluon degrees of freedom) regime in relativistic nuclear collisions. In the project, it is also suggested to make investigations of rare subthreshold and cumulative processes (for polarized colliding objects inclusive) and to select events by centrality degree using the measurement of secondary particle multiplicity. It is planned to study the yield of antiprotons and negative kaons. Interest in them is due to their production from "sea" quarks. At event selection according to centrality degree, one can observe a large difference in the production cross sections of antinuclei in nucleus-nucleus interactions. Such data are absent in the transition energy region.

The **SCAN-1** set-up is designed to study the fragmentation of target nuclei into two cumulative protons. The aim of the experiment is to measure the transverse size of the region of nucleus-nucleus interactions using the method for measuring the correlations of cumulative protons emitted at small relative momenta.

The project **SMS** (VBLHE and Moscow State University) is dedicated to the research of leading particles in proton-nucleus interactions. The research plans are to clarify the strong interaction mechanism of particles. The experimental set-up represents a one-arm magnetic spectrometer with variable geometry of the spectrometric part, and it is used to solve two basic problems: research of the space-time structure of hadron interaction and also measurement of the analyzing power of quasi-elastic scattering of polarized protons on nuclei. In the framework of the research program of interactions of polarized protons with nuclei, it is suggested to measure the one-spin scattering asymmetry of polarized protons on internuclear nucleons (for comparison with similar scattering on free nucleons) in an energy region of 1-4 GeV.

4.4. Applied Research Using the Nuclotron Relativistic Nuclear Beams

The Synchrophasotron has been used for applied research over a long period of time. The results of these investigations are very productive, and so they are being continued at the Nuclotron. What is more, the Nuclotron beams offer new possibilities of performing applied research, and their range will be extended.

The applied research performed at the VBLHE accelerator complex includes the following main trends: radiobiology and space biomedicine; influence of nuclear beams on microelectronic components; radioactive waste transmutation; electronuclear method of energy generation; use of a carbon beam for cancer treatment and so on.

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