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 $(4-7)\cdot 10^{-12}\ \mu_B$. 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 center. Analysis of the first phase allowed 6200 and 2064 h for the reactor ON and OFF periods to get a new neutrino magnetic moment upper limit of $5.8\cdot 10^{-11}\ \mu_B$. Preliminary analysis of the second phase (6798 h ON and 1020 h OFF), performed together with the first one gives $(3.8-4.0)\cdot 10^{-11}\ \mu_B$. The third phase was started in June 2008, it is in progress and is planned to go on up to the autumn 2009. As a result, the sensitivity at the level of $(2.0-2.5)\cdot 10^{-11}\ \mu_B$ is expected.

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 (LSM) located in the Frejus tunnel at a depth of 4800 m water equivalent.

In 2008, the double-beta decay of ^{100}Mo to the 0_1^+ and 2_1^+ excited states of ^{100}Ru was studied using the NEMO-3 data. After the analysis of 8024 h of data taking the half-life for the two-neutrino double-beta decay of ^{100}Mo to the excited 0_1^+ state is measured to be $T_{1/2}(2\nu\beta\beta) = (5.7^{+1.3}_{-0.9}(\mathrm{stat.}) \pm 0.8(\mathrm{syst.}))\times 10^{20}$ y. The signal-to-background ratio is 3. Information about energy and angular distributions of emitted electrons was also obtained. No evidence for neutrinoless double-beta decay to the excited 0_1^+ state was found. The corresponding half-life limit is $T_{1/2}(0\nu\beta\beta)(0^+ \to 0_1^+) > 8.9\cdot 10^{22}$ y (at 90% C.L.). The search for the double-beta decay to the 2_1^+ excited state allowed the determination of limits on the half-life for the two-neutrino mode $T_{1/2}(2\nu\beta\beta)(0^+ \to 2_1^+) > 1.1\cdot 10^{21}$ y (90% C.L.) and for the neutrinoless mode $T_{1/2}(0\nu\beta\beta)(0^+ \to 2_1^+) > 1.6\cdot 10^{23}$ y (90% C.L.) [1].

The main purpose of the **GERDA** (GErmanium Detector Array) experiment is to search for neutrinoless double-beta decays of ^{76}Ge. GERDA will operate with bare germanium detectors (enriched in ^{76}Ge) situated in liquid argon (LAr). The experimental setup is under construction in the underground laboratory of LNGS (Italy). The main parts of the GERDA setup were installed in November 2008. Eight enriched germanium detectors of HdM and IGEX are handled, characterized and tested, the same energy resolutions as previously are obtained. They are being refurbished for mounting in the cryoliquid. The LArGe test facility with one ton of liquid argon is designed. All elements of LArGe are produced and prepared for installation. The commissioning of the completed GERDA setup is scheduled for 2009.

The GERDA collaboration consists of about 80 physicists from 13 institutions coming from five countries. Scientists from JINR participate in the most important parts of the collaboration tasks. The radioactivity of a large fraction of the construction materials was measured by several low-background Ge gamma-spectrometers, in particular at JINR. The special facility for development and construction of a scintillator veto was prepared. Several modifications of the muon veto modules on the basis of plastic scintillator and optical fibers were developed and tested. As a result, the optimal modules were chosen and created. The first lot (10 of 40) of plastic scintillator modules was assembled, equipped with electronics and tested at JINR.

The point-like pure alpha source ^{148}Gd with the required activity has been prepared at JINR and incorporated in the Mini-LArGe setup to investigate its response function and uniformity of the light collection. With this source a good transparency of the LAr scintillator at the 0.5 m scale was demonstrated. A special system for coordinate manipulation with the alpha source inside the up-scaled LArGe facility was created. It was shown that Ge crystals can work directly in liquid argon with the leakage current and energy resolution corresponding to their standard values. Their parameters are stable after a few dozen cycles of removing from and submerging in the liquid gas. It shows the feasibility of the overall GERDA project.

Investigation of double-beta decay processes ($\beta^+\beta^+$, β^+EC, EC/EC) of ^{106}Cd was performed at the Modane underground laboratory using a low-background 32 detector spectrometer **TGV-2** (Telescope Germanium Vertical) with a total sensitive volume of ~ 400 cm^3 (about 3 kg of Ge). The evaluation of the experimental data accumulated for $\sim$ 10000 h of measurements (2007–2009 years) was made and the limit on the $0\nu EC/EC$ decay of ^{106}Cd $T_{1/2} \geqslant 1.5 \cdot 10^{20}$ y (90% C.L.) was obtained. The new limit on the half-life of the $2\nu EC/EC$ decay of ^{106}Cd was obtained: $T_{1/2} \geqslant 4.5 \cdot 10^{20}$ y (90% C.L.). The limits on the half-lives of other branches of ^{106}Cd decay were improved (at 90% C.L.): $T_{1/2}(2\nu\beta\beta^+) \geqslant 1.4 \cdot 10^{20}$ y and $T_{1/2}(2\nu\beta^+EC) \geqslant 1.1 \cdot 10^{20}$ y for the $0^+ \to 0^+$, g.s. transitions, $T_{1/2}(2\nu\beta^+\beta^+) \geqslant 1.6 \cdot 10^{20}$ y, $T_{1/2}(2\nu\beta^+EC) \geqslant 1.1 \cdot 10^{20}$ y and $T_{1/2}(2\nu EC/EC) \geqslant 6 \cdot 10^{19}$ y for the $0^+ \to 2^+$, 512 keV transitions, $T_{1/2}(2\nu\beta^+EC) \geqslant 1.5 \cdot 10^{20}$ y and $T_{1/2}(2\nu EC/EC) \geqslant 5 \cdot 10^{19}$ y for the $0^+ \to 0^+_1$, 1334 keV transitions [2].

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 Laboratoire Souterrain de Modane. EDELWEISS uses high purity Germanium cryogenic detectors with simultaneous measurement of phonon and ionization signals at a temperature about 20 mK. All parameters of the EDELWEISS-II setup were validated in 2006–2007 with calibration and low-energy background runs. The mean phonon channel energy resolution (for a charge collection voltage of 5 V) was measured to be 2 keV, while the best results are at a level of 1.2 keV for the Ge/NTD detectors. Energy resolutions of the ionization channels were around 1.5–2 keV. Gamma discrimination capabilities above 10^4 were measured. Now a low-backgrounds physics run is in progress with the 28-detector setup with the aim to reach sensitivity to the WIMP nucleon cross section of $\sim 10^{-7}$ pb for a WIMP mass of 100 GeV. Forty detectors will be added in the coming two years to enhance progressively the sensitivity to WIMPs [3–5].

Within the framework of the E391a experiment the analysis of the data earlier obtained is continued. The new upper limit for branching ratio of the $K^0_L \to \pi^0 + \nu + \nu$ decay $6.7 \cdot 10^{-8}$ (90% C.L.) is experimentally defined. The measured experimental value is now the most accurate in the world. The analysis of the work of the E391a main barrel calorimeter is carried out. Search for a new pseudoscalar particle in $K^0_L \to \pi^0\pi^0 + X$ decays is made. Such a particle with a mass of 214.3 MeV/c^2 was suggested by the HyperCP experiment. No evidence for X was found, and the upper limit on the branching ratio was set to be $2.4 \cdot 10^{-7}$ at 90% C.L. [6–8].

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. Data for $4.7 \cdot 10^6$ raw $\pi \to e\nu$ events were recorded, before analysis cuts are applied, the statistical uncertainty was $\dfrac{\delta B}{B} = 5 \cdot 10^{-4}$ [9].

In 2008, the first data-taking run was conducted with the **MEG** detector to search for the $\mu^+ \to e^+\gamma$ decay at a level of 10^{-14}. While this decay is forbidden in the Standard Model, some fundamental theories predict it at a level of about 10^{-14} to the main decay mode. Even nonobservation of the decay at the foreseen level of sensitivity would place a stringent constraint on these theories and on the general nature of the new physics.

In 2008, the **OPERA** experiment had a first long data-taking run with almost full intensity of the LNGS beam. About 1680 neutrino events were registered in the detector. In 2009, about 2500 new events are expected in the OPERA target. This means that the total number of the events registered together with the events of 2008 should be enough to find the first tau-neutrino in the CNGS muon neutrino beam. This will be the first observation of the neutrino oscillations in the appearance mode. So far, the experimental data have demonstrated the effect of oscillations only in the disappearance mode.

In 2008, the JINR group, along with active participation in the data-taking at LNGS, created the first automatic emulsion scanning station identical to those used by other OPERA participants. Along with this work, the activity related to the development of the software for the «brick finding» — localization of the neutrino event vertices — actively continued. For the simulated events, the efficiency of the vertex location in the first most probable brick was found to be $\sim 75\%$; in two most probable bricks — 87%. In 2008, when a large amount of real events became available, the efficiency was checked and the algorithms of the track reconstruction and hadronic shower analysis were tuned.

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 improvement of the result of the ^{7}Be solar neutrino flux measurement. At present a new analysis based on 192 live-days of data has been performed. The final result on the ^{7}Be neutrino flux is $49 \pm 3(\text{stat.}) \pm 4(\text{syst.})$ cpd/100 t of scintillator [10]. 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 C.L.

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% C.L.

The **TUS** space experiment has been proposed to address some of the most important astrophysical 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.

A few international space experiments like TUS/KLYPVE and JEM-EUSO are under preparation to increase statistics up to a factor of 100 together with a higher accuracy and additionally with the global data-taking: the latter is important for the search for the UHECR sources in whole sky space.

JINR and the ENERGY corporation are responsible for the design, production, and tests of the optical system based on the multimodule Fresnel mirror of complicated structure 1.8 m in diameter. A technological mirror prototype was produced using precise molds that were made and measured in Dubna.

The main aim of the **NUCLEON** experiment is measurement of 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. This measurement is motivated by the «knee» problem: a change in the slope and composition of the cosmic rays energy spectrum from $E^{-2.7}$ to $E^{-3.0}$ at energies about 10^{15} eV. The JINR responsibility is the design, production and tests of the scintillator trigger system including DAQ electronics, etc.

The beam test of the technological trigger system prototype was carried out in 2008 at the CERN SPS H2 test beam. Data were taken at different NUCLEON apparatus orientations with respect to the beam direction to check the trigger rejection efficiency.

PARTNERSHIP PROGRAMS AT UNIQUE ACCELERATORS

The main results of the **JINR/CDF** group in 2008 are the measurement of the top-quark mass (M_{top}) and the efficient operation of the CDF II. A contribution of principal significance to precise single M_{top} measurement in the «dilepton» mode at the integrated luminosity of 2.9 fb^{-1}, $M_{\text{top}} = 165.5^{+3.4}_{-3.3}(\text{stat.}) \pm 3.1(\text{syst.})$ GeV/c^2 was made [11, 12]. 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 3.0 fb^{-1} of the data analyzed at the CDF, and at DO, the 95% C.L. upper limits on Higgs boson production are a factor of 1.2, 1.0 and 1.3 higher than the SM cross section for a Higgs boson of mass $m_{\text{H}} = 165$, 170 and 175 GeV, respectively. The TEVATRON excluded the standard model Higgs boson of $m_{\text{H}} = 170$ GeV at 95% C.L. 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 [13].

In the framework of **D0** experiment the first direct observation of the beauty baryon Ω_b was performed. This discovery has been ranked among the few most significant achievements in physics in 2008 by the American Physical Society.

The Beijing electron–positron collider BEPC-II produced the first collisions in July 2008 in the detector **BES-III**, after several years of upgrading. Luminosity of $1.2 \cdot 10^{32}$ cm$^{-2} \cdot$ s^{-1}, which is 12% of the design value, is currently achieved. 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 program 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. Study of two-photon collisions at the BES-III was continued. A dedicated Monte-Carlo event generator was developed to provide a reliable tool for calculating hadron production in two-photon reactions at low energies. The JINR group studies selected decays of scalar charmonium states and D^0. A method to measure the branching ratio and decay product polarization for the $D^0 \to K^* + \rho^0$ decay was proposed. Preliminary Monte-Carlo study was carried out. It was shown that an accuracy comparable with the current PDG value can be achieved during the first stage of data-taking (1–2 months at luminosity 10% of nominal).

During 2008, 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 multibody 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, 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 [14].

Within the framework of the **ATLAS TileCal** project the pion energy reconstruction is performed by the new local hadronic calibration method on the basis of the 2004 combined test beam data in the energy range 10–350 GeV and $\eta = 0.25$ [15, 16]. In this method energies deposited in each cell are weighted. The weights are determined by the Monte-Carlo simulation. This method was modified by applying cuts in weights. The fractional energy resolution obtained with the conventional method of determination of the energy deposit in the dead material between the LAr and Tile calorimeters is $(67 \pm 2)\%/\sqrt{E} + (3.9 \pm 0.2)\% + (95 \pm 22)\%$. The energy linearity is within $\pm 1\%$. A neural network algorithm is developed and used to calculate energy loss of the hadronic shower in the dead material of ATLAS calorimeters. The energy resolution reached the design value for hadrons in the ATLAS detector $50\%/\sqrt{E} + 3\%$. A unique method for measurement of the noncompensation of the electromagnetic calorimeter is proposed and implemented. The noncompensation of the central liquid-argon electromagnetic calorimeter of the ATLAS experiment is measured to be $e/h = 1.74 \pm 0.04 \pm 0.04$. The developed method for measurement of the electron energy in the hadronic tile calorimeter allowed its noncompensation to be determined to a better accuracy, $e/h = 1.36 \pm 0.01 \pm 0.01$. Thorough electromagnetic calibration was carried out for 12% of the hadronic tile calorimeter modules, which allowed its energy scale to be set. A method for local hadronic calibration of the ATLAS calorimeter system is developed and implemented, which allows the energy of single hadrons to be determined with the design accuracy [17, 18].

Over the period under review, setting-up of the **JINR computer center** was carried out to adapt it to reception and processing of the data, preparation for the data analysis using Grid began, and establishment of the ATLAS monitoring station at JINR was practically completed. Participating in the EGEE–RDIG consortium, the Russian node of the Grid network, JINR plays the role of one of the simulation and data analysis centers **(Tier-2)** for ATLAS. In the late 2005, the ATLAS experiment software was installed in the computers of the common-access framework of the JINR Central Computer Complex; it is maintained and regularly upgraded. The data storage element of the central computer complex was integrated into the ATLAS Distributed Data Management (ATLAS DDM). JINR took part in overall tests of the system, which showed reliable operation of the computer center and, first of all, the JINR storage element as part of the ATLAS DDM. It was demonstrated that JINR is ready to receive the first ATLAS data.

A large amount of ATLAS data makes it impossible to employ traditional methods of analysis and requires special software for handling geographically distributed data. This complicates preparation for physical analysis and requires retraining of specialists. Since 2006, the work on mastering the distributed ATLAS data analysis programs (GANGA and PANDA) has been going on at JINR. User's programs for physical analysis are being adapted to provide wide access to Grid capabilities. Specialists are trained in data analysis using Grid. In 2007–2008, four training courses on the use of Grid tools in the distributed ATLAS data analysis were given to both JINR staff members and to specialists from other Russian research centers (ITEP, MEPI, PNPI, IHEP, MSU INP).

Modern information technologies make it simple to manage and monitor the ATLAS detector and allow the necessary data on its condition to be obtained practically from any point of the globe. To make this possibility available for JINR, it was decided to establish an ATLAS remote monitoring station JINR, which will allow anybody, including subsystem experts, to get the ATLAS status data at any time and to assess data quality directly from JINR. Now a possibility of remote participation in shifts is under consideration. The ATLAS remote monitoring station will also allow the staff members to get acquainted with the ATLAS monitoring and data quality assessment system and to be trained in using special software before taking part in data-taking runs at CERN. The work on establishing the ATLAS monitoring station at JINR was started in 2007. The groups of specialists from the Laboratory of Information Technologies (headed by V. M. Kotov) and the Dzhelepov Laboratory of Nuclear Problems (headed by A. S. Zhemchugov) took an active part in develop-

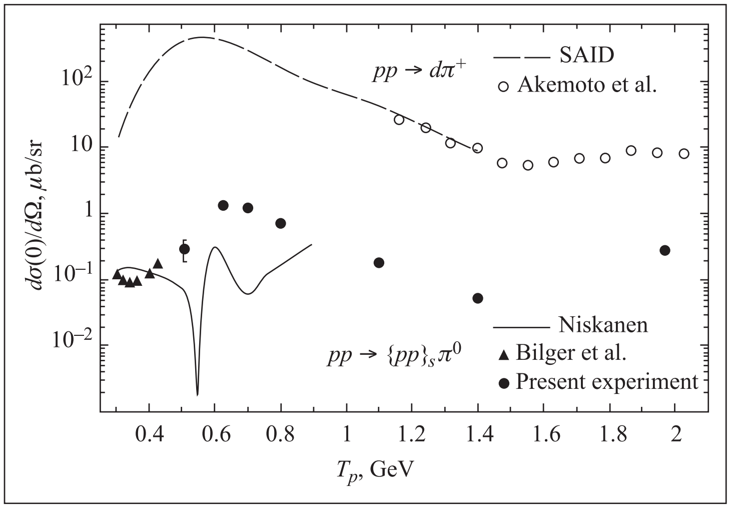

Fig. 1. Differential cross section of $pp \to \{pp\}_s + \pi^0$ (full circles), model predictions (J. Niskanen, full line) and comparison with the $pp \to d + \pi^+$ data (dashed line and empty circles)

ment of the ATLAS remote monitoring and data quality assessment software. The ATLAS remote monitoring station at JINR was put into service in October 2008.

In 2008, the JINR group worked mainly on the application of the **SANC** system to the LHC and e^+e^- collider physics. Its present status includes theoretical predictions for practically all Standard Model (SM) $1 \to 2$ and $1 \to 3$ decays and many $2 \to 2$ processes at the one-loop precision level. SANC version v1.10 is available at the servers at CERN http://pcphsanc.cern.ch/ and Dubna http://sanc.jinr.ru/.

The group continued precision study of Drell–Yan processes [19–21], which practically completed a large part of research in this direction. The precision calculations of various decay and production channels of the top-quark were continued. The study of fermion–boson processes, $ffbb$, at the partonic level was continued [22]. After a convolution with parton density functions, the processes $pp \to HZ, H, Z, ZZ$ are of interest for LHC physics and e^+e^- annihilation for electron linacs.

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 were finished, the $\pi^+\pi^-$ atom lifetime was found with the accuracy of 10%, and the results are ready for publication. The program for the off-line data analysis was updated in order to decode and analyse the data collected by new electronics modules of the upgraded DIRAC setup. The data collected in 2007 were processed and the paper about the search for the atoms consisting of π^+K^- and π^-K^+ mesons is prepared on the basis of these data.

In 2008, under the **SPRING** project the reaction $pp \to \{pp\}_s + \pi^0$ was studied in a wide energy range of 0.5–2.0 GeV with detection of a $^1S_0$ pp pair. This reaction is a kinematical analog of the well-studied process $pp \to d + \pi^+$, but the dominating contribution of the intermediate state Delta-isobar is suppressed due to spin-parity constraints, and therefore other mechanisms may become visible. The energy (Fig. 1) and angular dependences of the differential cross section were measured, the ratio of singlet and triplet matrix elements was deduced from the comparison with the $pp \to d + \pi^+$ data.

The process of inverse diproton photodisintegration, $pp \to \{pp\}_s + \gamma$, was observed for the first time at intermediate energies. Similar to the extensively studied

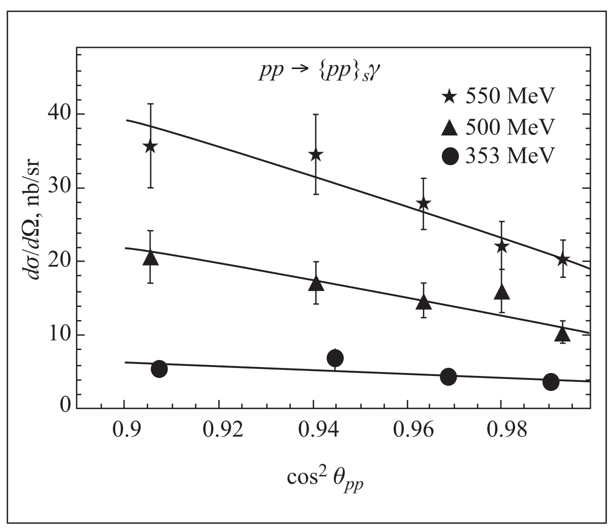

Fig. 2. Angular dependence of the differential cross section of $pp \to \{pp\}_s + \gamma$

deuteron photodisintegration, it gives information about NN interactions at short distances. Previous experiments on diproton photodisintegration were fulfilled using diproton configurations contained within light nuclei, and therefore suffered from large background arising from three-nucleon absorption. In contrast, the decay $pp \to \{pp\}_s + \gamma$ with free diprotons in the $^1S_0$ state involved is completely free of such complications. The angular dependence of the differential cross section was measured at the beam energies 0.35, 0.5 and 0.55 GeV (Fig. 2). Though the S-wave contribution of ΔN in the intermediate state is suppressed, the observed increase in the cross section with increasing energy may be explained by excitation of Δ in higher-order waves [23–26].

APPLIED SCIENTIFIC RESEARCH

A compact superconducting isochronous cyclotron **C400** has been designed at IBA (Belgium) in collaboration with JINR (Dubna). Carbon ions beams with energies up to 400 MeV/u are successfully used to treat radioresistant tumours. This cyclotron can accelerate all ions with the charge-to-mass ratio 0.5. Ions $_{12}C^{6+}$ and $_4He^{2+}$ 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 present status of the C400 design may be summarized as follows: the isochronous magnetic field with adequate focusing characteristics and optimized extraction is obtained by computer simulation with the 3D TOSCA code; beam dynamic simulations are done with multiparticle tracking codes for the acceleration and extraction regions; the axial injection line, inflector and central region are designed; ion losses due to residual gas interaction are calculated. A group of international experts emphasized the high quality of the research work done by JINR. The project will be ready for construction in the nearest future.

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 medico-biological 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.

The regular sessions of proton therapy aimed to investigate its effectiveness 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, total duration of 26 weeks, have been carried out. 87 new patients were fractionally treated with the medical proton beam. The total number of the single proton irradiations (fields) exceeded 4500. Other 27 patients were irradiated with Co-60 gamma-therapy unit «Rokus-M». The planned recharging of radioactive source in the gamma-therapy unit «Rokus-M» was carried out, which allows using the unit for clinical and radiobiological investigations till 2018.

Radiobiological research on the regularities of the manifestation of the adaptive response and «bystander» effect of the combined irradiation of fibroblast cells by different kinds of ionizing radiation was also continued.

Based on the results of experiments of the recent several years a patent for the invention is obtained: RU 2 330 695 C2 — method of protection against the damaging action of ionizing radiation in the experiment (authors: Voskanyan K. S., Mytsin G. V., Gaevskiy V. N.).

The research on chromosomal damages in cells at different stages of the cells cycle after the proton beam irradiation was continued in collaboration with the Laboratory of Radiation Biology using the model of human blood lymphocytes.

Within the framework of the fundamental research on radiation biology of animal and human genes, the first experiments on the study of heritable DNA alterations at the mini-gene black of Drosophila melanogaster after action of Co-60 gamma-rays were performed. The work on 2D–3D simulation and visualization of higher-order organization of the entire haploid male germ cell genome was successfully continued in collaboration with LIT, JINR and the Megarosette-loop model for such a genome was developed [27, 28].

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