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# DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS: RESEARCH ACTIVITIES IN 2003–2009 AND PLANS FOR 2010

Report to the 107th Session
of the JINR Scientific Council
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Объединенный институт
ядерных исследований

According to the JINR Road Map, the modern particle and nuclear physics program of research at DLNP was concentrated in four main domains: neutrino physics and rare phenomena; DLNP participation in the development of domestic facilities and research at these facilities; international partnership programs at unique accelerator facilities like Tevatron (FNAL), LHC (CERN), FAIR (GSI), ILC; applied research, in particular, proton therapy and medical accelerator facility development.

## *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 $(4 \div 7) \cdot 10^{-12}\ \mu_B$. 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 centre. Analysis of the first phase in 2008 allowed getting a new neutrino magnetic moment upper limit of $5.1 \cdot 10^{-11}\ \mu_B$. Data taking and analysis in 2009 this result to be improved to $3.9 \cdot 10^{-11}\ \mu_B$. 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 $(1.0 \div 2.0) \cdot 10^{-11}\ \mu_B$ is expected. In the third phase of the experiment (GEMMA III) the sensitivity will be improved to $(0.4 \div 1.0) \cdot 10^{-11}\ \mu_B$.

The main purpose of the **NEMO 3** experiment is the search for the double beta decay process with two (2νββ-decay) or zero (0νββ-decay) neutrinos in the final state in seven different ββ isotopes. The experimental search for the 0νββ-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 2002-2009 the following data for double beta decay of different isotopes were obtained [1, 2]:

$0\nu\beta\beta$ decay

| Isotope | Half-life data | effective neutrino mass |
|---|---|---|
| $^{100}Mo$ | $T_{1/2} > 5.8 \times 10^{23}$ y (90% CL) | $\langle m_\nu \rangle < 0.8 - 1.3$ eV |
| $^{82}Se$ | $T_{1/2} > 2.1 \times 10^{23}$ y (90% CL) | $\langle m_\nu \rangle < 1.4 - 2.2$ eV |
| $^{48}Ca$ | $T_{1/2} > 1.3 \times 10^{22}$ y (90% CL) | $\langle m_\nu \rangle < 29.7$ eV |
| $^{96}Zr$ | $T_{1/2} > 8.6 \times 10^{21}$ y (90% CL) | $\langle m_\nu \rangle < 7.4 - 20.1$ eV |
| $^{150}Nd$ | $T_{1/2} > 1.8 \times 10^{22}$ y (90% CL) | $\langle m_\nu \rangle < 4.8 - 7.6$ eV |

$2\nu\beta\beta$ decay

| Isotope | Half-life data |
|---|---|
| $^{100}Mo$ | $T_{1/2} = 0.711 \pm 0.002(\text{stat.}) \pm 0.054(\text{syst.})\ 10^{19}$ y |
| $^{82}Se$ | $T_{1/2} = 9.6 \pm 1.0(\text{stat.}) \pm 0.3(\text{syst.})\ 10^{19}$ y |
| $^{116}Cd$ | $T_{1/2} = 2.8 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})\ 10^{19}$ y |
| $^{150}Nd$ | $T_{1/2} = 0.920^{+0.025}_{-0.022}(\text{stat.}) \pm 0.072(\text{syst.})\ 10^{19}$ y |
| $^{96}Zr$ | $T_{1/2} = 2.3 \pm 0.02(\text{stat.}) \pm 0.3(\text{syst.})\ 10^{19}$ y |
| $^{48}Ca$ | $T_{1/2} = 4.4^{+0.5}_{-0.4}(\text{stat.}) \pm 0.4(\text{syst.})\ 10^{19}$ y |
| $^{130}Te$ | $T_{1/2} = 76 \pm 15(\text{stat.}) \pm 8(\text{syst.})\ 10^{19}$ y |

It is expected to improve the present measurement of the neutrino mass by the order of magnitude in the coming 7 years with the aid of the SuperNEMO experiment.

The study of the $0\nu\beta\beta$ decay will be continued with the aid of the **GERDA** experiment. The main purpose of this 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 tonne of liquid argon is designed. All elements of LArGe are produced and prepared for installation.

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.

Investigation of double beta decay processes ($\beta^+\beta^+$, $\beta^+$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 ~10000 hours of measurements (2007-2009) was made and the limit on the 0νEC/EC decay of $^{106}Cd$ $T_{1/2} \geq 1.5 \cdot 10^{20}$ y (90% CL) was obtained. The new limit on the half-life of the 2νEC/EC decay of the $^{106}Cd$ was obtained: $T_{1/2} \geq 4.5 \cdot 10^{20}$ y (90% CL). The limits on the half-lives of others branches of $^{106}Cd$ decay were improved (at 90% CL): $T_{1/2}(2\nu\beta\beta^+) \geq 1.4 \cdot 10^{20}$ y and $T_{1/2}(2\nu\beta^+EC) \geq 1.1 \cdot 10^{20}$ y for the $0^+ \rightarrow 0^+$, g.s. transitions, $T_{1/2}(2\nu\beta^+\beta^+) \geq 1.6 \cdot 10^{20}$ y, $T_{1/2}(2\nu\beta^+EC) \geq 1.1 \cdot 10^{20}$ y and

$T_{1/2}(2\nu EC/EC) \geq 6 \cdot 10^{19}$ y for the $0^+ \to 2^+$, 512 keV transitions, $T_{1/2}(2\nu\beta^+ EC) \geq 1.5 \cdot 10^{20}$ y and $T_{1/2}(2\nu EC/EC) \geq 5 \cdot 10^{19}$ y for the $0^+ \to 0^+_1$, 1334-keV transitions [3].

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. 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 type of detectors was about 10 months). The observation of one nuclear recoil candidate above 20 keV in an effective exposure of 144 kg.d (six months of data) 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 $10^{-43}$ $cm^2$ 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 [4, 5].

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

The rare kaon decay, $K_L^0 \to \pi^0 \nu\tilde{\nu}$, is considered as an ideal process for understanding the origin of CP violation and a critical test for the standard model. The theoretical uncertainty in the branching ratio, which is predicted to be $(3 \pm 0.6) \cdot 10^{-11}$ in the standard model with parametric uncertainties from other



experiments, is only 1-2%. The decay has been considered as an ideal process in the quark flavor physics for a critical test of the standard model as well as a search for new physics beyond it. The present experimental limit is $5.9 \cdot 10^{-7}$.

The KEK-PS **E391a** is the first dedicated experiment to search for this decay. It employs two main concepts - a pencil beam and a hermetic photon veto system in a highly evacuated decay region. The experiment started the data taking in February 2004 aiming at improving the current experimental limit by some orders of magnitude. As a result the single event sensitivity for the $K_L^0 \to \pi^0 \nu\tilde{\nu}$ decay was calculated as the reciprocal of the product of the averaged value of the numbers of $K_L^0$ decays estimated from $K_{\pi 2}$ and $K_{\pi 3}$ with the acceptance for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay estimated by a simulation to be $1.17 \cdot 10^{-7}$. Since there is no event in the signal region and the expected level of background is negligibly small, the upper limit for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay is $2.9 \cdot 10^{-7}$ at the 90 % confidence level, this is the main result in 2006. In 2008 the new upper limit for the branching ratio of the $K_L^0 \to \pi^0 \nu\nu$ decay $6.7 \cdot 10^{-8}$ (90% C.L.) is experimentally obtained. The measured experimental value is now the most accurate in the world. A completely new approach to $K_L^0 \to \pi^0 \nu\tilde{\nu}$ measurements for the E391 and KOTO experiments was developed. The E391 registration method is blind to the sort of particle decayed into two gammas. The mass of the decayed particles could not be reconstructed due to absence of methods for angle measurements. A new method for angle reconstruction of gammas detected by main CsI calorimeter was developed. This method is based on Neural Networks and provides a resolution comparable with the resolution for strip detectors [6-9].

Within the framework of the **PIBETA** project the final results of the analysis of the experimental data on radiative pion decay (RPD) were obtained. The decay $\pi^+ \to e^+ \nu\gamma$ was studied in three broad kinematic regions using the PIBETA detector and a stopped pion beam. The $\pi^+ \to e^+\nu\gamma$ data set was used to extract the weak axial $F_A$ and vector $F_V$ pion form factors. The RPD data set was used for probing the Standard Model. As a result the amount of data acquired during the PIBETA experiment is an order of magnitude greater than those obtained in previous studies. The results of SM minimizations are following: $F_V = 0.0259$ is fixed, $F_A = 0.0127(7)$, $\gamma = 0.49(1)$, $a = 0.0$. A hypothetical tensor term to the decay rate amplitude resulted in the upper limit $|F_T(0)| \leq 5.1\times10^{-4}$ at the 90% confidence limit. This limit is more than an order of magnitude smaller than the ISTRA collaboration re-analysis result.

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 $4.7\cdot10^6$ raw $\pi \to e\nu$ events were recorded, before analysis cuts are applied, the statistical uncertainty was $\frac{\delta B}{B} = 5\cdot10^{-4}$ [9]. The 2009 run was the second data taking run of the PEN experiment. During the 2008 and 2009 runs more than 107 events of the $\pi\to e\nu$ decay were recorded, which already allows the experimental accuracy of the branching ratio to be improved [10]. 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 the 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 $\gamma$ rays provide the best possible spatial, temporal and energy resolutions. Analysis of the 2008 experimental data yielded the decay branching ratio upper limit of $3\cdot10^{-11}$. 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 the branching ratio limit of $(2\div4)\cdot10^{-12}$ 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 very interesting phenomena of neutrino oscillations predicted by the DLNP physicist B. Pontecorvo are under the intensive study now in different experiments with the participation of the DLNP physicist. 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 this year. 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 the 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 [12, 13].

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 of the result of the $^7$Be solar neutrino flux measurement. The final result on the $^7$Be neutrino flux is $49\pm3(stat.)\pm4(syst)$ cpd/100 tonnes of scintillator.

The expected signal in the high metallicity Standard Solar Model is $74 \pm 4$ cpd/100 tonnes, the MSW-LMA scenario reduces this count to $48 \pm 4$ cpd/100 tonnes. The hypothesis of non-oscillating 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) [14, 15].

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, the Rocket Space Corporation "Energia", 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 been currently develope 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 his to be produced



in 2010-2011. The mission is planned for operation at the end of 2011 at the dedicated Mikhail Lomonosov satellite [16].

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. 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 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 at 2011.

## *Domestic Research and Partnership Programs at Unique Accelerators*

One of the major goals of the new 7-year plan of JINR in the field of particle and relativistic nuclear physics is development of high-energy heavy-ion collider complex NICA and experiments at this complex. DLNP physicists take part in the preparation of both the accelerator and the experiments parts of this project.

At present DLNP participates in the **NICA/MPD** Electromagnetic Calorimeter design and physics associated with the detection of lepton pairs and photons.

It was proposed to use as a baseline for the calorimeter design the so-called "shashlyk" structure with Lead/Scintillator tiles and WLS-fiber readout for the novel photo detectors developed at JINR (Fig.1). Apart from excellent energy resolution, this calorimeter will also provide good timing resolution, which extends the calorimeter features to the time of flight measurements and additional particle identification (Fig.2).

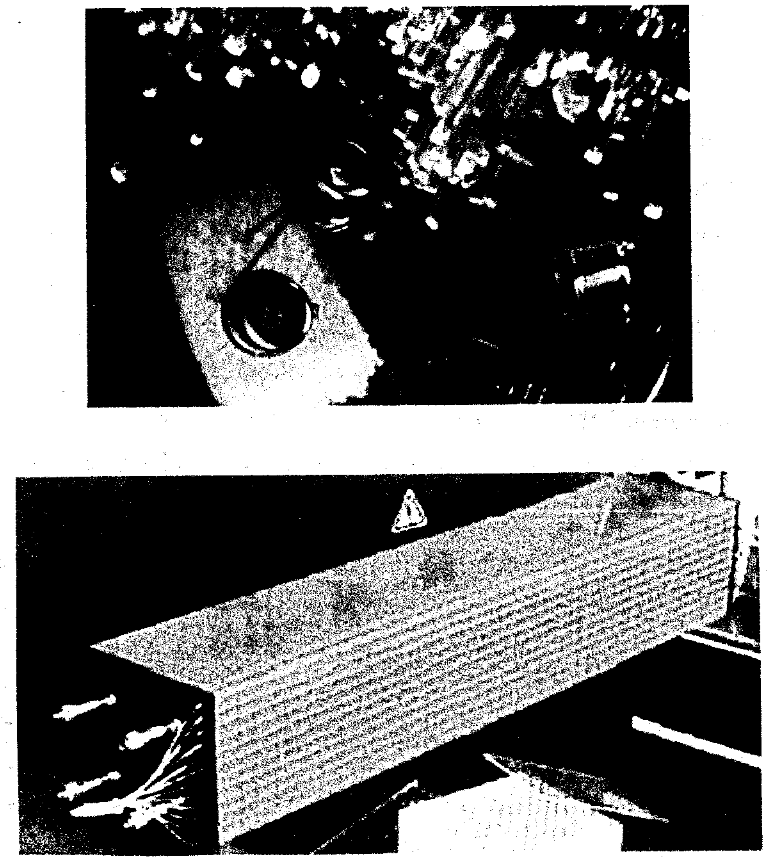

*Fig.1.* Photos of the calorimeter module.



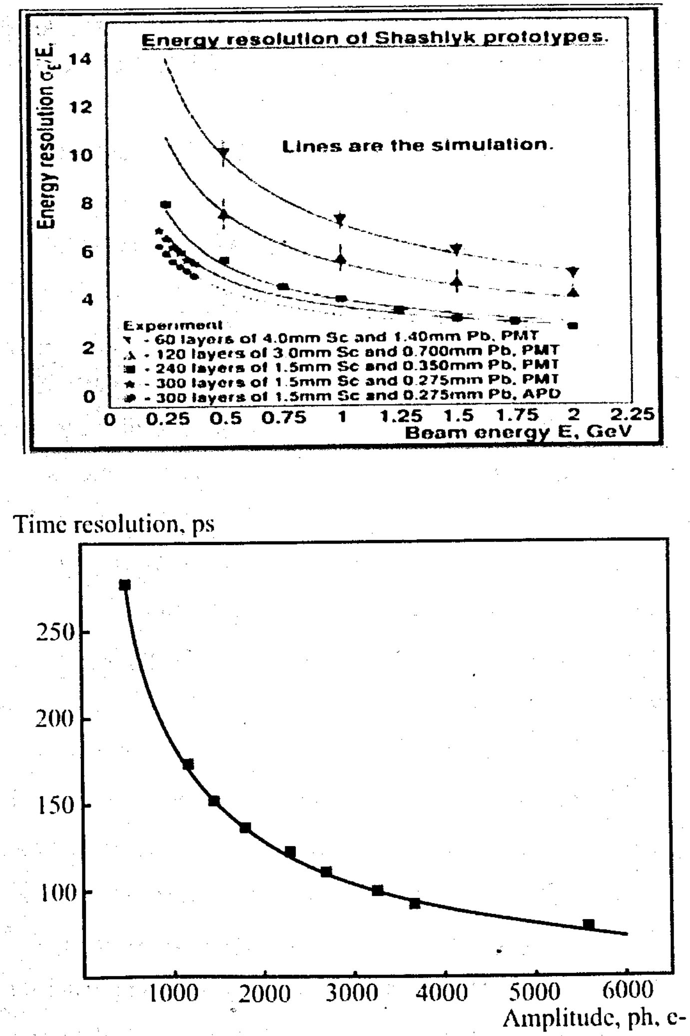


*Fig.2.* Energy (top) and time resolution (bottom) of the calorimeter module.

The main results of the **JINR/CDF** group 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$^{-1}$, $M_{top} = 165.5^{+3.4}_{-3.3}(stat.) \pm 3.1(syst.)$ GeV/c$^2$

was made [17]. 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% C.L. 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% C.L. 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 [18].

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

Within the framework of the **D0** project the first direct observation of the charged beauty baryon $\Xi_b$, which contains quarks from all the three generations, b, s and d, was made [19]. The data obtained with the D0 setup of the FNAL Tevatron (USA) during the years 2002–2006 were used. 35 millions proton-antiproton interactions at the cms energy of 1.96 TeV with muon pairs in the 2.5–3.6 GeV/$c^2$ mass region were analyzed. In these events, J/ψ particles and charged Ξ hyperons and antihyperons from the common secondary vertex were reconstructed. Their (J/ψΞ) mass distribution has the peak (19 events) at 5774 MeV/$c^2$ of width 37 MeV/$c^2$. The probability for such a peak to arise from background fluctuations does not exceed $3.3\times10^{-8}$ (background level is 3.6 events). All the test samples of the events have no peculiarities within this (J/ψΞ) mass region (Fig.3). The peak has been interpreted as the decay $\Xi_b \to J/\psi+\Xi$. The measured mass of the $\Xi_b$ agrees with theoretical predictions.



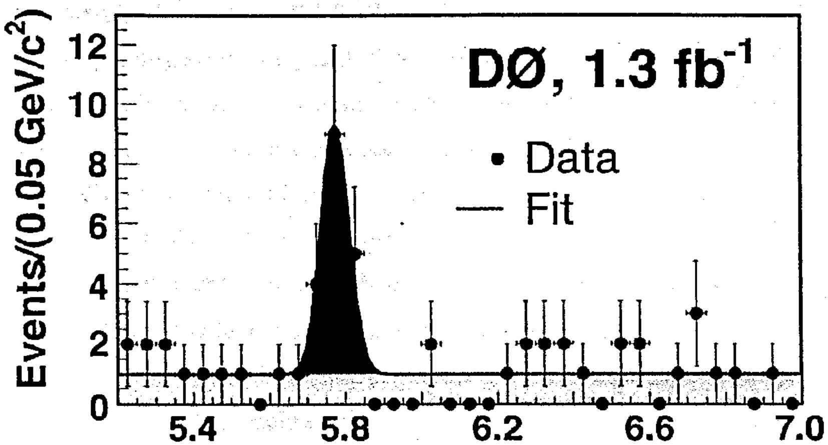


*Fig.3.* Event from the peak of the (J/ψΞ).mass distribution.

In 2008 the first direct observation of the beauty baryon $\Omega_b$ was made (Fig.4). This discovery was ranked among the few most significant achievements in physics in 2008 by the American Physical Society [20].

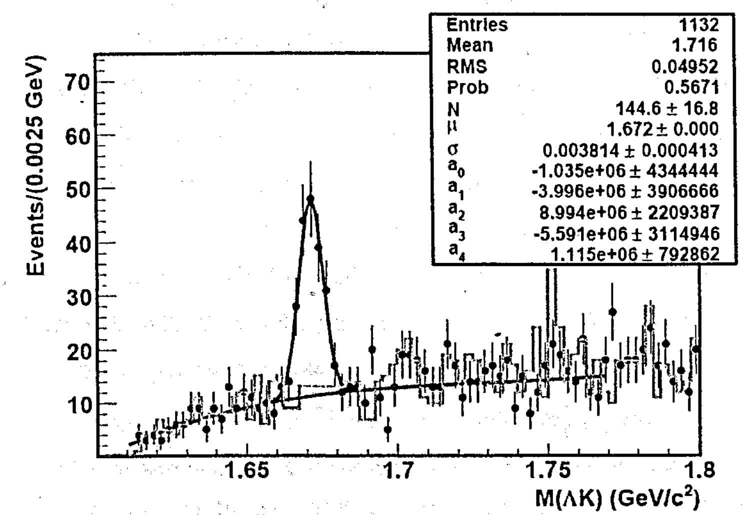


*Fig.4.* Event from the peak of the $\Omega_b$ mass distribution.

The Beijing electron positron collider BEPC-II produced the first collisions on 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 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.

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 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 $J/\psi$ decays into three pseudoscalar mesons and radiative decays into two pseudoscalar mesons. Event selection of $J/\psi$ and $\psi$ (2S) decays into two kaons and a photon, was elaborated for the future partial wave analysis [21].

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

In the middle of 2006, the full-scale assembly of the **ATLAS** calorimeter was completed. As far as investigations of the properties of the ATLAS calorimeter system and preparation of experimental data are concerned, the work done by the JINR group is the comprehensive analysis of the basic characteristics of the ATLAS



Tile Calorimeter and combined calorimeters using the Monte Carlo method and the experimental information obtained during exposure of the prototype and real modules of the Tile Calorimeter and prototype and real modules of the combined calorimeter (liquid-argon electromagnetic and hadronic tile calorimeters) to beams of pions, protons, electrons, and muons with the energies 10–350 GeV at the SPS accelerator (CERN).

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.

The work on application of the **SANC** results (CBRD (LNP), BLTP) 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. In 2008 other users began employing the SANC results [22, 23].

The main purpose of the **DIRAC** experiment is the lifetime measurement of $\pi^+\pi^-$, $\pi^+K^-$ and $\pi^-K^+$ 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 $\pi^+K^-$ and $\pi^-K^+$ 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 the accuracy of 10%. DIRAC took data during 6 months for observation of the atoms consisting of $\pi$ 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 $\pi K$ atoms were published. In total, 173±54 $\pi K$-atomic pairs were observed with a significance of 3.2σ [24].

The first measurements of Primakoff reactions (Fig.5) have been done at **COMPASS** experiment. The goal of these studies is to measure pion polarizability parameters to the precision matching the present theoretical predictions.

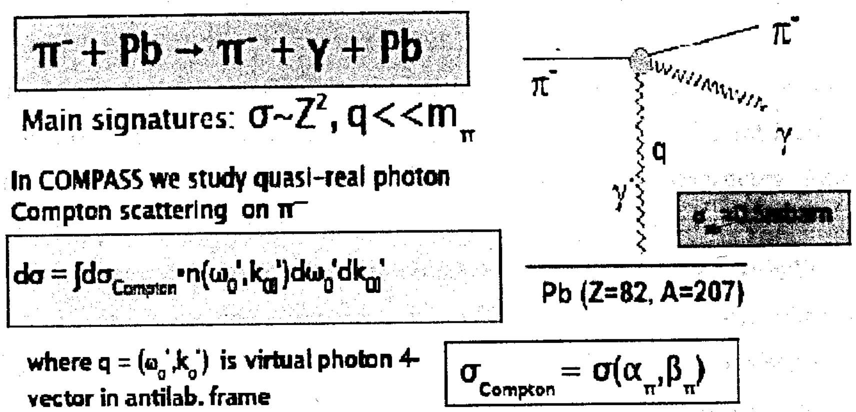


*Fig.5.*

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 program 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.

Extensive analysis has been completed for the data obtained with the **ANKE** setup at COSY-Julich 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 [25]. 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 $0^\circ - 12^\circ$ and the cross section energy dependence are measured. The distributions obtained in 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. The data are analyzed on the basis of the theoretical models developed earlier for the kinematically similar process $pd \to dp$, appropriate by modified for the diproton channel $pd \to \{pp\}_S n$. It is shown that the measured observables are highly sensitive to the short-range part of the nucleon-nucleon interaction.

## *Applied Scientific Research*

Since 2007 the **JINR Phasotron** has resumed its operation for Proton Therapy cancer treatment. In the coming years this experience, together with the experience in design of medical cyclotrons, will be used for the construction of Russian Proton Therapy centers. One of such centers is proposed to be built in Dubna and we are working on this project together with Federal Medical Biological Agency, Rosnano State Corporation, Administration of the Moscow region and Dubna Special Economic Zone.

Today, cancer is the second highest cause of death in developed countries. Its treatment still presents a real challenge. Protons and light ions allow depositing the radiation dose more precisely in a cancer tumor, reducing greatly the amount of dose received by healthy tissue surrounding the tumor with respect to electrons and photons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams have an extra advantage in radiation therapy: they have a different biological interaction with cells and are very effective even against some type of tumor cells which resist usual radiations.

A compact superconducting isochronous **cyclotron C400** has been designed at IBA (Belgium) in collaboration with JINR (Dubna). This cyclotron can accelerate all ions with the charge-to-mass ratio 0.5. ${}_{12}C^{6+}$ 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 270MeV/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 [27].

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.

Regular sessions of proton therapy aimed to investigate its effectiveness for treating different kinds of neoplasm were carry 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. 106 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". 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.



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