DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS

NEUTRINO PHYSICS AND RARE PHENOMENA

The main purpose of the **GEMMA** experiment is the measurement of the (anti)neutrino magnetic moment with sensitivity at the level of $(4-7)\cdot 10^{-12}$ μ_B. The GEMMA spectrometer consists of a 1.5 kg HPGe detector surrounded with a combined active and passive shielding. It is placed under 3 GW reactor 2 of the Kalininskaya Nuclear Power Plant 13.9 m away from the core centre. Analysis of the first phase in 2008 allowed getting a new neutrino magnetic moment upper limit of $5.1\cdot 10^{-11}$ μ_B. Data taking and analysis in 2009 improved this result to $3.9\cdot 10^{-11}$ μ_B. In 2009, simultaneously with GEMMA-I data taking and analysis, R&D and construction of the GEMMA-II spectrometer was in progress. As a result, the neutrino magnetic moment sensitivity at the level of less than $(1.0-2.0)\cdot 10^{-11}$ μ_B is expected. In the third phase of the experiment (GEMMA III) the sensitivity will be improved to $(0.4-1.0)\cdot 10^{-11}$ μ_B.

The main purpose of the **NEMO-3** experiment is the search for the double-beta decay process with two ($2\nu\beta\beta$ decay) or zero ($0\nu\beta\beta$ decay) neutrinos in the final state in seven different $\beta\beta$ isotopes. The experimental search for the $0\nu\beta\beta$ decay is of major importance in particle physics. If this process is observed, it will reveal the Majorana nature of the neutrino and allow an access to the absolute neutrino mass scale. The NEMO-3 experiment has been taking data since February 2003 in the Modane Underground Laboratory (Laboratoire Souterrain de Modane, LSM) located in the Frejus tunnel at a depth of 4800 m water equivalent.

The current NEMO-3 exposition is $\sim$ 2090 days (5.7 years). The new results for $0\nu\beta\beta$ mode were obtained in 2009 after analysis of 3.75-year exposition data. No evidence for $0\nu\beta\beta$ mode was found and the following limits have been obtained (90% CL):

$$T_{1/2}^{0\nu\beta\beta}(^{100}\mathrm{Mo}) > 1.1\cdot 10^{24}\ \mathrm{y},\ \langle m\nu\rangle < 0.45-0.93\ \mathrm{eV};$$
$$T_{1/2}^{0\nu\beta\beta}(^{82}\mathrm{Se}) > 3.6\cdot 10^{23}\ \mathrm{y},\ \langle m\nu\rangle < 0.89-2.43\ \mathrm{eV}.$$

The results for $2\nu\beta\beta$ mode have also been updated. The further studies of background and systematic errors were carried out during 2009.

The French–German–Russian **EDELWEISS** experiment is dedicated to the direct detection of WIMPs trapped in the Galactic halo. The experiment is operated in the LSM. EDELWEISS uses high-purity germanium cryogenic detectors with simultaneous measurement of phonon and ionization signals at a temperature of about 20 mK. All parameters of the EDELWEISS-II setup were validated in 2006–2007 with calibration and low-energy background runs. In 2009 the EDELWEISS-II collaboration performed a direct search for WIMP dark matter with an array of ten 400-g heat-and-ionization cryogenic detectors equipped with interleaved electrodes. EDELWEISS-II continuously operated with this type of detectors for eight months (total operation time with all types of detectors was about 10 months). The observation of one nuclear recoil candidate above 20 keV in an effective exposure of 144 kg$\cdot$d (six months of data taking) has been interpreted in terms of limits on the cross section of spin-independent interactions of WIMPs and nucleons. A cross section of $1.0\cdot 10^{-43}$ cm^2 is excluded at 90% CL for a WIMP mass of 80 GeV/c^2. This result demonstrates for the first time the very high background rejection capabilities of these simple and robust detectors in an actual WIMP search experiment [1–3].

The data accumulation in EDELWEISS-II is continued. It is planned that by April 2010 about 300 kg $\cdot$ d of statistics will have been in hands. This will allow achieving the best experimental sensitivity for direct WIMP search and verifying one observed event in the present data set.

Within the framework of the **PEN** international collaboration, the **PIBETA** detector has been upgraded to optimize it for a precise measurement of the $\pi^+ \to e^+\nu$ decay ratio at PSI. Data collection runs were successfully completed in 2008–2009. Data for $4.7 \cdot 10^6$ raw $\pi \to e\nu$ events were recorded, before analysis cuts are applied, the statistical uncertainty was $\delta B/B = 5 \cdot 10^{-4}$ [4]. The 2009 run was the second data taking run of the PEN experiment. During the 2008 and 2009 runs more than 10^7 events of the $\pi \to e\nu$ decay were recorded, which already allows the experimental accuracy of the branching ratio to be improved [5]. The final result will be obtained after completion of the last data taking run in 2010.

In 2009 the **MEG** experiment to search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ was continued at PSI. The goal of the experiment is to improve the existing limit on the decay branching ratio by two orders of magnitude and to reach a sensitivity of 10^{-13}. The experiment uses surface muons from one of the world's most intense sources, the $\pi E5$ channel at PSI. The detectors of positrons and γ rays provide the best possible spatial, temporal and energy resolutions. Analysis of the 2008 experimental data yielded a decay branching ratio upper limit of $3 \cdot 10^{-11}$. The characteristics of the detector have been improved using the experience gained during the 2008 run. With the help of the DLNP collaborators the drift chambers have been modified to enhance their efficiency and reliability. After processing the 2009 experimental data a branching ratio limit of $(2{-}4) \cdot 10^{-12}$ should be obtained. Continuation of the search for the $\mu^+ \to e^+\gamma$ decay in 2010 and 2011 would allow reaching the upper sensitivity limit up to 10^{-13}.

The **OPERA** experiment is using CERN's neutrino beam and experimental setup, which was constructed in Gran Sasso Laboratory (Italy) with a big contribution from Dubna. The first physics run was performed in 2008. About 1680 neutrino events were registered in the detector. In 2009 the OPERA experiment had a full-scale run on the CNGS neutrino beam and more than 3500 neutrino interactions were registered in the target part of the detector. The data analysis is in progress. The total amount of data accumulated in 2008–2009 gives a hope that the first tau neutrino candidates are already among the registered events and will be found after the completion of the analysis in the nearest future. The JINR group has developed a program to perform a vertex search based on the electronic detector analysis. The Dubna program has demonstrated a higher efficiency of the brick finding (by 8%) as compared to the algorithm which is currently in use. An automatic scanning station for the emulsion processing has been launched at JINR. At the end of 2009 the scanning station was equipped with an automatic plate changer which allows exclusion of most routine operations in emulsion processing. The automatic scanning station is a unique instrument which opens up many possibilities for other applications as well [6, 7].

The **Borexino** experiment continues data taking after the successful start in May 2007. The main efforts of the collaboration during the last year were aimed at improving the result of the ^{7}Be solar neutrino flux measurement. The final result on the ^{7}Be neutrino flux is $(49 \pm 3(\mathrm{stat.}) \pm 4(\mathrm{syst.}))$ cpd/100 t of scintillator. The expected signal in the high-metallicity Standard Solar Model is (74 ± 4) cpd/100 t, the MSW–LMA scenario reduces this count to (48 ± 4) cpd/100 t. The hypothesis of nonoscillating neutrinos is inconsistent with the measurements at 4σ CL. Another interesting result obtained with 192-day statistics is the new strongest limit on the neutrino magnetic moment. The study of the maximum allowed deviations from the pure electroweak electron recoil shape for ^{7}Be neutrinos performed with the Borexino data led to a new limit on the effective neutrino moment $\mu_\nu < 5.4 \cdot 10^{-11}\ \mu_B$ at 90% CL.

In 2009 the Dubna group participated in the data taking shifts, including two calibration campaigns. The results of calibration of the energy scale and the position reconstruction code were used to reduce systematics in the ^{7}Be neutrino flux measurement. The JINR group performed analysis for the collaboration article on the constraints on the violation of the Pauli principle in the ^{12}C nucleus and also participated in the Borexino data analysis aimed at detecting the antineutrino interactions (geo- and reactor antineutrinos) [8, 9].

The **TUS** space experiment has been proposed to address some of the most important astrophysics and particle physics problems — to study the energy spectrum, composition and angular distribution of the Ultra High Energy Cosmic Rays (UHECR) at $E \approx 10^{19}{-}10^{20}$ eV in the region of the so-called GZK cutoff. The free path of $5 \cdot 10^{19}$ eV protons is about 50 Mpc due to interaction of the primary particles, mainly protons with the relict CMB photons.

The JINR and the Consortium «Space Regatta» (Korolev) are responsible for R&D and production of the Fresnel mirror-concentrator that is the most complicated TUS system due to operation in open space in the ± 80°C temperature range. The full-scale technological Fresnel mirror prototype was produced during 2009. Measurement methods of the mirror optical parameters are being currently developed at JINR as the respective Monte-Carlo simulation programs. One of the optical control method is the measurement of the benchmark grid reflection in the mirror. The flight TUS detector has to be produced in 2010–2011. The mission is planned for operation at the end of 2011 at the dedicated Mikhail Lomonosov satellite [10].

The main aim of the **NUCLEON** experiment is measurement of the cosmic ray flux in the energy range 10^{11}–5.10^{14} eV and charge range up to $Z \approx 30$ in the near-Earth space. The JINR responsibility is the design, production and tests of the scintillator trigger system including DAQ electronics etc.

The NUCLEON scintillator trigger system selects useful events by the multiplicity measurement of charged particles that crossed the planes. The designed and manufactured technological level-1 and level-2 trigger modules were successfully tested at the CERN SPS pion beam. The main task of the NUCLEON collaboration in 2010 is to produce and test the flight option of the detector to be launched in space in 2011.

DOMESTIC RESEARCH AND PARTNERSHIP PROGRAMME AT UNIQUE ACCELERATORS

The main results of the **JINR/CDF** group are the measurement of the top-quark mass ($M_{\rm top}$) and the efficient operation of CDF II. A contribution of principal significance to precise single $M_{\rm top}$ measurement in the «dilepton» mode at an integrated luminosity of 2.9 fb^{-1}, $M_{\rm top} = (165.5^{+3.4}_{-3.3}({\rm stat.}) \pm 3.1({\rm syst.}))$ GeV/c^2 was made [11]. The method was updated for the top-mass measurement in the dilepton decay channel. To increase the number of the selected events, the so-called lepton + track selection was used.

With 2.0–4.8 fb^{-1} of the data analyzed at the CDF, and 2.1–5.4 fb^{-1} at D0, the 95% CL upper limits on Higgs boson production are a factor of 2.7 (0.94), higher than the SM cross section for a Higgs boson of mass $m_H = 115$ (165) GeV. The Tevatron excluded the standard model Higgs boson of $163 < m_H < 166$ GeV at 95% CL with the expected exclusion $159 < m_H < 168$ GeV. These results significantly extend the individual limits of each experiment and provide new information on the mass of the standard model Higgs boson beyond the LEP direct searches [12].

In 2010 the CDF collaboration plans to perform the high-precision $M_{\rm top}$ measurement using the b-tagging jet information on the maximum available CDF integrated luminosity, and to continue VHM study at CDF II.

The Beijing electron positron collider BEPC-II produced the first collisions in July 2008 in the detector **BES-III**, after several years of upgrading. The main goals of the experiment are studies in charmonium physics, physics of charmed mesons, tau leptons, and light hadron spectroscopy. The main activity of the JINR group in the BES-III experiment was participation in the preparation of the physics research programme of the experiment, development of the off-line software and physics analysis tools, and participation in the data taking. One of the main goals at the BES-III for the JINR group is physics of tau leptons. Another task is measurement of hadron spectral functions in tau decay, where BES-III could provide an independent cross-check of the existing measurements.

The JINR group joined a new research activity at BES-III, which is light hadron spectroscopy. It is one of the main BES-III goals. Partial wave analysis (PWA) is the most advanced and most suitable technique for light hadron spectroscopy to deal with complicated multi-body decay chains. However, to analyze BES-III data using PWA, one has to overcome several difficulties, caused by greatly increased size of a data sample in comparison with the previous experiment BES-II. During 2008 and 2009, a new analysis tool for PWA was developed by the JINR group together with the PNPI (Gatchina) group. Currently, this tool allows analyzing J/ψ decays into three pseudoscalar mesons and radiative decays into two pseudoscalar mesons. Event selection of J/ψ and ψ $(2S)$ decays into two kaons and a photon was elaborated for the future partial wave analysis [13].

The group plans to participate in the BES-III detector calibration and performance study, to perform partial-wave analysis of ψ $(2S)$ and J/ψ decays into a pion and kaon pair, to measure the branching ratio and decay product polarization for the $D^0 \rightarrow K^* \rho^0$ decay, using data taken in 2010.

JINR team has carried out so-called E/p calibration of the **ATLAS Tile Calorimeter** on the basis of simulated minimum bias samples. Only pions and kaons from these samples with an energy of 0.5–12 GeV were used as «calibration units». It was demonstrated that local calibration method with modified weights proposed by the team is much better than the commonly used one (official ATLAS software). The experience gained by the group will allow correct electromagnetic and hadronic calibration of the ATLAS calorimeter complex with real data (within Jet/EtMiss & Tau Combined Performance Groups and Standard Model QCD Physics Group). In particular, a procedure of electromagnetic calibration of TC (as well as in-situ hadronic E/p calibration) is tested and adjusted on the basis of single charged hadrons from minimum bias events (or from hadronic tau decays). Calibration of TC with jets is also tested.

Beam test of 11% of ATLAS Tile Calorimeter modules was carried out with JINR participation. Electromagnetic (EM) scale calibration constants were measured and analyzed for more than 200 calorimeter units, which were irradiated with SPS electron and muon beams. This analysis relied on recent modification of

TC Cs calibration method, charge injection calibration and energy reconstruction by means of fitting procedure. Averaged conversion factor between measured particle charge value and deposited energy (by the same particle) equals (1.050 ± 0.003) pC/GeV, with deviations of $(24 \pm 0.1)\%$. All uncertainty sources in determination of EM scale calibration constant were analyzed. It was shown that after inner Cs calibration of all TC cells and location (by means of electron beam) of EM scale in the first sector of TC, one has to increase signal values measured in the 2nd and 3rd sectors of TC up to 1–9%, to hold the unique EM scale for the whole TC.

In 2009, within **ATLAS–GRID**, activity JINR participated in central Monte-Carlo production and analysis, in functional tests of distributed data management (DDM) systems, in so-called stress-tests of computer-network ATLAS infrastructure, in combined tests of LHC Computing System (STEP09), and in development and commissioning of distributed software. Furthermore, special courses were organized for teaching and consultation of JINR people on the subject of how to work within ATLAS GRID-environment. Within so-called SARA GRID-cloud, some works were carried out on preparation for delivering and development of data within ATLAS distributed computing group.

JINR staff members (partly directly at CERN) support the Distributed Computing system of ATLAS (ADC). The system includes a set of CERN-located servers which distribute calculation jobs over 11 Tier-1 computer centres as well as data transfer from the ATLAS detector. At the ADC servers main software services like Distributed Data Management system (DDM), Tier0 system, Panda, Ganga, pAthena and ADC Monitoring are installed. These programs have to work continually on stable basis. In a case of a problem appears it should be fixed quickly (in an hour).

In 2009 a full prototype of the real-time ATLAS remote control room was put into operation at the DLNP. One has now a possibility to watch all ATLAS subsystems and to control data flow in real time regime via this remote control system. In future this facility is planned to be used for remote shift and on-call expert duties of JINR people. The room will be used for teaching JINR shifters as well.

The work on application of the **SANC** results to LHC physics has been carried out since 2004. SANC currently includes theoretical predictions for practically all three-particle and many four-particle processes of the Standard Model at the one-loop accuracy level. Over the period under review, the SANC group performed the precise analysis of Drell–Yan type processes, which together with inclusion of the simplest QCD processes in the SANC environment and allowance for the contribution from photon subprocesses practically brought to the end this part of investigations. Then the group carried out precise calculations of the probabilities for semileptonic decays of the top quark. Now these calculations are extended to the quark modes of the top quark decays and the single top quark production processes. It is assumed that during 2010 the SANC system will be extended for more complicated processes and work will start on its application to LHC physics [14].

The main purpose of the **DIRAC** experiment is the lifetime measurement of $\pi^+\pi^-$, π^+K^- and π^-K^+ atoms to test precise predictions of low-energy QCD. In 2008 the full setup tuning, including detectors and electronics, was finished. The six-month run for the setup tuning and data-taking with a Ni target at the upgraded DIRAC setup was carried out for observation of atoms consisting of π^+K^- and π^-K^+ mesons and for lifetime measurement of $\pi^+\pi^-$ atoms with an accuracy better than 6%. Processing and analysis of the data collected in 2001–2003 was finished, the $\pi^+\pi^-$ atom lifetime was found with an accuracy of 10%. In 2009 DIRAC took data during six months for observation of the atoms consisting of π and K mesons and improvement of the accuracy in the lifetime measurement of $\pi\pi$ atoms. The data collected exceed the amount of the 2008 data by 60%. The first results on searching for πK atoms were published. In total, 173 ± 54 πK-atomic pairs were observed with a significance of 3.2σ [15].

Extensive analysis has been completed for the data obtained with the **ANKE** setup at COSY-Jülich on reaction of the deuteron breakup $pd \to \{pp\}_S n$ with forward emission of a fast proton pair $\{pp\}_S$ in the ${}^1S_0$ state at 0.5–2.0 GeV proton beam energies [16]. In the collinear geometry used, the process involves high-momentum transfer and hence is sensitive to the nucleon structure at short distances. The differential cross sections and angular dependences in the range of proton pair emission angles $0{-}12^\circ$ and the cross-section energy dependence are measured. The distributions obtained at the relative energy less than 3 MeV and in the proton direction in the pp rest frame confirm the ${}^1S_0$ state of the proton pairs.

As a preliminary stage of the **PAX** experiment, the cross section of the spin transfer from polarized protons to electrons has been measured at COSY [17]. The cross section happened to be several orders of magnitude less than predicted by some of theoretical papers which proposed to use the process of spin exchange between electrons and (anti)protons in order to polarize the accelerator beam. Therefore, the measurements have demonstrated that another method, initially proposed in the PAX project, keeps to be a single feasible method to polarize the antiproton beam in a storage ring.

The QCD studies will be continued in experiments at the new facility FAIR, which is under construction at GSI. In particular, for the **PANDA** experiment Dubna physicists were working on the development of the physics programme, data analysis and preparation of the project of Dubna participation in the detector construction. The project was presented and was approved by the PAC in January 2010.

A compact superconducting isochronous cyclotron **C400** has been designed at IBA (Belgium) in collaboration with JINR. This cyclotron can accelerate all ions with the charge-to-mass ratio 0.5. The ${}_{12}C^{6+}$ and ${}_{4}He^{2+}$ ions will be accelerated to the energy 400 MeV/u and extracted by the electrostatic deflector, H_2^+ ions will be accelerated to the energy 270 MeV/u and extracted by stripping. The design review of the **K1600** cyclotron was a great success. The group of international experts emphasized high quality of the research done by JINR. The project will be ready for construction in the nearest future. Reports on the status of the C400 project were issued regularly [18].

The main goal of the topic **«Further Development of Methods and Instrumentation for Radiotherapy and Associated Diagnostics with the JINR Hadron Beams»** is to carry out medicobiological and clinical investigations of cancer treatment, to upgrade equipment and instrumentation, and to develop new techniques for treatment of malignant tumours and for associated diagnostics with medical hadron beams of the JINR Phasotron at the Medico-Technical Complex (MTC) of DLNP.

Regular sessions of proton therapy aimed at investigating its effectiveness for treating different kinds of neoplasm were carried out in collaboration with the Medical Radiological Research Centre (Obninsk) and the Radiological Department of the Dubna hospital. Six treatment sessions of total duration 28 weeks have been carried out. One hundred and six new patients were fractionally treated with the medical proton beam. The total number of the treated patients exceeded 595. The total number of the single proton irradiations (fields) exceeded 5650. Other 30 patients were irradiated at Co-60 gamma-therapy unit «Rokus-M». In collaboration with the Division of Radiation Dosimetry of the Institute of Nuclear Physics (Prague, Czech Republic), works were performed on measurements of control of dosimetry calibration of the Rokus-M gamma-therapy unit after source re-charge.

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