DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS

NEUTRINO PHYSICS AND RARE PHENOMENA

In 2013, the DLNP group within the **Daya Bay** collaboration performed two new analyses of the number of interaction events involving antineutrinos produced by the Daya Bay and Ling Ao reactors in the near/far detectors filled with Gd-doped liquid scintillator. The first analysis [1] was aimed at searching for antineutrino disappearance using the rate-only information (ignoring antineutrino energy) and about three times larger number of events than was used in the 2012 analysis which led to the discovery of the nonzero value of θ_{13} value. As a result the value $\sin^2 2\theta_{13} = 0.089 \pm 0.01\,(\text{stat.}) \pm 0.005\,(\text{syst.})$ was found. The second analysis [2] was based on even larger statistics and antineutrino energy information. The result was a further improved value of the oscillation amplitude $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ and the mass-squared difference $\Delta m^2_{ee} = 2.59^{+0.19}_{-0.20}$.

In 2013, the **OPERA** experiment continued to analyze the data collected at the CNGS neutrino beam over the period of 2008–2012. During five years of operation, OPERA collected about 18,000 neutrino interactions in the detector target, among them 56 charm events, 32 electron-neutrino events, and 3 tau-neutrino events. The discovery of the third tau-neutrino event in the muon mode was reported at the summer conferences. Now the analysis of the data continues at ten institutes in Japan and Europe (including JINR), where the automatic scanning stations are available. In 2013, efficiencies and backgrounds in the detector were revised. With these new estimations, observation of the three tau-neutrino events has a significance of 3.4σ, which is the evidence for $\nu_\mu \to \nu_\tau$ oscillations in the appearance mode.

In 2013, the main result of the collaboration **Borexino** is a new measurement of the geo-neutrino flux [7]. The results of the first stage of the Borexino experiment on the solar neutrino measurements are summarized in [8], where details of the previous measurements performed and new results of searching for seasonal variations of the Be-7 neutrino flux are presented. A paper on the study of the muon flux backgrounds [9] was published. The Borexino data were used to set limits on the heavy sterile neutrino mixing in the 8B decay. These limits are tighter than those obtained in previous laboratory-based experiments using nuclear reactors and accelerators [10].

In 2013, the **EDELWEISS** collaboration was busy testing and calibrating newly installed detectors with active rejection of the surface background. Novel 800-g FID detectors with a significantly increased fiducial volume were commissioned. Developed in 2012–2013, the FID800 detectors technology, fully interdigitized 800-g detectors with all surfaces covered by ring electrodes, shows at least an order-of-magnitude improvement of surface background suppression. About 10 kg of new detectors were tested and calibrated in 2013. Together with the new detectors the whole experimental setup was updated in 2013. First of all, the cryogenic system and shielding were improved, and new fast data acquisition was used [11, 12].

The **NEMO-3/SuperNEMO** project is aimed to search for neutrinoless double-beta decay ($0\nu\beta\beta$), which would be an indication of new fundamental physics beyond the Standard Model, such as the absolute neutrino mass scale, the nature of neutrino (either Dirac or Majorana), and neutrino hierarchy. Observation of $0\nu\beta\beta$ would also help to resolve the topical puzzles of fundamental physics: CP violation, leptogenesys, GUTs. The main advantage of the NEMO-3 /SuperNEMO project is a unique potentially zero-background tracking-calorimetric equipment, which allows obtaining full $\beta\beta$-signature consisting of electron tracks and energies measured in the Geiger chamber and the calorimeter, respectively. This will allow testing the $0\nu\beta\beta$-mode mechanism if discovered. The final analysis of the NEMO-3 data was carried out in 2013. The obtained limit $T_{1/2}$ $(0\nu\beta\beta) > 1.1 \cdot 10^{24}$ y (90% C.L.) corresponds to the limit on the effective neutrino Majorana mass $\langle m_e \rangle < 0.3{-}0.8$ eV, which is compatible with the best world $\beta\beta$-results [13]. The analysis of the final NEMO-3 "$\beta\beta$-factory" results ($0\nu\beta\beta$ and $2\nu\beta\beta$ modes for ^{100}Mo, ^{82}Se, ^{116}Cd, ^{130}Te, ^{150}Nd, ^{96}Zr, and ^{48}Ca) is in progress [14].

The **GERDA** experiment is aimed to search for the neutrinoless double-beta decay of ^{75}Ge using naked HPGe detectors of enriched ^{76}Ge which are immersed in liquid argon (LAr). Phase-I of the GERDA experiment was completed in 2013. Data for analysis were collected between November 2011 and May 2013 with a total exposure of 21.6 kg · y. The ultralow background level of $1 \cdot 10^{-2}$ counts/keV · kg · y was achieved after pulse shape discrimination. No signal was observed and a lower limit was obtained for the half-life of the neutrinoless double-beta decay of ^{76}Ge, $T_{1/2} > 2.1 \cdot 10^{25}$ y (90% C.L.). The combination with the limits from the previous HdM and IGEX experiments yields $T_{1/2} > 3.0 \cdot 10^{25}$ y (90% C.L.), and in this case the probability of the positive effect corresponding to $T_{1/2} = 1.19 \cdot 10^{25}$ y is estimated at 0.02% [15, 16]. Intensive preparation for GERDA Phase-II started.

In 2013, the **Baikal** project moved from trying out the elements of the detector to mounting the first cluster of the NT100 neutrino telescope with an effective volume of 1 km^3. During the winter expedition of 2013, three full-scale strings of the cluster were assembled and the setup was put into operation as a complete detector with all elements and systems of the cluster. The primary analysis of the data showed highly stable operation of the detecting elements and confirmed the expected accuracy of the measuring systems and the efficiency of the calibration methods as well as the event selection and noise suppression procedures.

A system for remote control and monitoring of the telescope was developed and constructed. Analysis of the results obtained in the field tests of pilot strings for the NT100 detector showed a quite high quality of the main string elements, such as the optical detection system, data acquisition and transfer system, cable lines and basic units. The scene is set for commissioning in 2015 the first cluster of the NT100 neutrino telescope comparable in aperture with the ANTARES detector.

HIGH-ENERGY PHYSICS

In 2013, the search for supersymmetric particles by **ATLAS** at the LHC in $p{-}p$ collisions at the initial energy of 8 TeV was continued. The data with the integrated luminosity 20 fb^{-1} were analyzed in final states containing at least one isolated lepton (electron or muon), with and without b-jet requirements, and large missing transverse momentum. No significant excess above the Standard Model expectation is observed. The results are used to set limits on s-particle masses for various simplified models covering the pair production of gluinos, first and second generation s-quarks and top s-quarks. Limits are also set on the MISUGRA/CMSSM model and on the parameters of the minimal Universal Extra Dimension model [17].

Predictions were made that a signal of the Fock states in proton, intrinsic charm (IC), could be observed at ATLAS in the production of prompt photons or vector bosons (W) in $p{-}p$ collisions accompanied by the c- or b-jets, respectively. The MC calculations showed that inclusion of these states in the PDF could increase spectra of photons or c- and b-jets, and leptons from the W decay versus their transverse momentum by a factor of about 2–3 at large p_T ($p_T > 100$ GeV/c) in comparison to the calculations that do not include the IC contribution.

A new theoretical interpretation of the ATLAS data on spectra of charged hadrons produced in $p{-}p$ collisions at not large transverse momenta was made. The distribution of the nonperturbative gluons at small transverse momenta was calculated and its parameters were found from the best description of the ATLAS data. It was shown that analyzing these data one could find information about the saturation scale of the gluon distribution at low transfer momentum squared Q^2 [18, 19].

The main results of the **CDF** project are the "Tevatron average" mass of the top quark obtained with the total uncertainty reduced to 0.87 GeV/c^2, study of the correlations in high-multiplicity charged hadron events, Dubna tests of the LYSO-type crystals to be used as elements of the e.m. calorimeter for the Mu2e experiment at FNAL, and tests of the scintillator counter efficiency in the neutron beam.

Using top-antitop pairs at the Tevatron proton-antiproton collider, the **CDF** and **D0** Collaborations with the Dubna group contribution measured the top quark mass in different final states for integrated luminosities up to 8.7 fb^{-1}. The combination of these measurements results in a more precise value of the mass than any individual decay channel can provide. Considering the correlated uncertainties, the resulting

Tevatron average mass of the top quark is $M_{\rm top} = (173.20 \pm 0.51\,(\mathrm{stat.}) \pm 0.71\,(\mathrm{syst.}))$ GeV/c^2, which corresponds to a total uncertainty of 0.87 GeV/c^2, which has a precision of $\pm 0.50\%$ [20], making this the most precise determination of the top-quark mass.

In 2013, the R&D was done for the future experiments at FNAL: tests of LYSO-type crystals to be used as elements of a new-generation e.m. calorimeter of the Mu2e FNAL experiment; tests of the scintillator counter efficiency in the neutron beam; a comparison of $30 \times 30 \times 130$ mm crystals from SICCAS, Saint-Gobain and Zecotek. For the Mu2e Collaboration, the effect of the neutron background on the Mu2e cosmic ray veto system was investigated and test measurements of the plastic scintillator counter were performed on the neutron beam line of the IBR-2 facility at JINR, Dubna [21].

In 2013, the Dubna group participating in the **D0** experiment, Fermilab, completed a new measurement of the important processes which were produced in proton-antiproton collisions at the summed Tevatron beam energy of 1.96 TeV and had highly energetic photons and associated jets in the final state. The comparison of the results [22] with the predictions of Quantum Chromodynamics indicated the necessity to refine the theoretical tools for describing strong interactions in a number of kinematical regions like the regions of large and small values of direct photon transverse momentum and for explaining the dependence on the relative orientations of the photon and the jet.

Within the framework of the **DIRAC** experiment, analysis of πK data collected in 2008–2010 was completed, the lifetime of $K^+\pi^-$ and π^+K^- atoms was preliminary estimated at $\tau = 2.5^{+3.0}_{-1.8}$ fs. Preliminary analysis of the $\pi\pi$ data collected in 2008–2010 was completed. About 22000 $\pi^+\pi^-$ atom breakup events were identified which doubles the statistics for $\pi^+\pi^-$ atom lifetime measurement. Preliminary analysis of the 2011–2012 data allowed the first observation of the long-lived states of $\pi^+\pi^-$ atoms.

The **SANC** project includes theoretical predictions for many three- and four-particle Standard Model (SM) processes at the one-loop precision level (QCD and EW NLO). The main result of 2013 is updating and creation of new versions of Monte-Carlo tools (integrator and generator) for the analysis of the LHC data with allowance for the interplay of the next-to-leading (NLO) QCD and EW corrections [23, 24]. These tools, complemented with calculation of NNLO QCD contributions using programs by other groups, were already used for the analysis of the LHC data.

The **BES-III** experiment at the Beijing electron-positron collider BEPC-II continued to take data in 2013. The main goal was to collect data in the energy range 4.2–4.4 GeV to study XYZ states. The largest statistics was obtained around resonances $Y(4260)$ and $Y(4360)$. In March 2013, the BES-III experiment announced observation of a new charged charmonium-like state $Z_c(3900)$ in a system of a charged pion and a J/ψ resonance [25]. Later this observation was independently confirmed by the BELLE experiment and then by the CLEO-c data. The properties of the new state imply that it consists of at least four quarks unlike conventional mesons and baryons. Thus, this observation provides strong evidence that exotic hadrons which were predicted by QCD and then were hunted for about 30 years, do exist. Later, a similar state was observed in the reaction $e^+e^- \to DD^*$ [26].

The data samples collected with the BESIII detector operating at the BEPCII storage ring at center-of-mass energies from 4.009 to 4.420 GeV allowed the transition $e^+e^- \to \gamma X(3872)$ to be observed for the first time with a statistical significance of 6.3σ. The measured mass of $X(3872)$ is $(38719 \pm 0.7\,(\mathrm{stat.}) \pm 0.2\,(\mathrm{syst.}))$ MeV/c^2, in agreement with previous measurements. The products of the cross section $\sigma(e^+e^- \to \gamma X(3872))$ and the branching fraction $B(X(3872) \to \pi^+\pi^- J/\psi)$ at center-of-mass energies 4.009, 4.229, 4.260, and 4.360 GeV are also measured [27].

Using the largest sample of $\psi(3770) \to DD$ events collected in 2010–2011, the BES-III experiment provided the most precise measurement of $\mathrm{Br}(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})) \cdot 10^{-4}$ [28]. This measurement together with the CKM matrix element $|Vcd|$ determined from a global Standard Model fit, implies the weak decay constant value $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV. Additionally, using this branching fraction measurement together with a Lattice QCD prediction for f_{D^+}, we find $|Vcd| = 0.2210 \pm 0.0058 \pm 0.0047$. In either case, these are the most precise results for these quantities to date.

The orbital ultrahigh-energy cosmic ray (UHECR) detector **TUS** is prepared for launching on-board the Lomonosov satellite in 2014. The TUS space experiment is aimed to study the energy spectrum and arrival distribution of UHECR at energies above $\sim 10^{20}$ eV. The detector consists of a large Fresnel-type mirror-concentrator ~ 2 m^2 in area and a photo-receiver placed in its focal plane (matrix of 16×16 PM tubes with a spatial resolution in the atmosphere near 5 km). The final TUS apparatus preflight tests were carried out in 2013 in assembly with the Lomonosov space platform. JINR and the "Space Regatta" consortium of the Korolev center participated in the design, production and measurements of optical parameter of the segmented Fresnel mirror which is completely fulfilled [29].

Measurements of the CR spectrum, composition and anisotropy in the wide energy interval are an important part of the particle physics study. The energy range 10^{14}–10^{16} eV is crucial for understanding the CR origin, acceleration, and propagation in our Galaxy. The available data do not enough adequately interpret the nature of the "knee" in the framework of the CR acceleration mechanisms. The real progress in solving the problem would be possible only with a long-term and large-aperture satellite experiment like **NUCLEON,** which will supply statistically conclusive data. The JINR responsibility is the production of the NUCLEON trigger system, which includes a two-level trigger system of six scintillator strip layers and FE and DAQ electronics. Three trigger modules were produced and were tested in assembly with other detectors in the CERN SPS beam during 2009–2013.

One of the latest SPS heavy ion beam tests was carried out in February 2013. It was found that the charge measurement system discriminates the nuclei up to $Z \sim 30$ with an accuracy of 0.2–0.3, which is sufficient both for discriminating separate primary CR components and for studying the abundance of secondary nuclei in CRs at high energies [30]. The NUCLEON detector is planed to be launched with the Sojuz rocket in 2014 for 3–5 years of data taking.

LOW- AND INTERMEDIATE-ENERGY PHYSICS

The **SPRING** experiments were carried out with the ANKE setup at the COSY accelerator in the field of intermediate-energy hadron physics using polarized proton (deuteron) beams and/or polarized hydrogen (deuterium) jet targets. Studies of spin observables were carried out in the double polarized approach, i.e., with the use of a polarized deuteron beam and a polarized hydrogen target. In the quasi-free reaction $\vec{n}\vec{p} \to \{pp\}_s\pi^-$ at 353 MeV per nucleon, the spin correlation coefficients $A_{x,x}$, $A_{y,y}$ and the vector analyzing power A_y were measured [31]. Combined partial wave analysis of these data together with previous results on the differential cross section and A_y for $p\vec{p} \to \{pp\}_s\pi^0$ led to three different acceptable solutions. This ambiguity can only be resolved by measuring the spin correlation coefficient $A_{x,z}$ using a longitudinally polarized beam, which is planned for 2014.

For the first time in the quasi-free kinematics of ANKE, the spin correlation coefficients $A_{x,x}$ and $A_{y,y}$ were measured [32] in the reaction $\vec{n}p \to d\pi^0$ for neutron energies close to 353 and 600 MeV. The results are in good agreement with SAID predictions for the isotope-related reaction $pp \to d\pi^+$ no sign for any breaking of isotope invariance was found.

The differential cross section and two tensor analyzing powers A_{xx} and A_{yy} were measured for the reaction $d\vec{p} \to \{pp\}_s n$ at the deuteron energies 1.2, 1.6, 1.8, and 2.27 GeV. At 1.2 and 2.27 GeV the hydrogen target was also polarized which allowed the spin correlation parameters C_{xx} and C_{yy} to be measured. The results essentially complement the neutron–proton part of the SAID data base. Excitation of $\Delta(1232)$ isobar was studied [33] for the same reaction at 1.6, 1.8, and 2.27 GeV. Analysis of the differential cross section showed that the results could be described only partly by direct excitation of Δ in the single-pion exchange mechanism.

The **MEG** experiment is one of the PSI "flagship" particle physics experiments at the proton accelerator facility in Switzerland. The goal of the experiment is the search for the $\mu \to e\gamma$ decay with a branching ratio sensitivity of 10^{-13} in order to explore the region predicted by many theoretical models beyond the Standard Model. In 2013, the collaboration presented the analysis of a data sample of $3.6 \cdot 10^{14}$ muons stopped on the target, which was collected by the MEG experiment at the Paul Scherrer Institute (2009–2011) aimed at the detection of the lepton flavor violating muon decay $\mu^+ \to e^+\gamma$. No excess over the background expectations was observed: a new upper limit on the branching ratio of this decay is set at $5.7 \cdot 10^{-13}$ (90% C.L.) [34]. This limit is four times more stringent than the previous world best limit set by MEG.

Developing on the rare pion and muon decay results of the PIBETA experiment, the **PEN** collaboration performed precise measurement of the $\pi^+ \to e^+\upsilon(\gamma)$ decay branching ratio ($\mathrm{BR}_{\pi e2}$), at the Paul Scherrer Institute to reduce the current 40 times lag of the experimental accuracy behind theory to $\sim(6-7)$. Because of large helicity suppression, $\mathrm{BR}_{\pi e2}$ is uniquely sensitive to contributions from non-$(V-A)$ physics, making this decay a particularly suitable subject of study. Even at the current accuracy, the experimental value of $\mathrm{BR}_{\pi e2}$ provides the most accurate test of lepton universality. During the runs in 2008–2010, PEN accumulated over $2 \cdot 10^7 \pi^+ \to e^+\upsilon$ ($\pi e2$) events; a comprehensive maximum-likelihood analysis is currently under way. The new data will also lead to improved accuracy of the earlier PIBETA results on radiative π and μ decays.

In 2013, the full-scale test of the experimental installation **TRITON** was performed. In February 2013 in the course of preparation of the Phasotron infrastructure, a technical run was carried out to optimize the parameters of the negative muon beam channel in the low-background laboratory. The following results were obtained: muon pulse at 100 MeV/c, beam intensity $1.4 \cdot 10^4$ μ/s at the accelerator current of 0.5 μA. The experimental run with the polystyrene dummy target was performed in March 2013 to test simultaneously the registration and data collection systems. The cryogenic tests of the target were conducted in November 2013 using the acquired cryogenic equipment (MKC MCMP-1504-5/20) with a cooling capacity of 10 W at 20 K. The accuracy of maintaining the temperature of liquid hydrogen in the target for a long time (tens of hours) is no worse than 0.1 K. In December 2013, a 10-hour session of physical measurements was conducted with a target filled with liquid hydrogen and exposed to the muon beam. As many as 140 significant muon stops in hydrogen per second were obtained. The baseline energy and time spectra of experimental events of muon-catalyzed fusion in pure (without addition of tritium) hydrogen were measured. The measured yield of 10^5 γ-rays with energy $E_\gamma = 5.5$ MeV from the muon catalysis process in the $pd\mu$ system (at a natural deuterium concentration of 10^{-4} volume fraction) indicates correct operation of all components of the facility [35].

The activity carried out in 2013 within the **MUON** project was aimed at studying the behavior of the polarized muons in condensed matter. In diamond, it occupies the tetrahedral interstitial site (MuT) or bond-centre site (MuBC). The behaviour of the muonium in two polycrystalline diamond samples and in the sample composed of a few single-crystal synthetic diamonds was investigated. The value obtained for the constant of the hyperfine interaction of the muon and the electron at MuT in the synthetic diamond samples is in agreement with that for the natural diamond. The muon spin relaxation rates in the MuT and MuBC states in the synthetic and natural samples of the IIa and IIb type are similar. It was found that in the IIa type single-crystal sample at 150 K, the contributions of the diamagnetic muon, MuT, and MuBC fractions are 1.5%, 57%, and 8.1%, respectively. The missing fraction of the muon polarization was 33.4%. It is known that for MuBC there is a certain "magic" field where the muon spin precession frequency is nearly independent of the orientation of the crystal. This effect allows observing a MuBC [36].

Within the **NN-GDH** project, in the experiment on Compton scattering of polarized photons at the polarized proton target performed by A2 collaboration at the MAMI C accelerator, the world's first estimate was obtained for the proton spin polarizability, which is a fundamental structure constant describing the proton spin response to the changing electromagnetic field. This result opens, in principle, a possibility for a precision study of nucleon spin structure in electromagnetic interactions. Within the framework of the "complete experiment" program, the world's first measurements of the polarization observables E, G in the photoproduction of π^0 and η mesons and pion pairs on the protons and deuterons were performed using the beams of circularly and linearly polarized photons with a maximum energy of 1.5 GeV from the MAMI C accelerator and the target with longitudinal polarization of protons and deuterons. These data (in combination with the earlier results for the observables T and F) form a basis for amplitude and multipole analyses of individual meson photoproduction channels [37, 38].

APPLIED RESEARCH AND ACCELERATORS PHYSICS

In 2013, the DLNP Department of New Accelerators was busy working on the project of the superconducting cyclotron **SCC250** intended for acceleration of protons to an energy of 250 MeV, which is considered to be optimal for the full-depth of penetration in an human body ($\sim$ 32 cm) and treatment of deep internal tumors. In the SCC250 cyclotron, beam current will be modulated by changing the current of the internal ion source with a frequency of up to 1 kHz, which will allow implementing a new promising proton therapy method based on active scanning with intensity-modulated beams.

Development of the magnetic system of the proton therapy cyclotron is based on the main parameters of the cyclotron with allowance for the interaction with other systems of the cyclotron: RF system, extraction system, cryogenic system. The ion orbital frequency found from the simulation of the magnetic field and beam dynamics is 37 MHz. In a cyclotron with four sectors and accelerating electrodes whose angular length is 45°, the optimum acceleration mode is the fourth one. If the SCC250 cyclotron operates with the fourth harmonic mode, the resonant frequency should be 148 MHz. Computer model of the cavity with the design frequency and the accelerating voltage increasing along the radius was developed, and simulation of the beam dynamics in the acceleration and extraction areas were performed.

The series of simulations and experiments on the cyclotron **AIC-144** was aimed at optimizing acceleration and extraction of the beam with a proton energy of $\sim$ 60.5 MeV for eye melanoma therapy. The energy spread in the extracted bunch of protons was minimized by tuning the phase motion of the accelerated beam which allowed obtaining the Bragg peak decrease of $\sim$ 0.8 mm at a level of 10–90%, a record value among the cyclotrons used for eye therapy. The development specification is prepared for the software for measurement of phase motion parameters of an accelerated bunch of protons [39].

The main goals of theme **"Medical and Biological Researches with the JINR Hadron Beams"** are to carry out medicobiological and clinical investigations on 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 in the DLNP medicotechnical complex (MTC) [40].

The regular sessions of proton therapy aimed to investigate its efficiency to treat different kinds of neoplasm were performed in collaboration with the Medical Radiological Research Centre (Obninsk) and the Radiological Department of the Dubna hospital. During the year, seven treatment sessions, total duration of 25 weeks, were carried out. Seventy-three new patients were fractionally treated with the medical proton beam. The total number of the single proton irradiations (fields) was about 4500. Other 15 patients were irradiated with the "Rokus-M"Co-60 gamma-therapy unit. A computerized system for verification of boluses — irregular-shape proton beam decelerators, manufactured at the MTC workshop using a CNC milling machine — was designed and constructed. The quality control of the boluses increases the "quality assurance" level of the performed radiotherapy.

Together with the Division of Radiation Dosimetry, the Institute of Nuclear Physics (Prague, Czech Republic), measurements of secondary-particle background in the patient treatment room were carried out using the thermoluminescent, track, and silicon MEDIPIX detectors; and LET spectra of the JINR Phasotron therapeutic proton beam were studied using the LIULIN and MEDIPIX detectors. In collaboration with the Great Poland Cancer Centre (Poznan, Poland), the experiments at the proton beam with radiochromic films and a heterogeneous "Alderson phantom" simulating human anatomy were continued to verify all technological stages of the preparation and procedure for therapeutic irradiation. The results confirmed high accuracy of matching of the maximum dose distribution with the irradiated target and were reported at the Particle Therapy Cooperative Group Meeting 52 (Essen, Germany, June 2013).

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