Report

on the theme 03-2-1101-2010/2016

Physics of Light Mesons

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Scientific program of the theme consists in investigation of interactions of particles and light nuclei at intermediate energies aiming to determine the symmetries and the interaction dynamics.

In 2016, the theme included three projects and four activities which are realized at the facilities in Russia (Dubna, Gatchina, Protvino), Germany (Jülich, Mainz), Switzerland (PSI) and Japan (J-PARC):

Name	Status	Project leader(s)	Terms of realization
GDH&SPASCHARM	Project	Yu.Usov A.Kovalik	2011-2019
SPRING	Project	A.Kulikov	2010-2016
COMET	Project	Z.Tsamalaidze	2014-2016
TRITON	Activity (Project in 2011-2015)	D.Demin	
MEG-PEN	Activity (Project in 2007-2015)	N.Kuchinsky	
MUON	Activity	V.Duginov T.Mamedov	
PAINUC	Activity	N.Russakovich G.Piragino	

Works on the theme are carrying out in collaboration with the Institutes of Russia, Belarus, Bulgaria, Canada, Croatia, Czech Republic, France, Georgia, Germany, Italy, Japan, Kazakhstan, Netherland, Poland, Romania, Switzerland and USA.

The results for each project and activity are briefly presented below.

1 Project GDH&SPASCHARM

Physics content of the project is study of the nucleon spin structure in strong and electromagnetic interactions. Experimental part is based on use of the solid state polarized targets which development, production and maintenance are under responsibility of the JINR group. Both longitudinal and transverse polarizations can be provided for proton and deuteron targets.

The members of the JINR group are world experts in solid state polarized targets and produced several high quality targets for experiments at different European accelerators.

The project covers two spin physics topics:
1) measurement of the spin-dependent asymmetries using the frozen-spin proton-deuteron target and Crystal Ball detector at the microtron MAMI (Mainz),

the polarized photon energies being up to 1.5 GeV; experimental verification of the Gerasimov-Drell-Hearn (GDH) sum rule;
2) study of single- and double-spin asymmetries in the production of light resonances and charmonium at the π^--beam of the Protvino accelerator including determination of the gluon contribution into the proton spin.

Рис. 1: The new dilution refrigerator for the Crystal Ball Frozen Spin Target.

In 2014-2016 there were about ten production runs with use of the Dubna-Mainz polarized target at the polarized photon beam of MAMI C accelerator. In these runs proton polarization was kept not less than 70%, the relaxation time being about 1500 hours. The measurements have led, in particular, to the following results:

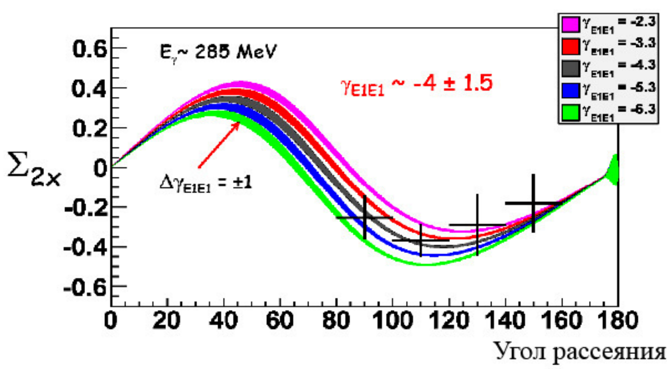


Рис. 2: Proton spin polarizability obtained from the measurement of the Compton scattering asymmetry.

• The Compton scattering asymmetries in the $\Delta(1232)$ resonance region have been measured using circularly/linearly polarized photon beam and longitudinally/transversely polarized proton target (Fig. 2). The world first experimental values were extracted for all four proton spin polarizabilities - fundamental structure constants describing the proton spin response to the changing electromagnetic field.

• The double polarization observable E and the helicity dependent cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ were measured for η photoproduction from quasifree protons and neutrons (Fig.3).

• In the framework of the complete experiment in meson photoproduction the first data on target and beam-target asymmetries for the $\gamma p \to \pi^0 \eta p$ reaction at photon energies from 1050 to 1450 MeV have been obtained.

• Differential cross sections for the $\gamma p \to \pi^0 p$ reaction have been measured with the A2 tagged-photon facility up to the center-of-mass energy 1.9 GeV. The new results, obtained with a fine energy and angular binning, increase the existing quantity of π^0 photoproduction data by one half. Owing to unprecedented statistical accuracy and full angular coverage, the results are sensitive to high partial-wave amplitudes.

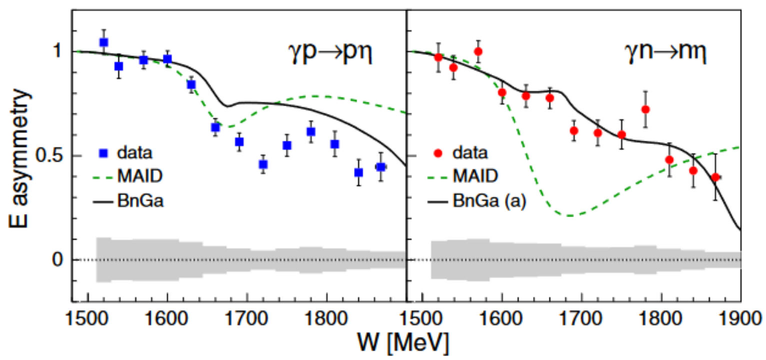


Рис. 3: Double polarization observable E for $\gamma p \to p\eta$ and $\gamma n \to n\eta$. Gray shaded areas: systematic uncertainties.

• The data on the neutron detection efficiency in NaI crystals of the Crystal Ball detector were obtained from study of a single π^0 photoproduction on deuterium using the tagged photon beam. The results were obtained up to a neutron energy of 400 MeV.

• A proposal has been suggested for the extraction of polarized halo antiprotons from the storage ring of the FAIR facility by means of a bent silicon crystal and magnetic septum, for experiments with a solid polarized target. For the typical 10 cm target the calculated luminosity equals $\sim 10^{30} cm^{-2} c^{-1}$.

In the SPASCHARM sub-project many works on instrumentation have been done: test of the magnet of the polarized target, some modifications of the target itself, study of new electronics and of the detector performance. With a modified polarized target a high proton polarization of 80% was achieved.

The plans for 2017-2019 include:

- Experimental verification of the sum rule Gerasimov-Drell-Hearn on quasi-free neutron with polarized photon beams at MAMI, Mainz (up to 1.5 GeV) and at ELSA, Bonn (up to 3 GeV). In the experiments it is planned to use the existing polarized target Dubna-Mainz (based on butanol and D-butanol) and

a new polarized target Dubna-Bonn, which is planned to be commissioned in 2017-2018.
- Precise measurement of scalar and vector (spin) polarizabilities of the proton. For measurement of the Compton scattering at energies below the threshold of π^0-meson production, the active polarized target Dubna-Mainz based on scintillation plastic (polystyrene) will be used, which is planned to be commissioned in 2018.
- Carrying out the research of the photoproduction of pseudoscalar mesons under the "full experiment program". This is an extensive program including measuring of up to eight polarization observables for each partial channel of the photoproduction in a wide range of energies and angles. In the first phase of the program it is planned to measure one- and two-spin observables T, F, E, G for the reactions $(\gamma, \pi^0), (\gamma, 2\pi^0), (\gamma, \eta), (\gamma, \eta')$ et al. at the energies up to 1.5 GeV.
- Testing of new materials to be used in frozen-type targets and investigations for further improvement of the target characteristics.

The recent papers (2014-2016) on the project are listed in [1–11]. At the 44th meeting of the PAC for Nuclear Physics the GDH&SPASCHARM project has been extended to 2017-2019.

2 Project SPRING

Project SPRING (Spin Physics at hadron storage RINGs) is realized at accelerator COSY in Jülich providing proton and deuteron beams up to 3.7 GeV/c momenta. The project includes three parts. The major JINR contribution has been done in investigation of the nucleon-nucleon interaction dynamics with the setup ANKE (Fig.4) using polarized/unpolarized proton and deuteron beams and polarized/unpolarized hydrogen or deuterium jet targets. Another part is investigation of the spin filtering process proposed by the PAX collaboration as a method to polarize an antiproton beam at FAIR in GSI. Finally, the third part, which was added only recently, is preparation for the experiment on search for permanent electric dipole moment of a deuteron. All three parts are united by similar approaches to polarization measurements and the methods to analyze polarization data.

In research at ANKE a large attention was given to processes of the *NN* interaction with formation of a $^1S_0$ proton pair, $\{pp\}_s$, (*diprotons*) in the final state of the reaction. Such processes are kinematically similar to well-studied reactions with final deuterons but allow more clear interpretation due to a simpler spin structure of the diproton. This field of research has been suggested by the JINR physicists and the corresponding experiments have been done with their decisive or very large participation. Study of reactions with formation of the diprotons makes high demands to the setup performance because a high resolution of the apparatus is required and cross sections are much smaller than in the case of deuterons. For this reason at the energies above 300-400 MeV there were no such measurements before studies at ANKE.

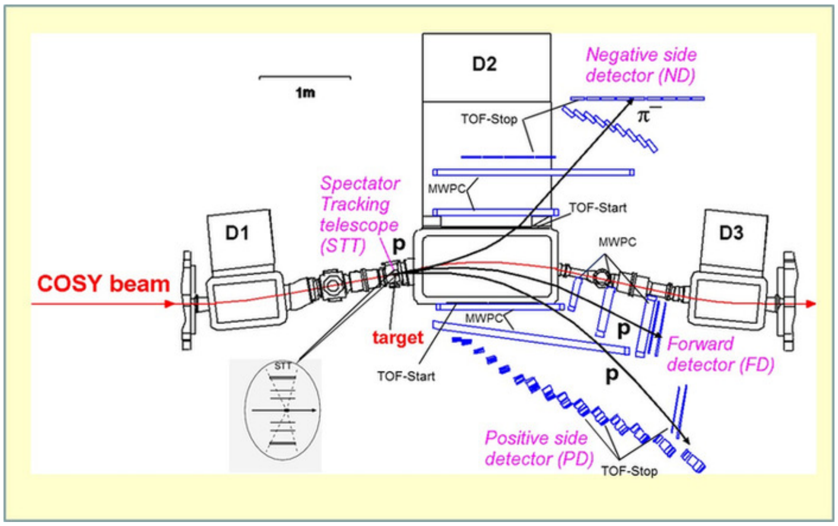


Рис. 4: Experimental setup ANKE at COSY.

The following results were obtained at ANKE in the recent years with the leading role of JINR:

• Near-threshold pion production using single and double polarization measurements. First, the differential cross section and vector analyzing power have been measured in reactions of 353 MeV polarized proton beam with unpolarized cluster jet hydrogen and deuterium targets [12,13]: $\vec{p}p \to \{pp\}_s\pi^0$ and $\vec{p}n \to \{pp\}_s\pi^-$. This allowed to make partial wave analysis and to extract the complex amplitudes of the processes.

• Then the studies of spin observables were carried out in a double polarized mode, i.e. with use of a polarized deuteron beam *and* a polarized hydrogen target [14]. In the quasi-free reaction $\vec{n}\vec{p} \to \{pp\}_s\pi^-$ at 353 MeV per nucleon the spin correlation coefficients A_{xx}, A_{yy} and the vector analyzing power A_y have been measured (Fig.5). Combined partial wave analysis of these data together with our previous single polarization data has led to three different acceptable solutions. Resolving of this ambiguity is only possible by measuring the spin correlation coefficient A_{xz} using a *longitudinally* polarized beam.

• Coherent pion production in proton-deuteron collisions [15]. Values of the proton analysing power in the $pd \to {}^3He\pi^0/{}^3H\pi^+$ reactions at 350-360 MeV per nucleon were obtained by using a polarized proton beam incident on a deuterium cluster-jet target and with a polarized deuteron beam incident on a target cell filled with polarized hydrogen (Fig.6). In addition, first data were obtained for the deuteron vector analysing power and the deuteron-proton spin correlations.

• The measurements of the differential cross section and the first measurement of the analyzing power A_y in the $\Delta(1232)$ excitation energy region of

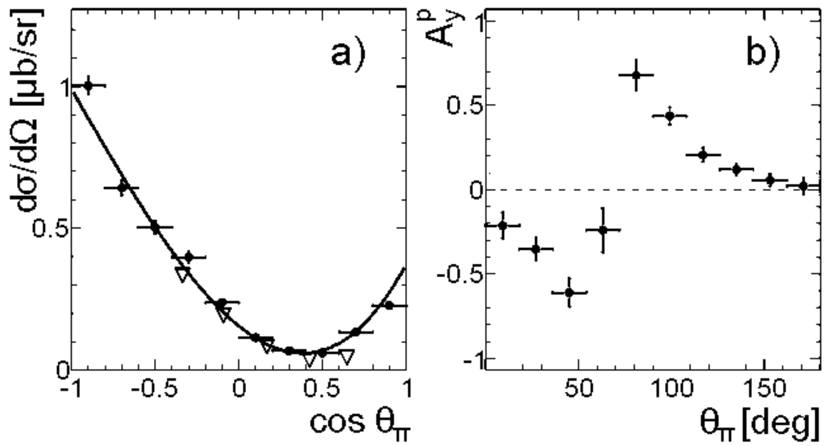


Рис. 5: Differential cross section (a) and proton analyzing power A_y (b) in the process $\vec{n}\vec{p} \to \{pp\}_s\pi^-$ at the deuteron beam energy 353 MeV per nucleon.

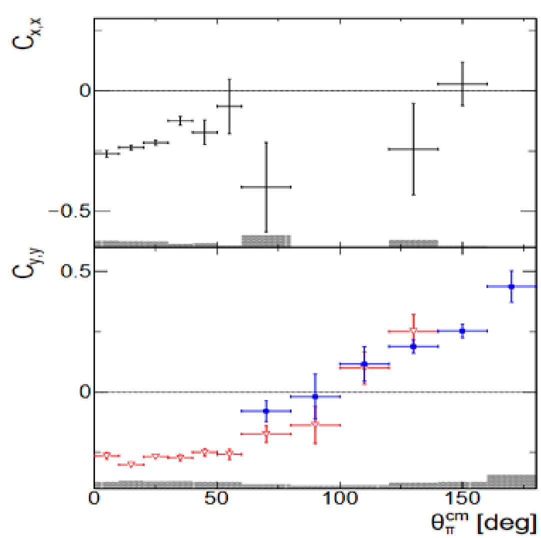


Рис. 6: Transverse spin correlation coefficients C_{xx} and C_{yy} in the $dp \to {}^3He\pi^0$ and $dp \to^3 H\pi^+$ reactions at 363 MeV per nucleon

the reaction $pp \rightarrow \{pp\}_s\pi^0$ have been done. The analysis resulted in a direct manifestation of two two-baryon resonance-like states with $J^P = 2^-$ and 0^- and an invariant mass of $2.2 GeV/c^2$ [16].

• The transverse spin correlations A_{xx} and A_{yy} in the $np \rightarrow d\pi^0$ reaction have been measured for the first time in quasi-free kinematics using a polarized deuteron beam incident on a polarized hydrogen cell target at the neutron energies close to 353 MeV and 600 MeV [17]. The results, in particular, cover the small-angle region, which was largely absent from previous data.

• The proton analyzing power in $\vec{p}p$ elastic scattering at small angles has been measured at 796 MeV and five other beam energies between 1.6 and 2.4 GeV using a polarized proton beam [18]. At the higher energies within this region the data lie well above the predictions of the SAID solution at small angles. An updated phase shift analysis that uses the ANKE results together with the world data has led to a much better description of these new measurements.

• The charge exchange of vector polarized deuterons on a polarized hydrogen target has been studied in a high statistics experiment at a deuteron beam energy of $T_d = 726$ MeV [19]. The results lend broad support to the current neutron-proton partial-wave solution.

Very large contribution has been done also to the following studies:

• The differential cross section for pp elastic scattering has been measured [20] at a beam energies from 1.0 to 2.8 GeV for small centre-of-mass angles in the range from $12^o - 16^o$ to $25^o - 30^o$ depending on energy. The achieved precision in the overall normalization is typically 3%.

• For reaction $\vec{d}p \rightarrow \{pp\}_s n$ at the deuteron energies 1.2, 1.6, 1.8 and 2.27 GeV the differential cross section and two tensor analyzing powers, A_{xx} and A_{yy}, have been measured [21]. At 1.2 and 2.27 GeV the hydrogen target was also polarized what allowed to measure the spin correlation parameters C_{xx} and C_{yy}. The obtained results essentially complement the neutron-proton part of the SAID data base.

• For the same $\vec{d}p \rightarrow \{pp\}_s n$ reaction at 1.6, 1.8 and 2.27 GeV excitation of the $\Delta(1232)$ isobar was studied [22].

• The vector and tensor analyzing powers, A_y and A_{yy}, of the $p\vec{d} \rightarrow n\{pp\}_s$ charge-exchange reaction have been measured at a beam energy of 600 MeV by using an unpolarized proton beam incident on an internal storage cell target filled with polarized deuterium [23].

Due to termination of COSY operation for hadron physics, in the ANKE-related part there will be no new measurements but a lot of data has been collected during the past years which we are planning to analyze. ANKE plus COSY is a unique complex for spin studies at intermediate energies and one has to extract as much as possible physics information from the data which cannot be obtained anywhere else.

Experiments at ANKE were a good basis for professional development of the JINR scientists. For the whole period of the ANKE operation there were prepared 6 diploma and 3 PhD theses, 2 more PhD theses are in the final stage of preparation, ANKE results were partly used in 3 doctoral theses. Twice the series of the ANKE papers were awarded the first prize of the Dzelepov Laboratory of Nuclear Problems.

In the PAX-related part of SPRING, the experiments on spin filtering at COSY have been done aiming to prove the method to polarize the beam. The initially unpolarized proton beam was circulating through the PAX polarized storage cell hydrogen target. Polarization arising in the beam was then measured at the ANKE position through detection of asymmetries in scattering of the beam particles off the unpolarized deuterium cluster jet target of ANKE. The measured effective polarizing cross section was found to be in a good agreement with the calculated value, thus confirming a good understanding of the spin filtering effect [24,25].

Another result was obtained [26] in re-analysis of the data on the beam depolarization which disproved another competitive method to polarize the beam by spin transfer from electrons to protons. New analysis has set even more strong confirmation of the previous conclusion about ineffectiveness of this method, thus leaving the proposed in PAX spin filtering method to be the only one capable to create a polarized antiproton beam in a storage ring.

Further plan for the PAX-related part of SPRING consists in study of the spin filtering with building-up a longitudinal polarization where a larger effect is expected. This measurement may become possible after implementation of the Siberian snake which has been produced and delivered to COSY.

The third part of SPRING is participation in the experiment at COSY on search for electric dipole moment (EDM) of charged particles. This experiment is of fundamental importance because observation of a sizable EDM would mean manifestation of so-called "new physics" beyond the Standard Model.

EDM, if exists, would exibit itself by generation of polarization in originally unpolarized beam of a dedicated storage ring. This polarization would have a tiny size but may accumulate, therefore very high demands are made to accelerator performance in terms of beam lifetime, polarization lifetime and other beam parameters.

In 2015-2016 the JINR physicists participated in experiments aiming to obtain the desired beam properties. First, the method of continious determination of the spin tune in storage rings was developed [27]. Then it was demonstrated that a polarization lifetime of the order of 1000 second can be reached [28]. These results open the way for further progress in preparations for the EDM search.

We do not apply for extension of the project but we are planning to continue it as an activity within the theme. The main content of this activity will be analysis of the ANKE data and participation in the experiment on EDM search..

The recent papers (2012-2016) related to SPRING are listed in [12-39].

3 Project COMET

The project aims at a search for neutrino-less muon-to-electron conversion, $\mu^- + N(A,Z) \to e^- + N(A,Z)$. This charged-lepton-flavor violation process is considered today as a very important and sensitive test for so-called "new physics" beyond the Standard Model. For this purpose a high intensity muon beam with a special muon transport system will be created at J-PARC together with a dedicated detector system. In COMET it is planned to reach a record single event sensitivity $B(\mu^- N \to e^- N)$ at the level of $10^{-16} - 10^{-17}$ what is 4 orders of magnitude exceeds the highest precision attained in experiment SINDRUM-II in PSI.

The COMET experiment will be realized in two phases. The purpose of Phase-1 is testing the innovative technologies of the superconductive muon transport system, studying different background processes in real beam conditions and searching for $\mu - e$ conversion with an intermediate sensitivity which will be 2 orders of magnitude better than the present one.

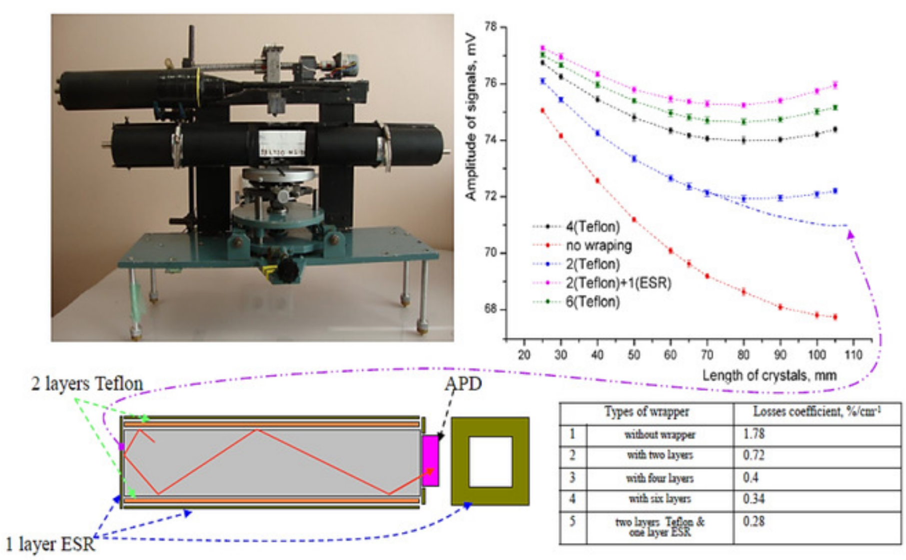
Phase-1 is currently under preparation. A shorter muon transport system, less beam power and a different detector arrangement will be used at this stage. This is a necessary step before transfer to Phase-2 where a challenging extremely high sensitivity is required.

Project COMET in JINR has started in 2014. JINR physicists fulfilled numerous simulation studies which contributed a lot in TDR of the experiment. At the present stage of the setup creation, the JINR COMET group has two important tasks related with development and construction of the straw tracker and of the electromagnetic calorimeter. The JINR group is responsible for production of all straw tubes for the tracker and for testing of crystals (LYSO type) for the electromagnetic calorimeter.

The walls of the straw tubes have to be as thin as possible in order to minimize multiple scattering which is essential at the electron energies of about 100 MeV. For this reason the R&D has been done and the production technology was properly tuned. As a result, reliable manufacturing of the $20\,\mu$ thick tubes and $9.8\,mm$ diameter was attained (Fig.1), while only $36\,\mu$ tubes could be produced before. In 2015 the JINR group has produced a full set of 2500 tubes (Fig.7) needed for Phase-I, thereby completely fulfilling its obligations. Starting from 2017, the JINR physicists will take part in assembling and testing the straw tracker.

The next step ahead consists in R&D for production of even thinner walls and smaller diameter tubes, $12\,\mu$ and $5\,mm$, respectively, because this is required for the Phase-2 of the experiment. It is planned to fulful R&D at the site of the Dzhelepov Laboratory of Nuclear Problems (previous straws have been produced by the DLNP manpower but using the facility of the VBLHEP).

Рис. 7: Straw tubes of $20\,\mu$ wall thickness.



Types of wrapper		Losses coefficient, %/cm⁻¹
1	without wrapper	1.78
2	with two layers	0.72
3	with four layers	0.4
4	with six layers	0.34
5	two layers Teflon & one layer ESR	0.28

Рис. 8: Test bench and results of probing different wrapping.

Another JINR task is testing of the LYSO crystals which are the best choice for obtaining high energy resolution of the electromagnetic calorimeter near 105 MeV, the latter is the electron energy in the $\mu - e$ conversion. The first portion of crystals (50 pieces) has been inspected at the test facility in JINR and then used for construction of a first calorimeter prototype. The prototype has been tested with an electron beam in Japan together with the other type crystals (GSO). The beam test data were analyzed in Japan and JINR independently and produced the same conclusion about a better performance of the LYSO crystals. This has led to decision of the COMET collaboration to use the LYSO crystals in the experiment.

A new facility for test of crystals has been arranged in DLNP in 2015 with improved parameters (Fig.8). It will be used for test of all crystals, the number of crystals will be more than two thousand at Phase-2. Investigation of the crystal parameters is currently under way.

The JINR group participates also in engineering design works and in simulations concerning the detector performance.

Proposal to extend project COMET to 2017-2019 will be submitted at the 46th meeting of PAC for particle physics in January 2017.

The papers related to the project are listed in [40–47].

4 Experiment TRITON

This experiment [48] continues the program of *muon catalysis*, the summary of mu-atomic and mu-molecular processes caused by negative muon in hydrogen isotope mixture (H, D, T).

The rates of the muon catalyzed fusion reactions $d+d$, $p+d$ and $t+t$ have been measured in many previous experiments, and they turned out to be in a good agreement with theory. This is not the case for the $p+t$ fusion rates

$$pt\mu \to {}^4He\mu + \gamma + 19.82\,MeV \quad (1)$$
$$pt\mu \to {}^4He\mu + 19.81\,MeV \quad (2)$$
$$pt\mu \to {}^4He\mu + e^+ + e^- + 18.79\,MeV \quad (3).$$

There was only one experiment on $p+t$ fusion (at PSI), and it has shown that the experimental yield of reaction (1) exceeds theoretical value 8 times and that of (2) even much more – several hundred times. Reaction (3) was not detected at all.

In order to clarify the problem, in project TRITON all three reaction channels are measured simultaneously using the setup shown in Fig.9.

The experiment is carrying out at the LNP JINR Phasotron with a liquid hydrogen/tritium target of 50 cc volume at 1% (0.1%) tritium concentration. The target has been produced (by the contract with VNIIEF, Sarov, Russia) and a full-scale test of the target filled with liquid hydrogen has been done in LNP. There were several technical runs at Phasotron which allowed to achieve the required parameters of the muon beam and to test all the detectors and the data acquisition system in real beam conditions.

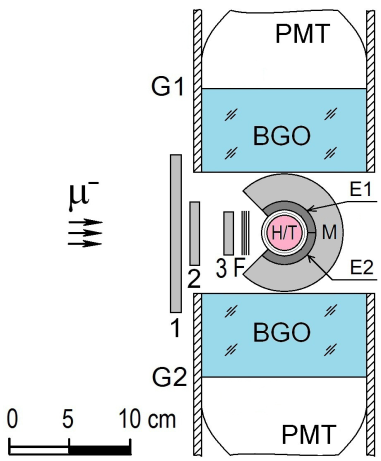


Рис. 9: Experimental setup of the TRITON experiment.

In May and November 2016 there were two successful physics runs. In the first run, with 1% tritium concentration in the target, two already known reaction channels with emission of single gammas (1) and muons (2) were observed. For the first time the channel (3) with emission of e^+e^--pairs was detected, and an indication was obtained to discovery of a new channel with emission of two gamma-quanta,

$pt\mu \to {}^4He\mu + \gamma + \gamma + 19{,}82$ MeV. (4)

This impressive result has led to recommendation of the 44th PAC meeting to undertake an additional run for further exploration of the subject.

In November run the experiment was done with reduced to 0.1% tritium concentration, and using two detector geometries. Existence of the reaction channel with emission of two gammas has been confirmed. Preliminary analysis of data with different concentration also confirmed the predictions (of PSI, 1993) about the dependence of the yield of channels (1,2) on the tritium concentration.

The measurements with different detector geometries revealed the presence of an angular correlation in emission of e^+e^--pairs, and, on the hand, the absence of such correlation in the channel (4) with emission of two gamma-quanta (Fig.10).

The activity on TRITON will be continued in order to fulfill a detailed analysis of the obtained data and to extract physics information about the muon catalyzed fusion reaction $p+t$.

The recent papers related to TRITON are listed in [47-51].

5 Experiment MEG-PEN

The goal of the activity is study of rare decays $\pi \to e\nu$ and $\mu \to e\gamma$ with the best up to date precision. The experiment is realized by the international

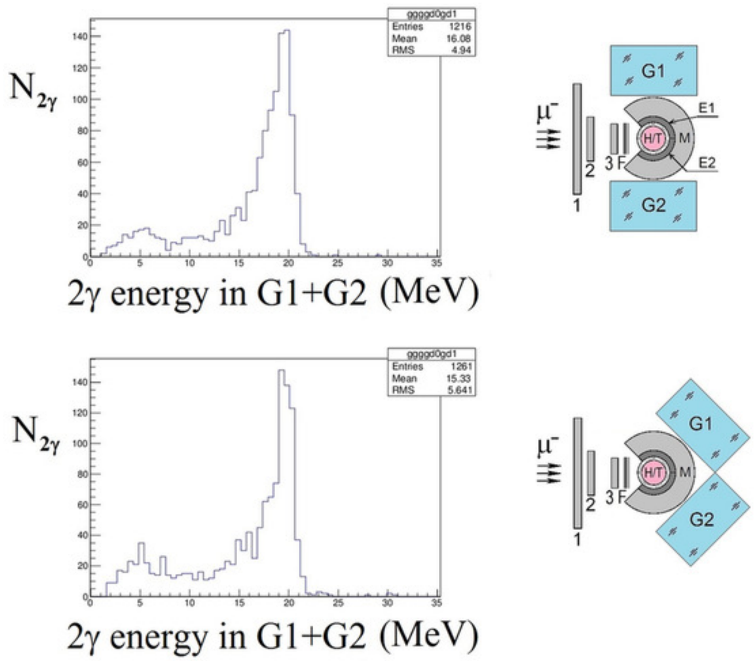


Рис. 10: Spectrum of two gammas at different detector geometries.

collaboration at the Paul Sherrer Institute (PSI).

Calculations of the relative probability of the $\pi \to e\nu$ decay (PEN subproject) in the Standard Model reached a precision of $1 \cdot 10^{-4}$. Meanwhile, the experimental precision is more than one order of magnitude worse. The measurements in PSI were carried out using the PIBETA detector. JINR has made a large contribution in this experimental setup: cylindrical proportional chambers with electronics, pure CsI crystals for the calorimeter. Some later especially for this experiment a new mini-TPC chamber has been developed [52] and implemented in the detector by the JINR physicists. Works on instrumentation received further development in [53,54]

Collection of statistics for this process is finished, and JINR participates in analysis of data (Fig.11). There were detected about 23 million decays $\pi \to e\nu$, more than $1.5 \cdot 10^8$ $\pi \to \mu \to e$ decays as well as a great amount of radiative muon and pion decays. The expected total error including both statistics and systematics for $\pi \to e\nu$ will be $\delta B/B < 5 \cdot 10^{-4}$ as originally planned. The results of the data processing will be available in 2017.

In the MEG part of the project a search is carrying out for the decay $\mu \to e\gamma$ forbidden in the Standard Model. This decay, as well as other charged lepton flavor violation processes, is considered as a very important and sensitive test for a new physics beyond the SM.

Two important results have been obtained concerning the background in the $\mu \to e\gamma$ search: measurement of the muon beam polarization [55] and measurement of the radiative decay of polarized muons, $\mu \to e\nu\bar{\nu}\gamma$ [56].

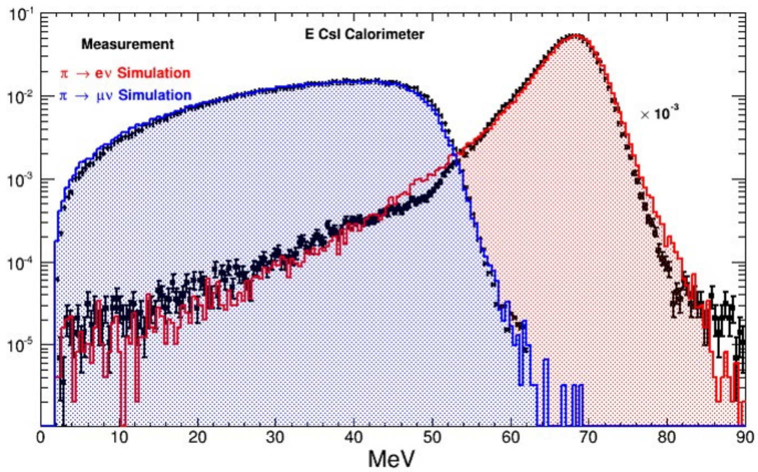


Рис. 11: Observed and simulated energy spectra for $\pi \to e\nu$ and $\pi \to \mu\nu$ events.

The data analysis for the lepton flavor violating decay $\mu^+ \to e^+\gamma$ based on the full dataset collected in the MEG experiment in the period 2009-2013 and totalling $7.5 \cdot 10^{14}$ stopped muons on target has been finished. No significant excess of events is observed and a new upper limit on the branching ratio of this decay, $\mathrm{B}(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$ (90% confidence level), is established [57] which represents the most stringent limit on the existence of this decay to date. The new measured upper limit improves the previous result [58] of the same group by a factor 1.4.

A big upgrade of the setup, MEG-II, is going on with the aim to reach in 2018-2020 the upper limit of the $\mu \to e\gamma$ decay 4-5$\cdot 10^{-14}$ what is about one order of magnitude better than the current value.

These works will continue as the activity within the theme.

The recent papers related to MEG-PEN are listed in [52-58].

6 Experiment PAINUC

Experiment PAINUC studies the pion-nucleus interactions at the Phasotron of DLNP JINR using the technique of self-shunted streamer chambers. A remarkable feature of this device is a possibility to detect tracks of very low energy particles. For example, with helium as a working gas in the chamber, the track length of a proton with an energy of only 1.3 MeV (or 5.0 MeV for α-particle) exceeds 20 *cm*. The technique of self-shunted streamer chambers was developed about 30 years ago in the LNP JINR together with the Turin section of INFN for investigation of pion elastic scattering on helium nuclei.

The analysis is in progress. As an interim result, it is stated that in interactions at 106 MeV no angular correlation is observed in three-prong events between the two strongly-ionizing secondaries, and distribution of their total momentum is consistent with total disintegration of the helium nucleus (Fig.12).

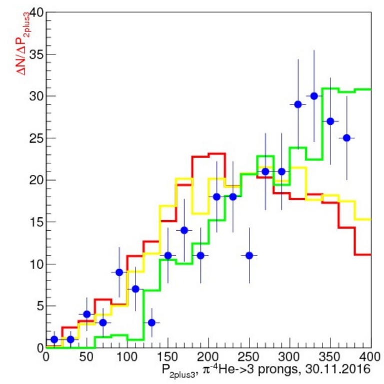


Рис. 12: Distribution of total momentum of the two heavy strongly ionizing secondaries produced in $\pi^{-4}He$ three-prong interactions at 106 MeV. The histograms show results of simulation for reaction channels $\pi^{-4}He \to \pi^{-}\,{}^{3}Hp$ (red), $\pi^{-}\,{}^{4}He \to \pi^{-}\,dd$ (yellow), $\pi^{-}\,{}^{4}He \to \pi^{-}ppnn$ (green).

7 Experiment MUON

In this experiment muons and muon-based methods are applied for the tasks of the condensed matter physics. The scientific program includes study of the superfine interactions in semiconductors, of magnetic fluids and other compounds with unusual magnetic characteristics.

Using polarized negative muons there was studied the behaviour of acceptor centers in diamonds produced by the method of chemical vapor deposition. In particular, the muon spin relaxation rates have been measured for different semiconductor structures and the temperature dependence of the spin relaxation velocity of negative muons was investigated.

The probabilities of finding the positive muon in various states in synthetic single crystal and polycrystalline diamond were studied. In the IIa-type single-crystal sample at 150 K the relative contributions of the diamagnetic muon, 'normal', and 'anomalous' muonium have been measured.

There was continued the study of systems with magnetic nanoparticles in the μSR experiment performed in Gatchina. Comparison of the muon behaviour in ferroliquids of different composition and different concentration of the magnetic particles was done. It was shown that the shift of the muon precession frequency as a function of the external magnetic field (Fig.13) is described by the Langevin function typical for paramagnetic magnetization. The magnetic properties of ferroliquids depend on the history of a sample: was it cooled in a magnetic field or without it.

It is planned in the frame of the MUON activity to study the behavior of the shallow acceptor impurities in different semiconductors (Ge, Si, diamonds)

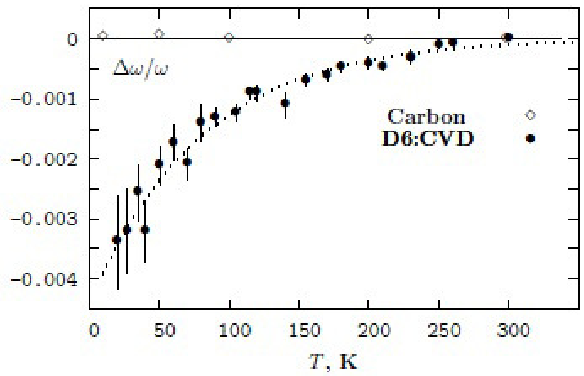


Рис. 13: The precession frequency shift of the negative muon spin measured in the synthetic diamond sample D6 and in the graphite sample at the magnetic field of 14 kOe.

and to continue a study of the local magnetic fields in the samples with the magnetic nanoclusters.

The recent papers related to MUON are listed in [59-63].

8 Conclusion

A lot of new results was obtained in the frame of the theme 1101 "Physics of light mesons" using the experimental facilities at different intermediate energy accelerators. The results have been published in the world leading journals and presented at international conferences. Some analyses still have to be finalized. In order to complete most of activities, we apply for extension of the theme for 1 year, till the end 2017.

Theme leader

A.Kulikov

Appendix: list of papers published in 2012–2016.

GDH&SPASCHARM

1. C.S. Akondi et al. Measurement of the Transverse Target and Beam-Target Asymmetries in η Meson Photoproduction at MAMI. **Phys. Rev. Lett. 113** 102001 (2014).

2. J.R.M. Annand et al. First measurement of target and beam-target asymmetries in the $\gamma p \to \pi^0 \eta p$ reaction. **Phys. Rev. C 91** 055208 (2015).

3. P.P. Martel et al. Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities. **Phys. Rev. Lett. 114**, 112501 (2015).

4. P. Adlarson et al. Measurement of π^0 photoproduction on the proton at MAMI C. **Phys. Rev. C 92** No. 2, 024617 (2015).

5. M. Martemianov et al. A new measurement of the neutron detection efficiency for the NaI Crystal Ball detector. **Journal of Instrumentation JINST**, **10** T04001 (2015).

6. G.M. Gurevich et al. On the feasibility of using an extracted polarized antiproton beam of the HESR with a solid polarized target. XVI International Workshop in Polarized Sources, Targets and Polarimetry. PSTP2015, Ruhr-University Bochum, Germany, 14-18 September 2015, PoS(PSTP2015)043.

7. Yu. Usov. Frozen spin target developed at Dubna. Hystory and Traditions. XVI International Workshop in Polarized Sources, Targets and Polarimetry. PSTP2015, Ruhr-University Bochum, Germany, 14-18 September 2015, PoS (PSTP2015)021.

8. S. Schumann et al. Threshold π^0 photoproduction on transverse polarized protons at MAMI. **Phys. Let. B 750** 252-258 (2015).

9. J.R.M. Annand et al. T and F asymmetries in π^0 photoproduction on the proton. **Phys. Rev. C93** 055209 (2016).

10. L. Witthauer et al. Insight into the narrow structure in η photoproduction on the neutron from helicity-dependent cross sections. **Phys.Rev.Lett. 117** (2016) 132502.

11. V.V.Abramov et al. Analyzing power in the reaction $p + \vec{p} \to \pi^0 + X$ in the fragmentation region of the polarized target at 50 GeV energy. (*in Russian*) **Yad. Fiz. 77**, №5, 629 (2014).

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12. D.Tsirkov et al. "Differential cross section and analysing power of the $pp \to \{pp\}_s \pi^0$ reaction at 353 MeV." **Phys. Lett. B 712** (2012) 370.

13. S.Dymov et al. "Differential cross section and analysing power of the quasifree $pn \to \{pp\}_s \pi^-$ reaction at 353 MeV." **Phys. Lett. B 712** (2012)

375.

14. S.Dymov et al. "Measurement of spin observables in the quasi-free $np \to \{pp\}_s\pi^-$ reaction at 353 MeV." **Phys. Rev. C 88** (2013)014001.

15. S.Dymov et al. "Coherent pion production in proton–deuteron collisions." **Phys. Lett. B 762** (2016) 102.

16. V.Komarov et al. "Evidence for excitation of two resonance states in the isovector two-baryon system with a mass of 2.2 GeV/c^2." **Phys. Rev. C** 93 (2016) 065206.

17. V.Shmakova et al. "First measurements of spin correlations in the $\vec{n}\vec{p} \to d\pi^0$ reaction." **Phys. Lett. B 726** (2013) 634.

18. Z.Bagdasarian et al. "Measurement of the analyzing power in proton-proton elastic scattering at small angles." **Phys. Lett. B 739** (2014) 152.

19. S.Dymov et al. "Analysing powers and spin correlations in deuteron-proton charge exchange at 726 MeV". **Phys. Lett. B 744** (2015) 391.

20. D.Mchedlishvili et al. "Measurement of the absolute differential cross section of pp elastic scattering at small angles." **Phys. Lett. B 755**, 92 (2016).

21. D.Mchedlishvili et al. "The neutron-proton charge-exchange amplitudes measured in the $dp \to ppn$ reaction." **Eur. Phys. J. A 49** (2013) 49.

22. D.Mchedlishvili et al. "Excitation of the Delta(1232) isobar in deuteron charge exchange on hydrogen at 1.6, 1.8, and 2.3 GeV." **Phys. Lett. B 726** (2013) 145.

23. B.Gou et al. "Study of the $p\vec{d} \to n\{pp\}$ charge-exchange reaction using a polarized deuterium target." **Phys. Lett. B 741** (2015) 305.

24. W. Augustyniak et al. "Polarization of a stored beam by spin-filtering". **Phys. Lett. B 718** (2012) 64.

25. C.Weidemann et al. "Toward polarized antiprotons: Machine development for spin-filtering experiments." **Phys. Rev. ST-AB 18** (2015) 020101.

26. D.Oellers et al. "New experimental upper limit of the electron–proton spin-flip cross-section." **NIM A 759** (2014) 6.

27. D.Eversmann et al. "New method for a continuous determination of the spin tune in storage rings and implications for precision experiments". **Phys. Rev. Lett. 115** 094801 (2015).

28. G.Guidoboni et al "How to reach a thousand-second in-plane polarization lifetime with 0.97-GeV/c Deuterons in a Storage Ring". **Phys. Rev. Lett. 117** 054801 (2016).

29. Qiujian Ye et al. "The production of K+K- pairs in proton-proton collisions below the phi-meson threshold." **Phys. Rev. C 87** (2013) 065203.

30. M.Mielke et al. "Isospin effects in the exclusive $\vec{d}p \to^3 He\pi^+\pi^-$ reaction."

Eur. Phys. J. A 50 (2014) 102.

31. M.Papenbrock et al. "Absence of spin dependence in the final state interaction of the $\vec{d}p \to^3 He\eta$ reaction." **Phys. Lett. B 734** (2014) 333.

32. Yu.Uzikov. "Phenomenology of Spin observables in the reactions of meson production with the 1S0 diproton $pN \to pp_sX$." **Yadernaya Fizika 77**, №5 (2014) 646.

33. Yu.Uzikov, J.Haidenbauer. "Spin Dependence of the Interaction of Antiprotons with the Deuteron." **PEPAN Letters, 45**, v.1 (2014) 196.

34. Yu.Uzikov, J.Haidenbauer. "Elastic pbar d scattering and total pbar d cross sections." **Phys.Rev.C 87** (2013) 054003.

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38. Yu.Uzikov, A.Temerbaev. "Null-test signal for T-invariance violation in pd scattering". **Phys.Rev.C 92** (2015) 014002.

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40. V.Kalinnikov, E.Velicheva. "Investigation of LYSO and GSO crystals and simulation of the calorimeter for COMET experiment." **PEPAN Letters**, **11**, №3 (2014) 259.

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45. A.D.Volkov. Control of the tube tension in straw detectors (*in Russian*). **Uspechi prikladnoi fiziki 2**, №4, 413 (2014).

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50. L.N.Bogdanova, D.L.Demin, V.V.Filchenkov. "Study of the mechanism of muon catalyzed t+t fusion reaction."JINR Communication E15-2013-115, Dubna, 2013.

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60. T.Mamedov et al. "Muonium in synthetic diamond." **Diamond and Related Materials, 31** (2013) 38.

61. T.Mamedov et al. "Muonic atom as an acceptor centre in diamond." **Journal of Physics, Conference Series, 551** (2014) 012046.

62. T.Mamedov et al. "Magnetic properties investigation of a ferrofluid with cobalt ferrite nanoparticles used by polarized muons."**Journal of Optoelectronics and Advanced Materials, 17**, №7, (2015) 1086. 63. V.Duginov et al. "Study of the systems with cobalt ferrite nanoparticles using polarized muons". 14th Int. Conf. on Magnetic Fluids, 4-9 July 2016, Ekaterinburg. Book of Abstracts, p.86.