Low- and Intermediate-Energy Physics

Users' Request Facility Phasotron and its Development

05-2-1038-2001/2006

Priority of the project:	1
Status:	Realization

Improvement and Development of the JINR Phasotron Fundamental and Applied Research

Leader from JINR: L. Onishchenko

Participating countries and international organizations:

Scientific Program

- Commissioning of the Phasotron upgraded beam channels to increase intensity of the positive and negative pion beams up to 10^{7} s^{-1} μA^{-1} and 10^{-6} s^{-1} μA^{-1}, respectively.
- Construction of the proton beam channel for the electronuclear investigations with the SAD installation.
- External Injection into the JINR Phasotron.
- Specialized Cyclotron for Proton Therapy.
- Improvement of the parameters of the isochronous cyclotron AIC-144, Krakow, Poland.
- Theoretical studies, numerical simulations, development of concepts and designs of new cyclotron systems to achieve the best parameters of the RI Beam Factory at RIKEN, Japan.
- Numerical simulations, elaboration and design of new cyclotron systems to achieve the best capacities and parameters of the TESLA Accelerator Installation, Belgrade, Serbia and Montenegro.
- Improvement of the parameters of the cyclotron U-115T, Tashkent.
- Development of the Compact Cyclical Accelerator Technologies for Producing Effective High-Current Proton and Gamma Beams for Explosive Detecting using Nuclear Resonance Absorption.

Expected main results in 2004

- Beam channel № 3 commissioning and measurement of the pion beam parameters for different energies.
- Computer simulation of the beam dynamics in the channel; computation of the magnets and lenses; design of the bending magnet analogous with OM-1 and of the quadruple analogous with ML-3.
- Computer simulation of the beam acceleration up to extraction radius (~30000 turns); technical proposal for the main (magnet, RF, injection, extraction) systems of the 5MeV cyclotron-injector; technical proposal for the resonator-forinjector.
- Consideration of the cyclotron variants aiming at the determination of the particles type and their energy; computer simulation of the beam dynamics and choosing the magnetic and accelerating fields parameters; computation of the magnet and of the resonator.
- Creation and development of the code helping the cyclotron operator to choose the cyclotron operational parameters.
- Computer code development for estimation of the cyclotron beam space charge effects by the 3-dimentional integral method with higher order moments in the particle distributions and other enhancements.
- Completion of the magnetic field simulation and conducting magnetic field measurements for the VINCY Cyclotron, NAC, Belgrade.
- Design of the new ion source for the У-115 cyclotron.
- Conceptual design of the customs cyclotron.

Experiments and Facilities at Phasotron

05-2-1039-2001/2006

Priority of the project:

Status: Data taking

Project DETECTOR

Leader from JINR: V. Sandukovsky

Participating countries and international organizations: Bulgaria, Czech Republic, France, Poland, Russia, Sweden, Switzerland, the USA.

Research and development of new types of semiconductor radiation detectors (SRD) and plastic scintillators (PS). The SRD occupy a prominent place in experimental nuclear physics as precision spectrometric instruments. In the number of the experimental problems of non-accelerator physics (the growing interest in which is observed in recent years) it is necessary to have the low energy threshold of registration. These are the searches for dark matter, the measurement of magnetic momentum of neutrino and coherent neutrino scattering on the nuclei, the search for double beta decay, spectroscopy of the radioactive nuclei, oriented in magnetic fields at ultraslow temperatures, etc. Low energy threshold can be achieved by deep cooling of SRD. However, number of questions about operation of SRD at temperatures lower than 77K remains open until now. Experimental data in the scientific literature contain incomplete, sufficiently obsolete, and sometimes contradictory information. The Project has assumed:

- Comprehensive study of the behavior of main characteristics of various types of detectors made of germanium and silicon in the temperature range 1–77 K. Search for the low-temperature limit for operation of SRD as spectrometric instruments. Manufacture SRD capable of working at ultraslow temperatures without the degradation of the spectrometric parameters.
- Study of the possibility to produce spectrometric SRD with the internal amplification of signals and with low energy threshold of the registration (≤ 0.5 keV) respectively.
- Study of special segmented coaxial HPGe samples as a prototype of detectors made of Ge-76 which is developing for the experiment MAJORANA (together with Duke University).
- R&D of wide-aperture planar germanium detectors with thin “dead” layers, which will be used in the further development of spectrometer TGV (Modane, France) and in the experiment on the search for exotic nuclear states on the accelerator CELSIUS (Uppsala, Sweden).

The central objective of scientific developments in the field of scintillation detectors is the creation of the new types of plastic and liquid scintillators with increased efficiency for specific radiations due to its enriching by some elements. It includes the development of (number) procedures for obtaining:

- lithium containing PS, ytterbium containing PS, calcium containing plastic and liquid scintillators;
- PS with the increased content of gadolinium and neodymium (to 5–8% throughout the mass);
- PS, which contain heavy elements (Pb, Sn, Bi, W).

Successful solution of these and technological problems will allow us to obtain the scintillation materials which do not have analogues in the world practice, and it will give to JINR additional possibilities for the participation in various scientific projects.

05-2-1039-2001/2006

Priority of the project:

Status: Data taking

Project YASNAPP-2

Leader from JINR: V. Kalinnikov

Participating countries and international organizations: Bulgaria, Czech Republic, Poland, Romania, Russia, Uzbekistan, France.

The objective within the project YASNAPP is to study systematically the decay characteristics of radioactive nuclides, including earlier unknown ones, and the structure of the ground and excited nuclear states of various shape; to reveal and investigate in more detail the features of the beta decay as a weak interaction process; to investigate interaction of atomic shell electrons with nuclei of various elements from light to the heaviest ones; to study some nuclear reactions by nuclear-spectrometric and radiochemical methods and to determine physicochemical properties of condensed matter.

The radioactive decay of nuclides is studied both in the on-line and off-line modes. Properties of short-lived nuclei are investigated with the YASNAPP-2 ISOL complex consisting of a mass separator on the extracted Phasotron proton beam and various spectrometers on the beams of radioactive ions separated by the mass separator (MUK and UMKS spectrometers, MLS time spectrometer on the basis of the magnetic-lens spectrometer). The spectrometers comprise semiconductor detectors of various types and volumes for measuring γ-ray, X-ray, conversion electron, α-particle, and γγt coincidence spectra. Positron spectra are measured with an HPGe detector by a special technique. The detectors and the spectrometric equipment are mainly ORTEC and Canberra products and meet all present-day experimental requirements. In addition, a beta spectrometer of the miniorange type, a Dodecahedron multiple coincidence spectrometer from the INP (Řež), a total gamma-ray absorption spectrometer from the Radium Institute (St. Petersburg) are used in the off-line mode. A lifetime measurement technique using a single-crystal scintillation spectrometer (miniball) is developed. A two-detector four-dimensional triple-coincidence spectrometer is created to search for isomers in the nanosecond and microsecond ranges in short-lived nuclei.

Spectra of low-energy electrons ($E_e \leq 50$ keV) are measured with an ESA-50 combined electrostatic spectrometer, which consists of a spherical moderator and a cylindrical two-cascade mirror analyzer. Electrons are recorded by a barrier-free channel multiplier. The resolution of the instrument is better than 3 eV.

To carry out condensed matter investigations, a four-detector perturbed angular γγ correlation (PAC) spectrometer is created. It comprises a press for producing a pressure up to 60 GPa in the samples.

The nuclides for off-line investigations are produced by irradiation of targets at the Phasotron (internal beam), FLNR accelerators, and IBR-2 with subsequent radiochemical processing of the targets and mass separation of the reaction products. Special techniques are developed for production of thin radioactive sources.

The experimental resources of the project allow competitive (with CERN, Darmstadt, Lanzhou, Gatchina) investigations of radionuclides with half-lives $T_{1/2} \geq 0.1$ s by methods of full spectrometry of nuclear radiations.

The following results obtained in 2001–2003 are worth mentioning:

- measurements of ^{156,158}Er, ^{158}Er, ^{157}Tm masses, which resolved the conflict with Wapstra's tables;
- investigation of the isomers of various nature in the ^{156}Ho nucleus and the role of F-forbidden γ-transitions in nuclei with N=89;

- the Gamow–Teller resonance with M_T=+1 is identified for the first time by the strength function for the ^{147g}Tb β-decay and its theoretical interpretation is given;
- investigation of gamma spectra of nuclides in the ^{238}U and ^{229}Th decay chains in order to establish the validity limits of nuclear models, to determine their parameters, and to use for analyzing the background in fundamental experiments at low-background underground laboratories;
- making an atlas of low-energy electron spectra (LEES) of Z=24–95 radionuclides;
- deep purification of unique (~20 g) amounts of the enriched ^{48}Ca isotope from radioactive impurities for searching for its 2β0ν decay (NEMO-3 and TGV-2 experiments);
- for the first time the ^{111}In→^{11m}Cd generator is produced for studying after effects of radioactive decay of nuclides in condensed matter.

YASNAPP-2 tasks in 2003–2006

- Search for new short-lived isotopes and isomers among products of deep spallation of Ta and W targets by fast protons (E_p=660 MeV) at the YASNAPP-2 ISOL complex. Investigation of decay characteristics of the new nuclides. Identification of isomeric excited nuclear states in the submicrosecond range with the 4π scintillation time spectrometer.
- Study of nuclear mass shells in the rare-earth and actinide regions (masses of nuclei far away from one another, pair and separation energies of nucleons, proton stability line B_p≈0) of the techniques of semiconductor α- and β-spectrometry and β-γ coincidences.
- Investigation of structural features of nuclei with different equilibrium deformation in the vicinity of doubly magic nuclei ${}^{146}_{64}Gd_{82}$ and ${}^{208}_{82}Pb_{126}$ and at the beginning of the deformation region (N≈88) — neutron-deficient Tm, Er, Ho, and Dy isotopes and daughter products of the long-lived ^{229}Th "generator" — by combined spectrometric methods.
- Experimental investigation of spectra of Auger electrons from the decay of radionuclides for refining the theory of Auger transitions.
- Development of the energy reference in the region of 20 keV on the basis of the natural electron source for precise electron spectroscopy.
- Development and application of the gamma-gamma-PAC method as a tool for investigations of condensed matter (aqueous and non-aqueous solutions).
- Production of radioactive sources with unique physicochemical characteristics by radiochemical methods.

05-2-1040-2001/2006

Priority of the project:

Status: Data taking

Project DUBTO

Leader from JINR: N. Russakovich, G. Piragino

Participating countries and international organizations: Italy, JINR.

DUBTO represents a joint JINR–INFN project aimed at studying pion-nucleus interactions at energies below the Δ-resonance. The experimental device STREAMER is a self-shunted streamer chamber filled with helium at atmospheric pressure, in a magnetic field, equipped with two CCD video cameras for registering nuclear events occurring in the fiducial volume of the chamber, and is exposed to the ~ 100 *MeV* pion beam of intensity $1–5\cdot 10^4 s^{-1}$ of the JINR phasotron of the Laboratory of Nuclear Problems.

This technique was developed in the 1970s at the JINR Laboratory of Nuclear Problems in collaboration with the Turin section of INFN (Italy). Dedicated software has been developed for reading, measuring and analysing video images, recorded as sets of pixels of the CCD matrix of the video camera.

The distribution of $\pi^{\pm 4}$He events obtained over the DUBTO runs is shown in Table 1.

Table 1. Distribution of $\pi^{\pm 4}$He events over DUBTO runs

runs	May, Nov. 1999	June 2000	Nov. 2000	April 2001	Oct. 2001	July, Nov. 2002	April 2003
Total	871	1283	337	817	856	~3000	~12000

Certain problems in low-energy pion-nucleus physics can be resolved only if the complete kinematics of all the charged reaction products is measured.

Approximately 100 events of the reaction $\pi^{+4}\text{He}\rightarrow\pi^{+}2p2n$, that satisfied rigorous selection critieria, revealed a distribution (see Fig.1) of the effective invariant πNN mass differing from the simulated phase-space distribution and exhibiting the same resonance behaviour as the distribution obtained in a study of proton-proton interaction at an energy of 920 MeV at ITEP, and a maximum at ~ 2.07GeV.

A similar result is obtained with negative pions. At present, the statistic of approximately 20000 events is being processed.

Another physical result, obtained by our collaboration, consists in the first observation (see Table 2) of positive pion bremsstrahlung on helium nuclei. This was possible owing to measurement of the momenta of recoil nuclei in two-prong π^{+4}He interaction events that permitted to separate events of purely elastic scattering from events of pion bremsstrahlung on ^{4}He.

Table 2. Branching ratios for 2-prong π^4He interaction processes

Reaction	1980: diffusion chamber	2003, present work
1. $\pi^+He^4\rightarrow\pi^+He^4$	0.588±0.076	0.380±0.021+0.049–0.043
2. $\pi^+He^4\rightarrow\pi^+He^4\gamma$	–	0.322±0.019±0.112–0.026
3. $\pi^+He^4\rightarrow\pi^+He^3n$	0.240±0.038	0.136±0.013±0.025–0.018
4. $\pi^+He^4\rightarrow\pi^0He^3p$	0.176±0.053	0.162±0.014±0.000–0.000

Runs of DUBTO will be performed at various incident pion beam energies and with various gases for clarifying the dependence of the obtained results upon energy and nuclei.

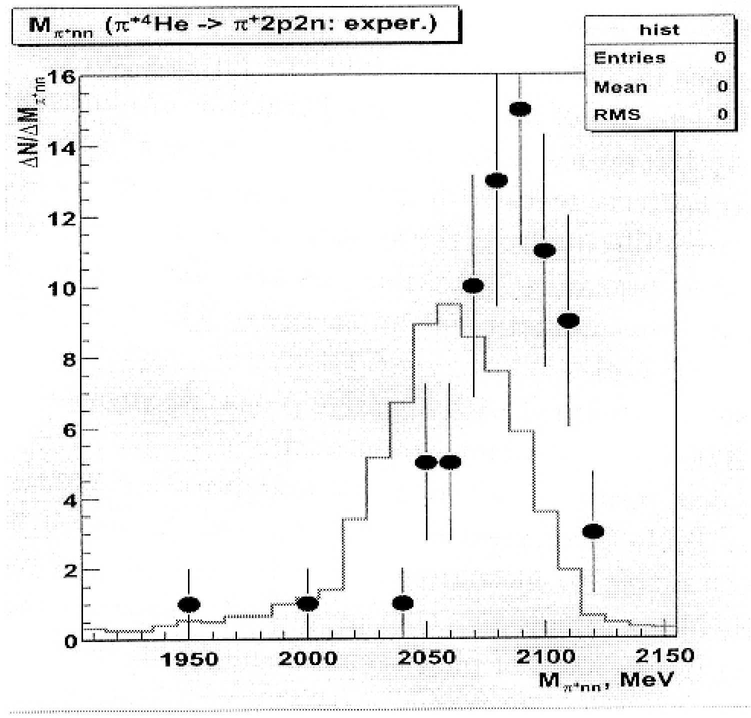

Fig.1. $\pi^{+}nn$ mass distribution: histogram — simulation; full circles — experiment.

05-2-1040-2001/2006	Priority of the project:
	Status: Completed

Experimental Verification of NN-Decoupled Dibaryon Resonance d_1^*(1956) Production in Proton-Proton Collisions Below the Pion Production Threshold (Project DIB2γ)

Leader from JINR: A. Khrykin

Participating countries and international organizations:

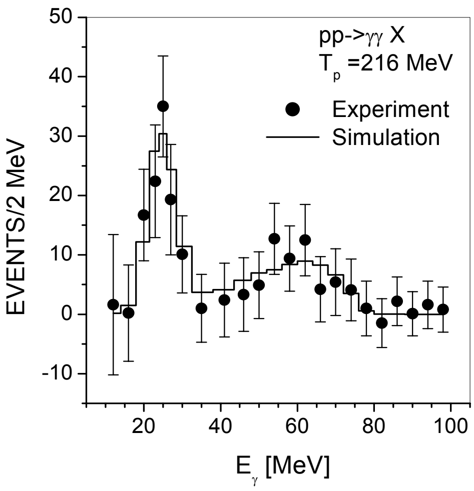

Fig.1. The process at 216 MeV measured at 90^0 and the spectrum calculated with the help of Monte Carlo simulation for energy spectrum of coincident photons from the pp→γγX the process pp→γd_1^*→ppγγ with a d_1^* mass of 1956 MeV.

The primary goal of the present project is to make crucial experimental verification of the existence of the NN decoupled dibaryon resonance d_1^*(1956) and to determine most probable values of its mass, width and quantum numbers (spin, isospin and parity). Strong evidence for the presence of this exotic resonance was first found in the energy spectrum of coincident photons emitted at ±90° from the process pp→γγX at the proton energy about 216 MeV measured by the DIB2γ collaboration at JINR. Behavior of the measured spectrum shown in Fig.1 conforms to the signature of the NN decoupled dibaryon resonance d_1^*(1956) that is believed to be formed in the radiative process pp→γd_1^* and then to decay via the d_1^*→ppγ mode, thereby contributing to the pp→γγX reaction. The photon energy spectrum calculated with the help of Monte Carlo simulations under the assumption that the process pp→γd_1^*(1956)→ppγγ is the only mechanism of the pp ppγγ reaction proved to be in reasonable agreement with the experimental one.

Existence of the dibaryon resonance d_1^*(1956) and, consequently, the new mechanism of direct photon production in NN collisions is also supported by energy spectra of photons emitted in NN and nucleon - nucleus (NA) collisions below the pion production threshold (πNN) measured in a few laboratories of the world. Our analysis of the available experimental spectra shows that they have one common feature — a characteristic structure in the same energy region which should be occupied by γ rays due to the existence of the dibaryon resonance d_1^*(1956). The presence of such a structure leads to considerable disagreement between the experimental spectra and conventional theory taking into account only the mechanism of photon production due to NN bremsstrahlung. Meantime, as it is shown in Fig.2 for the case of the pdγ reaction, simple addition of the d_1^*(1956) contribution to the theoretical spectrum enables easy to eliminate this disagreement.

In addition ppγγ events extracted from the data obtained in the experiment carried out at the KVI in Groningen to study the usual pp→ppγ bremsstrahlung reaction at 190 MeV show strong evidence for the presence of the mechanism of two photon production in pp collisions which we ascribe to the existence of the dibaryon d_1^*(1956).

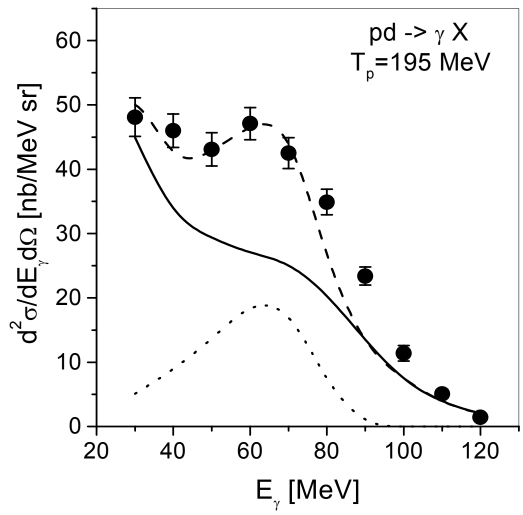

Fig.3. The experimental (solid circles) and calculated (solid line) energy spectra of photons emitted at 90° from the pdγ reaction at 195 MeV. The dotted line shows the contribution of the $d_1^*(1956)$ with the total production cross section σ_{tot} =9.4 μb and the dashed line shows the sum of the calculation and $d_1^*(1956)$ contribution.

Nevertheless, we believe that in order to draw a final conclusion about the existence of the dibaryon d_1^* and to determine its proper parameters (mass, width) and most probable quantum numbers (spin, isospin and parity) it is necessary to carry out additional careful studies of the two-photon production process pp→γγX below the pion threshold. The studies we are planning to carry out include: Precision measurements of the energy spectra of photons emitted at ±90° from the process pp→γγX for two different proton beam energies and angle distributions of both photons from this process including an opening angle distribution at 215 MeV. These measurements will allow rigorous verification of the dibaryon d_1^* existence and establish most probable values of its mass, width and quantum numbers.

So far, we have been studying of the process pp→γγX using the experimental setup developed and designed for test measurements of the photon energy spectra of this process. To perform the measurements planned in the present this should be substantially improved. We are planning to make the following improvements in the setup:

- To develop and install a new liquid hydrogen target **T** with a total thickness of entrance and exit windows at least half that of our old target. This target will ensure at least two times lower background of photons produced in collisions of protons with the windows of the target.
- To develop and install two high-resolution γ ray detectors of a cylindrical NaI(Tl) crystal 20 cm in diameter and 25 cm in length. The Monte Carlo simulations show that such γ ray detectors will allow us to reliably register photons in the energy range of interest with the energy resolution about 6%.

In addition, we intend to replace a few modules of analog and digital electronics of the detectors and data acquisition system by more effective and reliable electronic modules. In the first place we are planning to install new pulse amplifiers, pulse shapers, pulse discriminators, coincidence circuit, time-to-digital and analog-to-digital converters.

05-2-1040-2001/2006

Priority of the project:

Status: Preparation

The Study of Nuclear Reactions in Muonic Molecules Collider (DESY) Project Mu-CATALYSIS

Leader from JINR: V. Zinov

Participating countries and international organizations: Russia, the Netherlands.

The Project Mu-CATALYSIS is a continuation of the experimental program aimed at the investigation of the muon catalyzed fusion (MCF) process is carried out at the Dzhelepov Laboratory of Nuclear Problems of JINR. Our recent results in the determination of main MCF parameters in double D/T mixture cover a wide range of experimental conditions: temperature 45–800 K, tritium content 17–70%, mixture density 0.2–0.9 of liquid hydrogen density (LHD). The measured values of MCF cycling rate corresponding to the density 0.4 LHD are depicted in Fig.1. We propose MCF experiments in tritium and deuterium at low temperatures (6–40 K), in D/T and H/D/T mixtures at super-high temperatures (900–1800 K) and a search for the muon catalyzed radiative dd capture in deuterium at room temperature. By means of muon catalysis we address to phenomena in dd and tt fusion which have not so far been investigated and are at the frontier of nuclear few-body physics. Moreover, we pinpoint mechanisms of recently discovered MCF effects in deuterium at low temperatures.

Four experiments are planned:

1. Search for the radiative deuteron capture

$$d + d \rightarrow {}^4He + \gamma + 23.8 \text{ MeV}$$

for the orbital angular momentum L=1 where it must be strongly suppressed due to the isotope spin selection rule. This two-deuteron state is just realized when the ddμ-molecule is resonantly formed with the total angular momentum J=1. The measurement of the relative yield of this rare reaction from the p-wave state of deuterons in a muonic deuterium molecule at the level 10^{-7} will establish the degree of the isospin selection rule violation.

2. Experimental investigation of the influence of ortho-para components of D_2 molecules on MCF processes

$$d + d \rightarrow {}^3He + n,\ t + p$$

in deuterium at low temperatures 6-40 K. Such measurements should clarify the reason for the sharp disagreement of the solid deuterium MCF data with the “standard” theory of the resonant ddμ-molecule formation and check theoretical models developed for the explanation of the solid-state effects.

3. Investigation of tt fusion reaction from the J=1 state of muonic ttμ-molecule

$$t + t \rightarrow {}^4He + n + n + 11.3 \text{ MeV}$$

will probe a mechanism of p-wave fusion by measuring correlations n-n and α-n in the final state. We expect to determine MCF parameters in tritium with an accuracy several times exceeding the available world data. Detailed study of the t+t fusion process can give the information on the reaction mechanism and, in principle, on the properties of the nuclear system with A=6.

4. Experimental investigation of the dt MCF reaction

$$d + t \rightarrow {}^4He + n + 17.6 \text{ MeV}$$

in double D/T and triple H/D/T mixtures in high-temperature region 900–1800 K. These unique measurements in the unexplored temperature range are very important since the Maxwell distribution of mesoatoms more fully overlaps the most intensive mesomolecule formation resonances namely at high temperatures.

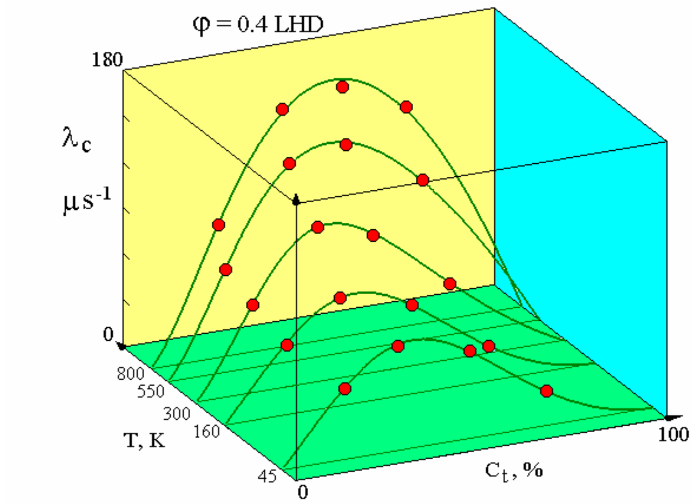

Fig.1. The results of LNP measurements of muon catalyzed fusion cycling rate λ_c in double D/T mixture with different tritium content $\mathbf{C_t}$ in the temperature range **T** = 45-800 K, density of the mixture is 0.4 of that of liquid hydrogen (LHD).

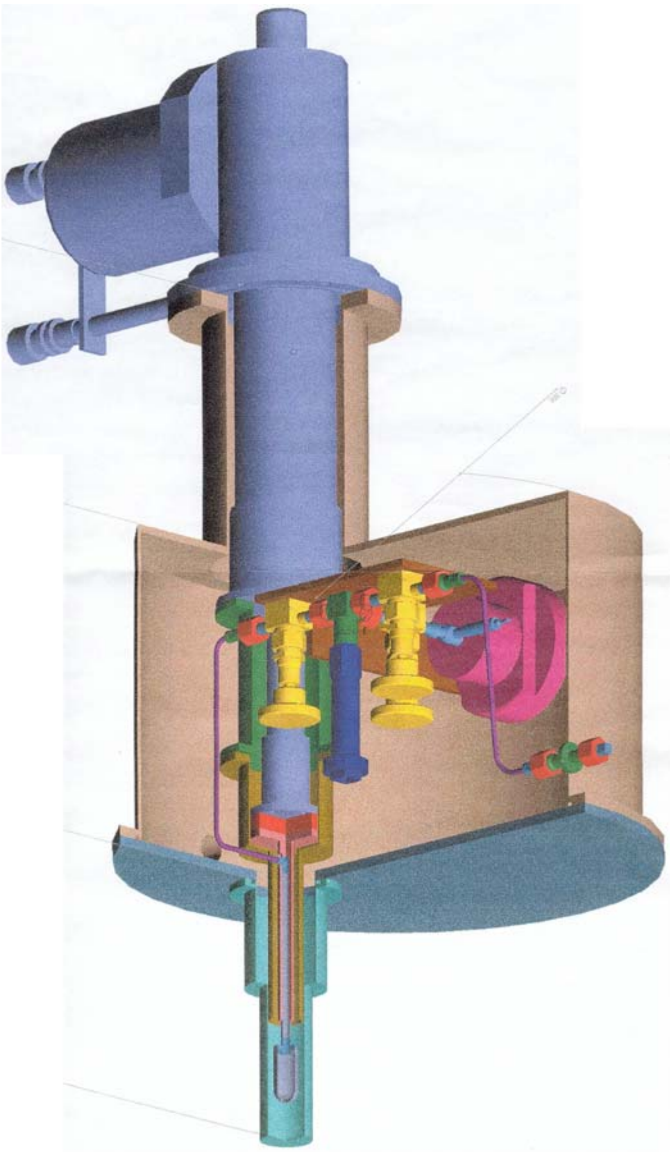

Fig.2. Liquid tritium target used in the experimental investigation of **tt** fusion reaction.

05-2-1040-2001/2006

Priority of the project:

Status: Preparation

Search of the Two-Particle Muon Decay on an Electron and Goldstone's Massless Boson — Familon (Project FAMILON)

Leader from JINR: V. Duginov

Participating countries and international organizations: JINR, Russia.

The experiment is based on the hypothesis of the existence of familon elementary particles, which are responsible for the breaking of horizontal symmetry of the lepton family. The existence of such particles must result in neutrinoless decays of leptons: $\tau \to \mu\alpha$, $\tau \to e\alpha$ and $\mu \to e\alpha$. The search for the decay of μ^+-meson into positron and familon is prepared at the DLNP JINR phasotron.

The search of events of the two-particle decay $\mu \to e\alpha$ will be realized making use of the $\mu \to e\nu\bar{\nu}$ decay data near the high-energy edge of the positron spectrum. The direct observation of the monochromatic line resulting from the rare channel $\mu \to e\alpha$ is connected with the number of problems:

- the high energy resolution;
- the difficulties of the absolute measurements (the background events, the scattering effects and so on).

Many difficulties can be avoided when investigating the decay of the polarized muon and analyzing the energy and angular distributions of positrons.

In the 1990s we proposed and realized at PNPI the method and created the apparatus for investigation of the rare muon decays. The idea is to detect the high energy positrons resulting from the muon decay by the wide acceptance magnetic β-spectrometer. Such system was used in the PNPI÷JINR experiment which was carried out on the intensive surface muon beam of the LNP JINR phasotron when investigating the process of the muonium-to-antimuonium conversion. The FAMILON set-up is installed at the beam of surface muons; methodical runs have been carried out.

The main element of set-up is the spectrometric magnet (∅80 cm, the gap between of poles 24 cm). The necessary value of the magnetic field is ~3 kG to provide the bend angle 102^o.

The nearest task of the physical investigations on the FAMILON-setup (2004-2005) is to obtain the first direct experimental estimation for the probability of the neutrinoless muon decay $R_\alpha = \Gamma(\mu \to e\alpha)/(\mu \to e\nu\bar{\nu}) < 10^{-5}$ (~300 hour accelerator run, making use of the surface muon beam of the DLNP JINR –phasotron).

The further progress of investigation is connected with the design of the magnetic spectrometer with the high energy ($\sim 10^{-4}$) and time (~0.25ns) resolution.

The main steps are:

- On the basis of the parallel plate avalanche detector we will design the active target which consist will of 3 gaps to fix the muon stop point. Such target with 2 proportional coordinate chambers allows determining the muon decay point with the accuracy 0.5–1 mm.
- The application of the active target needs to increase of DAQ rapidity to 10^{-5}/sec. The technical project of this system is prepared. The new system will be in operation in 2004.
- The geodesic adjustment of the set-up elements will be performed.
- The optimization of the set-up geometry will be completed.
- The preparation of the software for the reconstruction of the positron pulse will be finished. The programs will have two modes — the fitting of the part of the events during the experimental runs, and the OFF-LINE analysis on the whole set of experimental data.

- The estimation of the set-up parameters will be obtained on the basis of the Monte-Carlo simulations.
- The assembling of the optimal configuration (target station, track detectors, scintillation detectors etc) will be performed.
- Computer system with the elements in the participating institutes connected by INTERNET will be established.

2004

- The manufacturing of the new DAQ system for the proportional chambers.
- Test of the new system. The methodical and the physical runs at the JINR phasotron. (100 hrs).

2005–2006

- The experimental runs at the JINR phasotron (300 hrs) Analysis of the experimental results.
- Preparation of the publications.

Cost and resources estimation Budget expenditures

The equipment and materials (detectors, CAMAC modules etc) — 5000 $/year
Collaboration (visits to PNPI) — 500 $/year
Phasotron beam — 300 h/year

Additional sources of financing

The FAMILON experiment is performed in the framework of the scientific and technical program of Russia "The research and development in the priority directions of the development of science and technique for civil use", the subprogram "The fundamental nuclear physics", the project "The physics of rare decays", the RAS-program" The neutrino physics", the RFFI-project (the grant 99-02-17943-a).

05-2-1040-2001/2006

Priority of the project:

Status: Preparation

Project Aerogel

Leader from JINR: A. Filippov

Participating countries and international organizations:

Title of the experiment: Development of the silicon aerogel technology and design of Cherenkov counters with radiators of this aerogel.

The goal of the investigation is to develop and improve the technology for production of silicon dioxide aerogel samples and to develop Cherenkov counters on the their basis for wide use in intermediate- and high-energy physics. These counters can be used to make detectors for very effective separation of beam particles in the particle momentum range from 0.4 to 2 GeV/c, which is impossible or difficult to do with the currently used detectors.

To realize the aerogel production procedure, a chemical shop for purifying raw material and production of silicon dioxide alcogel was established and an area for its drying at critical parameters was provided and equipped with 1-litre and 27-litreautoclaves (pressure 120 atm, temperature 260º).

The available equipment and the developed technologies allow us to produce high-quality aerogel samples with the refractive index 1.06–1.02, 60·60 mm2 to 160·160 mm2 in size, 30 mm thick (Fig. 1).

Work on improving qualitative parameters of silicon dioxide aerogel samples (transparency, hydrophobic behavior, etc.) continued, samples were produced to study their characteristics under working conditions. In addition, attempts were made to develop technology for production of samples with the refractive index n ~ 1.008 (problems arise from very high shrinkage of the sample).

Cherenkov counters with radiators of n ~ 1.05 aerogel were tested with beams of particles from the ITEP and LHE accelerators. The average number of photoelectrons was ~ 6 for radiators 6 cm thick. Similar data were obtained in the same experiments for aerogels produced at KEK (Japan) and in Novosibirsk.

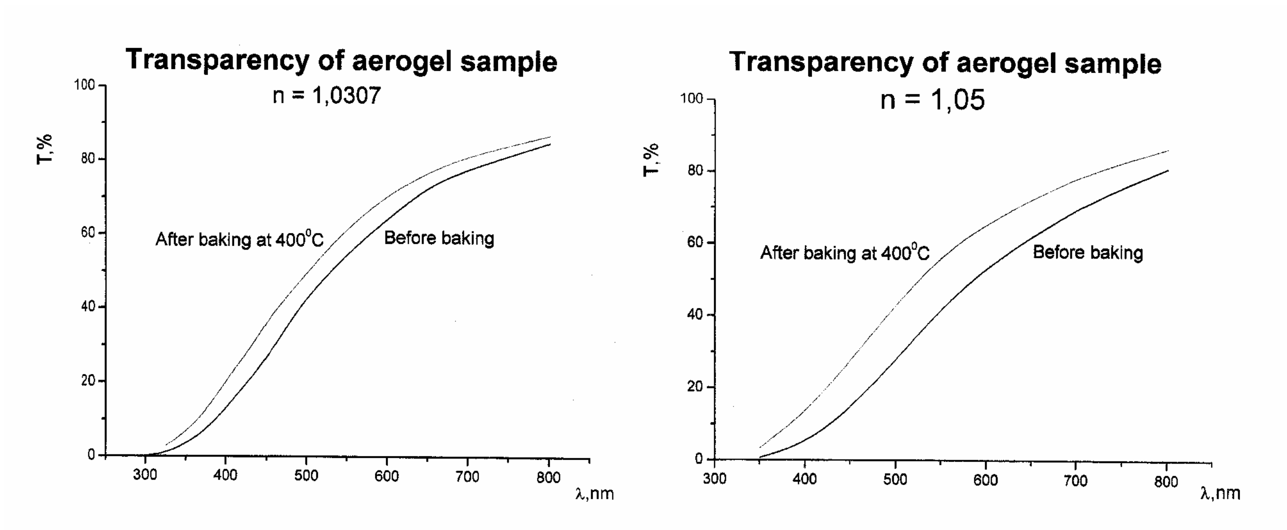

Fig.1. The high-quality aerogel samples with the refractive index 1.06–1.02, 60·60 mm^2 to 160·160 mm^2 in size, 30 mm thick.

05-2-1038-2001/2006

Priority of the project:

Status: New

Project SAD

Leader from JINR: V. Shvetsov

Participating countries and international organizations: JINR, Russia, Bulgaria, Czech Republic, Poland, Romania, Germany, France, Spain, Sweden.

SAD project is targeted to design and construction of the experimental installation on the basis of JINR Phasotron accelerator and subcritical blanket with uranium-plutonium mixed oxide (MOX) fuel for experiments on long lived fission products and minor actinides transmutation (Fig.1). The present conceptual design of the experimental subcritical assembly in Dubna (SAD) is based on the core with a nominal thermal power of 15–20 kW. This corresponds to the multiplication coefficient $k_{eff} \approx 0.95$ and the accelerator beam power of 0.75–1.0 kW.

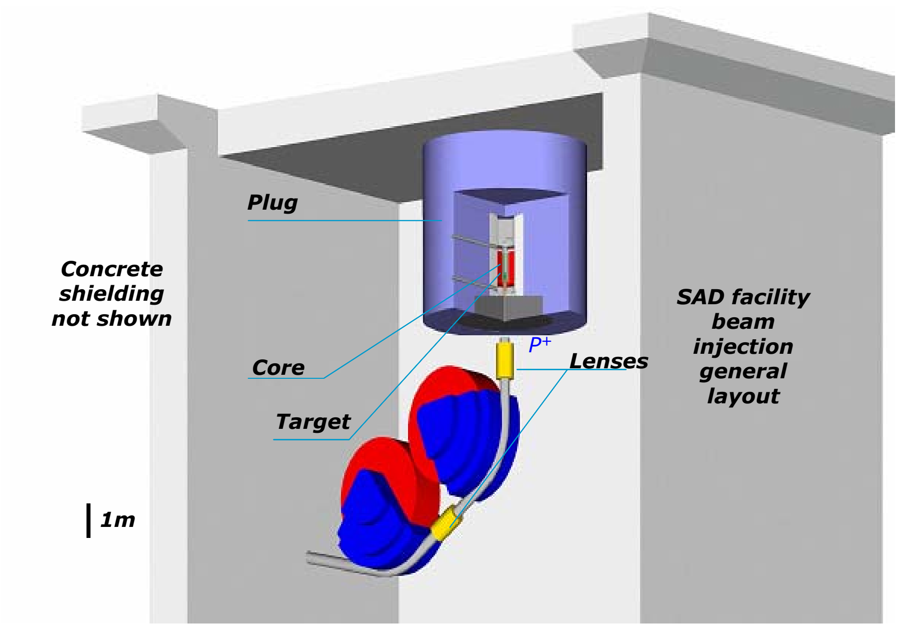

Fig.1. SAD facility general layout

Project main tasks

- Design and construction of the experimental prototype of subcritical assembly driven by proton accelerator SAD for subsequent realization of wide research program.
- Studying of the heavy neutron producing targets characteristics (neutron yield, spectral and angular distributions, composition and properties of products of interaction of primary protons and nuclear cascade particles with the target).
- Creation and test of technique for measurements and monitoring of reactivity, neutron noises of subcritical assembly based on it’s kinetic properties, substantiation of safety.
- Adjustment and test of relevant computer codes and data bases, used for calculations of the ADS characteristics

Guessed results and their usage

During implementation of the project the experimental installation will be created including the following main components:

- Subcritical assembly based on modernized fuel elements (FE) of BN-600 type with MOX fuel. FE contain 27%PuO_2+73%UO_2, average density of fuel 10.2 g/cm3. The content of 239Pu in PuO_2 is not less than 95%. Uranium in oxide is depleted one (0.4% 235U).
- Heavy replaceable target (Pb, W, Pb-Bi).
- Beam transport channel.

After realization of the project on the basis of SAD installation it is planned to implement next research program:

- Studying the operation modes of subcritical assembly in combination with the proton accelerator, development of techniques of measurement and control of parameters of the facility.
- Studying the problems of target and subcritical assembly integration, including influence of the target size and position on main SAD characteristics.
- Measurement of absolute value of a power gain of installation (for the decision of this task systems with a low level of power are most appropriate).
- Measurement of shielding efficiency (especially in a direction of a primary proton beam).
- Analysis of the neutron producing targets after long irradiation by protons, analysis of special samples (MA, LLFP), irradiated in ADS experimental channels (including the radiochemical analysis).
- Measurements of transmutation rates for MA and LLFP in different neutron spectra;

Project financing

Project financing is planed in main at the expense of resources of International Scientific and Technical Centre (ISTC). ISTC — international, intergovernmental organization founded in 1992 on the basis of the agreement between the European Union, Russian Federation, United States of America and Japan. From its headquarters in Moscow, Russian Federation, the Center provides weapons scientists from CIS countries with opportunities for redirecting their scientific talents to peaceful science. This is reflected in the Center Objectives and all activities and programs conducted at the Center. Since 1992, other Parties (member nations) have joined the Center in recognition of its important nonproliferation mission. The Parties support the activities of the ISTC operating Bodies, and organize regular Governing Board meetings. ISTC Governing Board allocated $ 1,200,000.00 for project financing.

JINR's Participation in Experiments at External Facilities

| 05-2-1039-2001/2006 |

| Priority of the project: |
Status: Data taking

The Double Beta Decay Experiment NEMO (Project NEMO)

Leader from JINR: V. Brudanin

Participating countries and international organizations: Czech Republic, Finland, France, Japan, JINR, Russia, Switzerland, the UK, the USA.

The NEMO project is devoted to search for neutrinoless double-beta decay ($0\nu\beta\beta$)

$$N(A,Z) \rightarrow N(A,Z+2) + 2e^-$$

which, when experimentally observed, will be a manifestation of new fundamental physics beyond the SM. Recent proof of neutrino oscillations phenomena (Super Kamiokande, SNO, and KamLand) indicates that neutrino is a massive particle. Nevertheless, the absolute value of neutrino mass remains a fundamental problem to be solved. Moreover, the nature of neutrino (either Dirac or Majorana) is unknown. The study of $0\nu\beta\beta$-decay is the best way to probe these two questions. Observation of this process would be a signature for neutrinos to be Majorana particles and it fixes the neutrino mass absolute scale.

The main goal of the NEMO project is to study double beta-decay of various isotopes and to probe half-life of $0\nu\beta\beta$-mode up to ~ 10^{25} years, which corresponds to (0.1–0.3) eV sensitivity for the effective majorana neutrino mass ($<m_\nu>$).

NEMO project was launched at 1988 passing two stages of development since that time. Construction of the NEMO-1 and NEMO-2 prototypes made it possible to optimize experimental techniques, and to investigate background conditions. In addition, the world's best values of $2\nu\beta\beta$-decay half-lives were measured with the NEMO-2 spectrometer for a set of isotopes (^{100}Mo, ^{96}Zr, ^{116}Cd, and ^{82}Se). Since February 2003 the NEMO-3 detector has been taking data in the Modane Underground Laboratory (4800 m.w.e., LSM, France).

The principal scheme of torroidal (∅3,1 m · 2.8 m height) NEMO-3 is shown in Fig.1. Tracks of two electrons emitted from thin foils (30–60 mg/cm^2) of $\beta\beta$-decay sources (7 isotopes with the total mass ~10 kg, and the main source is 6.9 kg of ^{100}Mo) are detected with Geiger chamber (~20 m^3, 6180 cells) and their energies are measured by a calorimeter (1940 scintillator/PMT channels). In addition to the sum energy of $\beta\beta$-decay electrons, the single electron spectrum and angular $\beta\beta$-distribution are measured by NEMO-3. This information can't be obtained from traditional geochemical and calorimetric methods of $\beta\beta$-decay measurements.

The γ-quanta are also detected by calorimeter (hits without tracks), which is very efficient for background investigation and rejection. A set of other features (TOF-measurements, use of magnetic field, passive iron (20 cm) and neutron (wood+water+paraffin) shielding) assist in essential reduction of background.

First results from the NEMO-3 were successively reported at different conferences (NANP03 (Dubna, Russia), NDM03 (Nara, Japan, June 2003), etc.). $2\nu\beta\beta$-decay spectrum of ^{100}Mo is presented in Fig.2.

After 5 years of data taking we plan to reach the announced sensitivity (0.1-0.3) eV for $<m_\nu>$ for ^{100}Mo. In addition, the NEMO-3 data allow us to choose the best $\beta\beta$-isotope for future investigations of $0\nu\beta\beta$-decay. The new stage of project (NEMO-4) is discussed inside the NEMO collaboration at the present moment. Preliminary estimations show that one can reach sensitivity ~ 1.5–2·10^{26} years ($<m_\nu>$ ~ 0.04÷0.1 eV) with 100 kg of ^{82}Se only. This makes NEMO-4 a more realistic project in comparison with the modern ton-source $0\nu\beta\beta$-decay projects. One needs also to keep in mind the possible observation of $0\nu\beta\beta$-decay in NEMO-3, as far as the modern theory doesn't exclude 0.1 eV scale for <m_ν>. Finally, it should be emphasized that in the coming 5–10 years new results in the investigation of the double beta decay will be associated primarily with NEMO-3. This is the time that new projects of this scale need to pass from R&D stage to practical implementation.

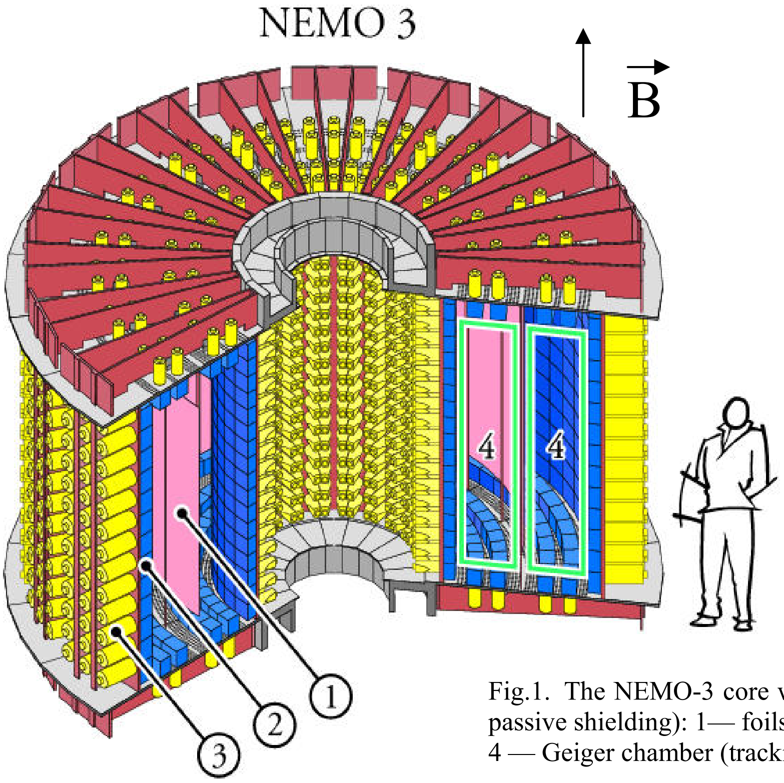

Fig.1. The NEMO-3 core without surroundings (magnetic coils and passive shielding): 1— foils-sources; 2— scintillators; 3 — PMT; 4 — Geiger chamber (tracking detector).

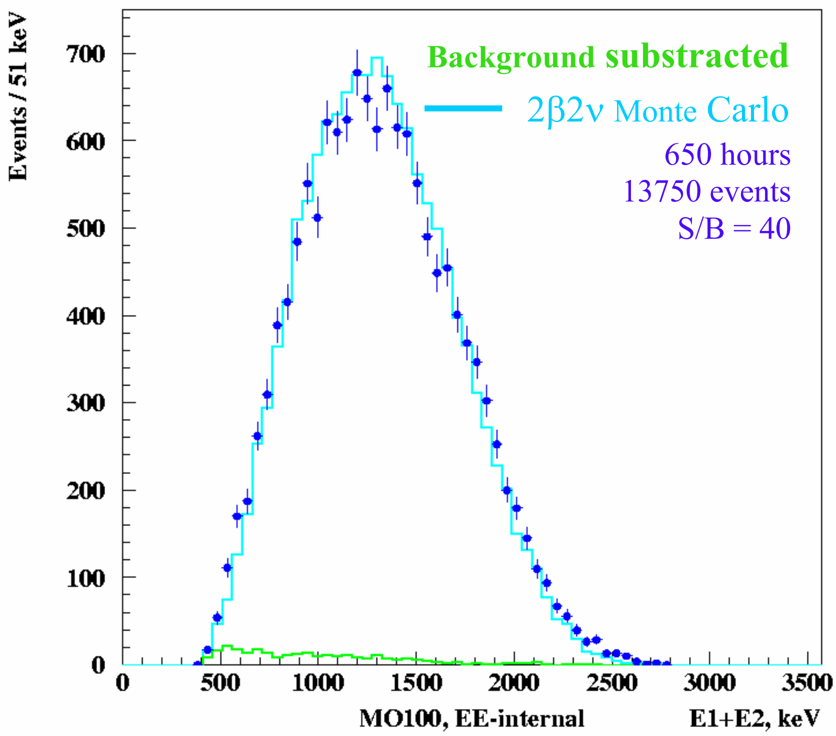

Fig.2. The spectrum of sum energy of electrons in double two-neutrino beta decay of ^{100}Mo from first portion of NEMO-3 data.

$T_{1/2}$=7.8±0.09 (stat)±0.8 (syst)·10^{18}y

05-2-1039-2001/2006

Priority of the project:	
Status:	Data taking

Experiment TGV-2 for the Investigation of Double Beta Decay of ^{48}Ca and Double Electron Capture of ^{106}Cd (Project TGV)

Leader from JINR: V. Brudanin, I. Stekl

Participating countries and international organizations: JINR, Czech Republic, France.

Investigation of ultra-rare double beta decay processes (e.g. $\beta^-\beta^-$, $\beta^+\beta^+$, β^+/EC, EC/EC) is of major importance for particle and nuclear physics as a powerful tool for the study of lepton conservation in general and neutrino properties in particular. The goal of the TGV project is to study of 2β 2ν, 2β 0ν decays of ^{48}Ca, and 2K2ν, 2K0ν decays of ^{106}Cd, using a low-background multi-detector spectrometer TGV-2 (Telescope Germanium Vertical). ^{48}Ca and ^{106}Cd are the most favorable candidates for searching double beta decay and double electron capture processes. However, the small natural abundance (0.187% for ^{48}Ca and 1.25% for ^{106}Cd) and the unfeasibility of producing sufficient quantities of these isotopes make studies of rare decays rather difficult. The mentioned problem can be partly solved by using a double beta spectrometer with extremely high efficiency for the investigation of passive (external) sources. The spectrometer TGV-2 has been developed using the experience gained from application of the HPGe spectrometer TGV for studying of double beta decay of ^{48}Ca with only of 1 g of enriched isotope.

Spectrometer TGV-2 is created on the base of 32 planar type HPGe detectors with sensitive volume of 2040 mm^2·6 mm each (about 3 kg of Ge). Detectors are mounted vertically one over another together with thin (50 mg/cm2–100 mg/cm^2) homo-genius double beta emitters in a special design ultra low-background U–style cryostat. Constructive details surrounding detectors and the parts of the cryostat were made from materials with ultra low level of radioactive impurities (U+Th<0.1 ppb). The distance between the surfaces of the detectors and the double beta emitters is <1.5 mm. Detectors are cooled by liquid nitrogen. The total sensitive volume of detectors is about 400 cm^3. The energy resolution of the detectors is in the range from 3.0 to 4.0 keV (^{60}Co, 1332 keV).

The detector part of the TGV-2 is embedding into a passive shielding of 20 cm thick copper, a steel airtight box against Radon, a 10 cm thick lead and a neutron shielding made from polyethylene, filled with boron, with a thickness of 16 cm. The spectrometer TGV-2 is mounted in the Modane underground laboratory (4800 m w.e.), France.

The base electronic scheme of TGV-2 (for the investigation of double beta decay of ^{48}Ca) consists of 32 identical channels (NIM and CAMAC modules) and provides information about the particle energy (pulse amplitude), particle type (pulse rise time) and time difference between coincidence pulses. Some methods of an active suppression of the radioactive background, namely selection of only double coincidence events from neighboring HPGe detectors and distinguishing β particles and γ-rays by the different rise time of the detector pulses, are used in the TGV-2 for the study of double beta decay of ^{48}Ca. In case of double electron capture investigation, electronic scheme changes. Two separate spectroscopy amplifiers with different shaping time are used in each channel to obtain an additional suppression of electronic noise in the low energy region (<50 keV). The main part of TGV-2 electronic modules are produced by JINR.

The background of the spectrometer TGV-2 was investigated in a series of long term measurements and obtained suitable for the study of 2β 2ν, 2β 0ν decays of ^{48}Ca, and 2K2ν, 2K0ν decays of ^{106}Cd.

To prepare a study of double beta decay of ^{48}Ca, powder of enriched ^{48}Ca (enrichment 73%) was chemically purified from ^{60}Co, ^{226}Ra, ^{228}Th and then tested using a 400 cm^3 low-background

HPGe detector in the Modane underground laboratory. Mentioned measurements with an external source of 24.6 g of enriched $^{48}CaF_2$ (about of 10 g of ^{48}Ca) lasted 1590 hours and new limits on β^- decay of ^{48}Ca→^{48}Sc and $\beta^- \beta^-$ decay of ^{48}Ca to excited states of ^{48}Ti were obtained. The limits for β^- decay to the 6^+ ground state, excited 5^+ and 4^+ states in ^{48}Sc are $1.6 \cdot 10^{20}$y, $2.5 \cdot 10^{20}$y and $1.9 \cdot 10^{20}$y at the 90% CL. For the $\beta^- \beta^-$ decay to ^{48}Ti the limits to the first 2^+, second 2+ and first 0^+ excited states are $1.8 \cdot 10^{20}$y, $1.5 \cdot 10^{20}$y and $1.5 \cdot 10^{20}$y at the 90% CL. The mentioned limits were improved in our measurements by more than an order of magnitude.

To prepare thin (50 mg/cm^2–100 mg/cm^2), homo-genius double beta emitters for TGV-2 an original method of pressing investigated isotopes between teflon and polyethylene foils has been developed. At present, about 10 g of enriched ^{48}Ca are ready after purification to be installed in TGV-2 and start the main measurement.

The main exposition with each type of double beta emitters (^{48}Ca and ^{106}Cd) will last on TGV-2 for no less than one year. Additional long term measurements of natural Ca and Cd samples, and background are also needed to be done. Thus, the project TGV is proposed to be prolong at for 3 years.

05-2-1039-2001/2006

Priority of the project:
Status: Data taking

Measurement of the Muon Capture Rates for 2β-decay Project ANCOR

Leader from JINR: V. Egorov

Participating countries and international organizations: JINR, France, Finland.

One of the most powerful means to check the nature of the neutrino is the process of double beta decay. In addition to an allowed, but very rare $2\beta2\nu$ decay mode, there may be an "exotic" $2\beta0\nu$ mode which is forbidden by the minimal Standard Model and would be an evidence of a non-zero Majorana neutrino mass. At the same time, the corresponding partial decay rate $\lambda_{2\beta0\nu}$ depends not only on the neutrino mass m_ν and the phase-space factor F, but also on the value of the nuclear matrix element M:

$$\lambda_{2\beta0\nu} \sim (\langle m_\nu\rangle/m_e)^2 \times |M_{0\nu}|^2 \times F_{0\nu}$$

When considering the end-point energy $Q_{\beta\beta}$, the best candidates for 2β-experiments are those presented in Table 1. However, even with high $Q_{\beta\beta}$-values (and, therefore, high F-factor), the probability of both processes is extremely low and can be completely killed by a small M-value which is not so easy to calculate with sufficient precision.

It is generally accepted that the 2ν and 0ν double beta decays of a (A, Z)-nucleus proceed via virtual transitions through 1^+ and other multipole states of an intermediate (A, Z+1) nucleus (Fig.1).

Table 1: Nuclei for 2β-decay.

Isotope	Decay	$Q_{\beta\beta}$ [MeV]	Nat. abundance
^{48}Ca	$2\beta^-$	4.276	0.19 %
^{150}Nd	$2\beta^-$	3.368	5.64 %
^{96}Zr	$2\beta^-$	3.351	2.80 %
^{100}Mo	$2\beta^-$	3.034	9.63 %
^{82}Se	$2\beta^-$	2.992	8.73 %
^{116}Cd	$2\beta^-$	2.804	7.49 %
^{106}Cd	$2EC$	2.770	1.25 %
^{130}Te	$2\beta^-$	2.529	33.80 %
^{136}Xe	$2\beta^-$	2.467	8.90 %
^{136}Ce	$2EC$	2.400	0.19 %
^{76}Ge	$2\beta^-$	2.039	7.44 %

A reliable theoretical description of these transitions needs to be experimentally tested, mainly the calculated transition amplitudes. Unfortunately, only one (the lowest) virtual transition through the ground state of the (A, Z+1) nucleus can be probed by the traditional electron-capture or β^--decay measurements.

In our work we use the ordinary muon capture (OMC, Fig.2) to the relevant excited states as a probing tool for the nuclear wave functions involved in the amplitudes of many virtual transitions of the 2β-decay.

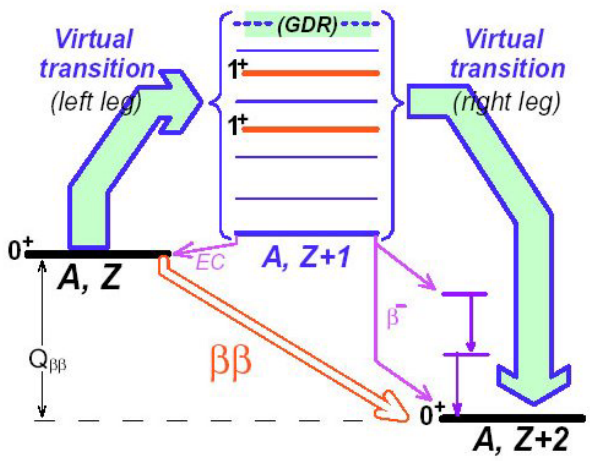

Fig.1. 2β-decay of a hypothetic (A, Z) nucleus.

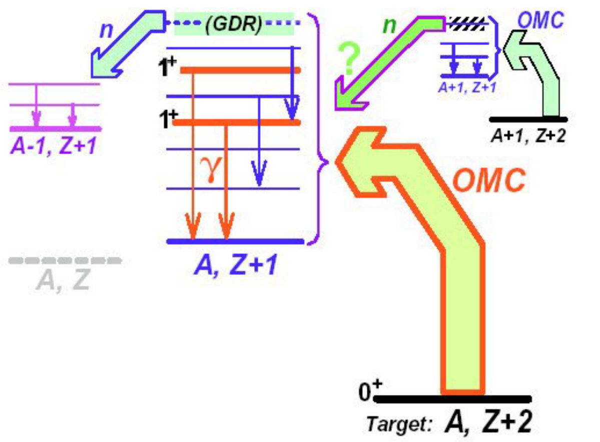

Fig.2. Excited states of the (A, Z+1) nucleus can be populated in μ-capture by the (A, Z+2) and (A+1, Z+2) targets.

In order to obtain reliable information for the most interesting 2β-decaying nuclei, we proposed to measure, with high-precision HPGe detectors, the partial μ-capture rates in ^{48}Ti and other enriched targets (high enrichment is certainly necessary to suppress the background (μ, νn)-reaction on the A+1 isotope which can populate the same levels and thus distort the γ-lines intensity, as shown in Fig.2).

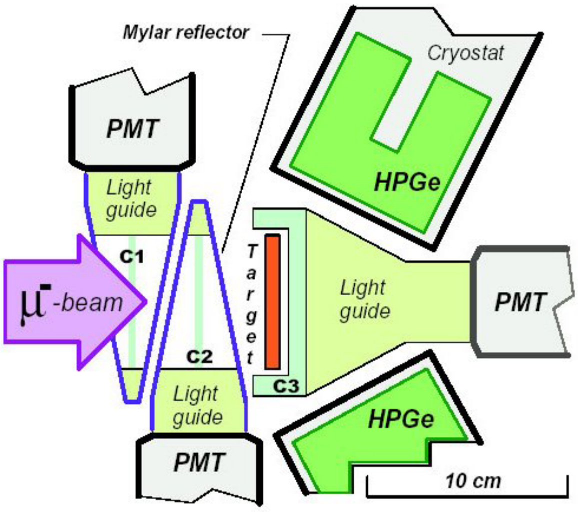

Fig.3. Experimental setup.

As the first step, one-gram targets of ^{48}Ca, ^{48}Ti, ^{76}Se, ^{106}Cd, ^{116}Sn and ^{150}Sm were irradiated with slow muons at the $\mu E4$ area of the PSI "muon factory" (Villigen, Switzerland) and measured with four large volume HPGe detectors (Fig.3).

Spectra of γ-rays following the μ-capture were analysed as a function of time after the muon stops in the target. The most intense γ-lines corresponding to the process under consideration were singled out, and the time-evolution of their intensities was investigated. This allowed us to eliminate completely background components caused by muons stopped in the atoms other than those investigated[1].

As a result, the total muon-capture rates have been extracted with a good accuracy. Fig.4 shows an example of such measurements performed with enriched ^{48}Ca and ^{48}Ti targets compared to a natural metallic calcium (97% of ^{40}Ca).

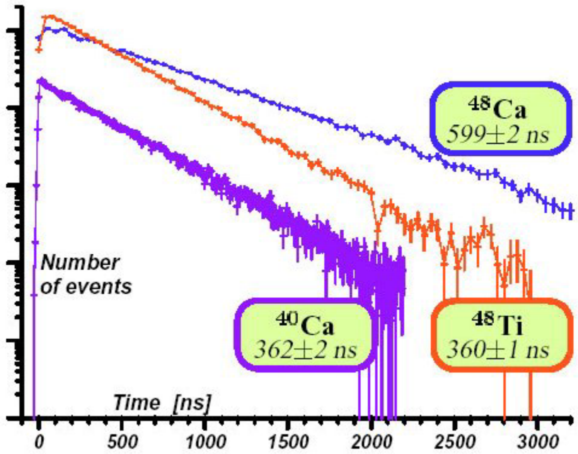

Fig.4. Time evolution of γ-lines following the μ-capture by ^{40}Ca, ^{48}Ca and ^{48}Ti targets (spectra are not normalized).

The highest attention was paid to the ^{48}Ti target. It was measured almost during one week and provided statistics high enough to get the intensities of most of the γ-lines and to analyse their balance in order to extract the partial capture rates with the required precision (10–20%). Detailed data analysis is in progress, and our future plans depend on its results.

This work is partially supported by the Russian Fund of Basic Research (grant 02-02-16800)

[1] Normally, an enriched isotope is delivered not in a form of a single element but as an associated compound (oxide, carbonate, etc.).

AC/μC : Angular Correlations in Muon Capture

In the Standard Model (SM) all weak interaction processes are of the V-A type. Although there is strong experimental evidence for the V-A form of the charged weak current, the possible admixture of genuine scalar (S) and tensor (T) type interactions cannot be excluded and — as a matter of fact — is even present in most scenarios for physics beyond the SM, such as leptoquarks or Rparity violating interactions in supersymmetry. In principle, charged Higgs particles could also induce such a coupling. As a consequence, considerable efforts were undertaken in the beta-decay sector to search for possible effects, which could signal deviations from the SM.

The present work extends the search for the genuine scalar interaction on the muonic sector. Here the genuine scalar coupling C_S could be different and even enhanced and would contribute to various observable quantities in muon capture summed with the induced scalar coupling: $(C_S + g_S)$.

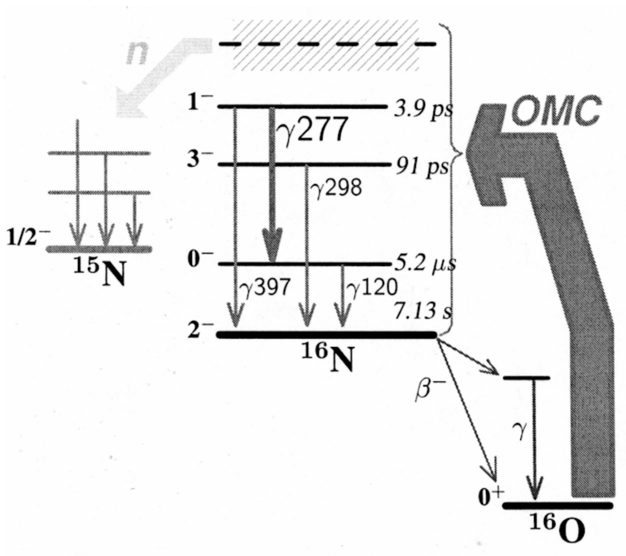

Fig.1. Muon capture on ^{16}O and decay scheme.

The investigated reaction of (Fig.1) is a two-step process which consists in the first-forbidden ($0^+ \rightarrow 1^-$)-transition of ordinary muon capture (OMC) in a zero-spin ^{16}O nucleus followed by γ-emission from the excited recoiling daughter nucleus.

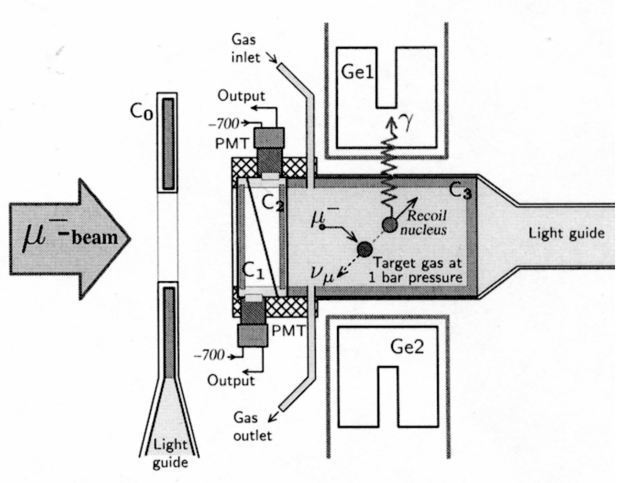

Fig.2 Gas target operating at atmospheric pressure.

As the life time of the 1^--level is relatively long (almost 4 ps), a low density target — oxygen gas at a few bar pressure — must be used in order to reduce the slowing-down of the recoil nuclei in the target material. At the same time, the percentage of muons stopped in the gas with respect to other constructional materials should be as high as possible. Following these conditions, a special gas target (Fig.2) was constructed and used at the μ E4 beam-line[2] of PSI.

Figure 3 shows an example of γ-spectra measured at atmospheric pressure with HPGe detector in a 3-weeks experiment.

Using the method based on the Doppler effect and developed in our previous work, one can investigate the correlation between the moment $\vec{q}$ and $\vec{k}$ of the neutrino and the γ-quantum. In this case the shape of the Doppler-broadened γ-line is determined by the convolution of the detector response function (calibrated with a reference ^{169}Yb source) and the correlation function W which can be approximated by:

$$W = 1 + a_2^1 \cdot P_2(\vec{k}\vec{q}) \ , \qquad (1)$$

[2] The feature of this beam is an excellent monochromaticity which allows us to stop muons in a very thin target.

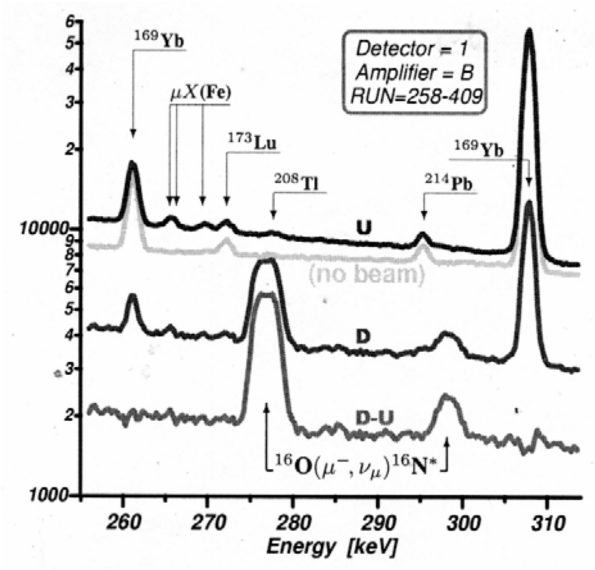

Fig.3: Fragments of γ-spectra measured with an oxygen gas target: *U* — Uncorrelated (with and without beam), *D* — Delayed, *D-U* — Differential.

where $P_2(\cos\theta)$ is a Legendre polynomial. The correlation coefficient a_2^1 depends on the relative values of the nuclear matrix elements (NME) and the Weak Interaction couplings. In our experiment the following a_2^1 value has been obtained:

$$a_2^1=0.096\pm0.020\ . \qquad (2)$$

To transform this model-independent value to the Scalar coupling estimation (Fig.4), we used the NME calculated with three different residual interactions: ZBMI, REWIL and ZWM. All of them lead to the similar (C_S+g_S) value different from zero.

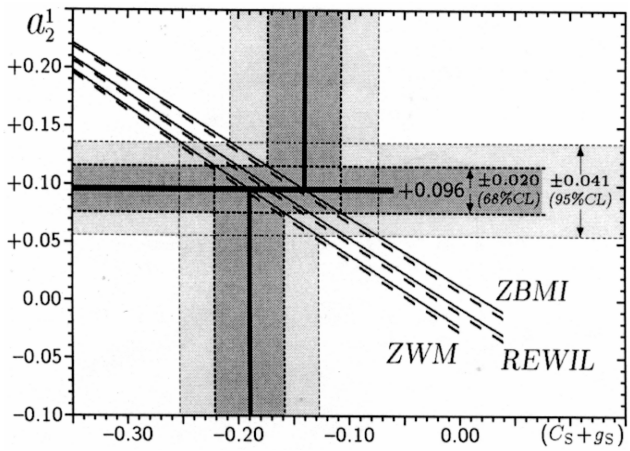

Fig.4 Transformation of the correlation coefficient a_2^1 to the (C_S+g_S) value.

The best way to confirm or to disprove such non-trivial result (as well as the results of our previous experiments with ^{28}Si indicating significant quenching of the Induced Pseudoscalar interaction) would be a repetitive experiment with another target nucleus. After several tests, neon gas at atmospheric pressure has been chosen as the most promising candidate.

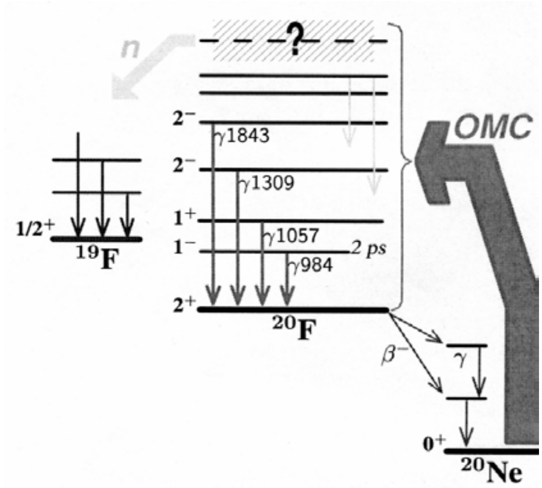

Fig.5 Muon capture on ^{20}Ne and decay scheme.

Several interesting processes take place when a muon is captured by the ^{20}Ne nucleus (Fig.5). Among them are: the first-forbidden ($0^+\to1^-$)-transition sensitive to the Scalar coupling, the allowed ($0^+\to1^+$)- and two unique ($0^+\to2^-$)-transitions sensitive to the Induced Pseudoscalar coupling, and also transitions to the Giant Dipole Resonance states followed by the neutron emission.

The γ-lines corresponding to the above processes are Doppler-broadened due to the nuclear recoil caused by the neutrino and the neutron emission.

To calibrate the response function of the detectors, a radioactive ^{60}Co source was placed near the target; the corresponding γ-lines are narrow and their intensities do not change in time. On the other hand, the lines of ^{19}F have a typical “triangle” shape caused by the contribution of two recoil components — from the neutrino and the neutron. Analysis of this shape should provide information on the intermediate GDR-states which are not detected direct.

05-2-1039-2001/2006

Priority of the project:

Status: Data taking

Investigation of Interactions between Light Nuclei at Ultralow Energies by Using Liner Plasma (Project LESI)

Leader from JINR: V. Bystritsky

Participating countries and international organizations: JINR, Russia, Poland, the USA.

Over the period from 1996 to 2003 at the HCEI SD RAS (Tomsk) on high-current pulsed accelerators the SGM and MIG experiments for studying reactions between light nuclei at ultralow energies using liner plasma have been carried out.

For the first time experimental values of the astrophysical S-factor and the effective cross section of the dd reaction at ultralow deuteron collision energies 1.8, 2.06, and 2.27 keV are obtained.

In 2000 we carried out investigations of the dynamics of the inverse deuterium Z-pinch formation.

For the first time the characteristics of the deuterium liner accelerated in the inverse Z-pinch scheme up to velocities $(2.8–7.2)\cdot 10^7$ cm/s are measured, the character and the level of the neutron and γ radiations accompanying the liner acceleration process are investigated.

A new optical method for measurement of energy distribution of accelerated liner ions based on detection of the liner optical radiation (H_α and H_β lines) was investigated in parallel with the study of the inverse Z-pinch formation dynamics.

Figures 1 and 2 show the dd reaction research results obtained by us for the first time.

All our results indicate that the proposed method of the research of strong interactions in the region of ultralow collision energies with use of the direct and “inverse” Z-pinch holds promise and allows the study of nuclear reactions between light nuclei in the energy range inaccessible to the classical accelerators.

In addition, interaction of the ion beam characterised by a rather large energy spread with the targets was theoretically considered. Simple analytical expressions are obtained for the estimation of the product output of the reactions between light nuclei.

Since 2001, in parallel with the work at the HCEI SD RAS, investigations of possibility to use plasma counter fluxes for study of the dd, pd and dHe reactions in the collision energy region 3–7 keV have been conducted at the TEMP facility at the NPI TPU.

Over the period from 1996 to 2003 we have published 16 papers within the framework of the “LESI” project.

In 2003 the experimental facility at a more powerful pulsed accelerator MIG (I=1.8 MA, τ=80 ns) of the HCEI SD RAS was installed and commissioned. This transition has been carried to continue the study of the mechanism of the reactions between light nuclei at higher energies 3–7 keV (in comparison with the achieved befor energy region at the accelerator SGM).

These researches at the MIG will make it possible not only to obtain for the first time the results in the given energy region, but also to compare them correctly both with the calculations and with the results obtained at classical accelerators.

We plan to carry out the study of the of the pd, dd and d^3He- reactions in the 2004–2006 in the collision energy ranges 3.0–7.0 keV and 3–10 keV, respectively. 16 scientific articles devoted to proposal LESI were published.

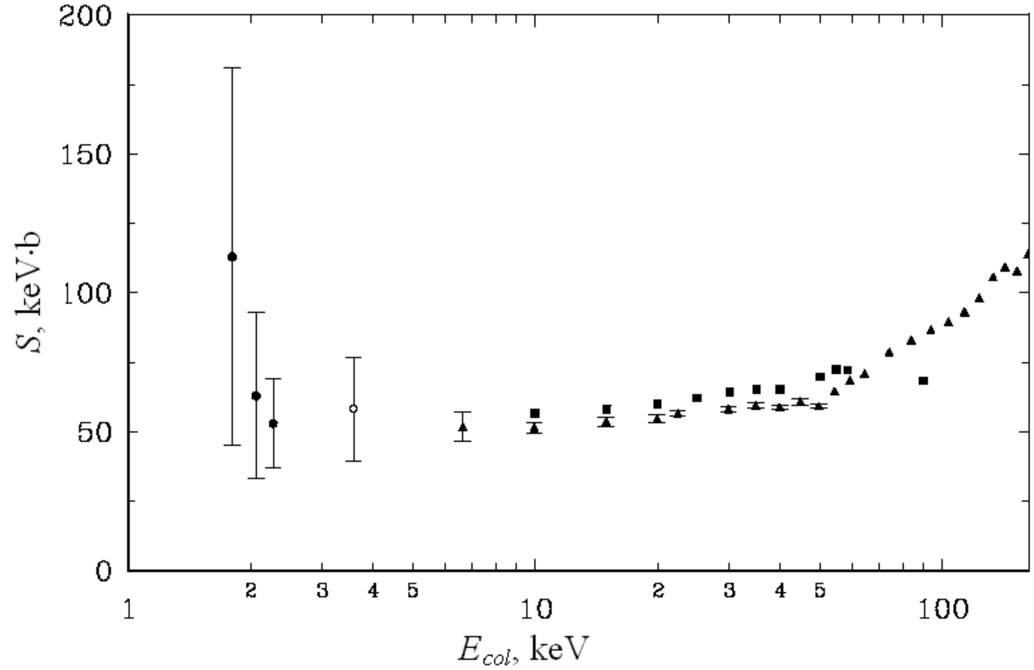

Fig.1. Astrophysical S-factor for dd reactions as a function of the deuteron collision energy: •, ○ are the results of the "LESI"collaboration; ■, ▲ are the data from the papers by R.E.Brown and N.Jarmie, Phys.Rev.C41 (1990) 1391; A.Krauss , H.W.Becker, H.P.Trautvetter et al., Nucl. Phys. A465 (1987) 150.

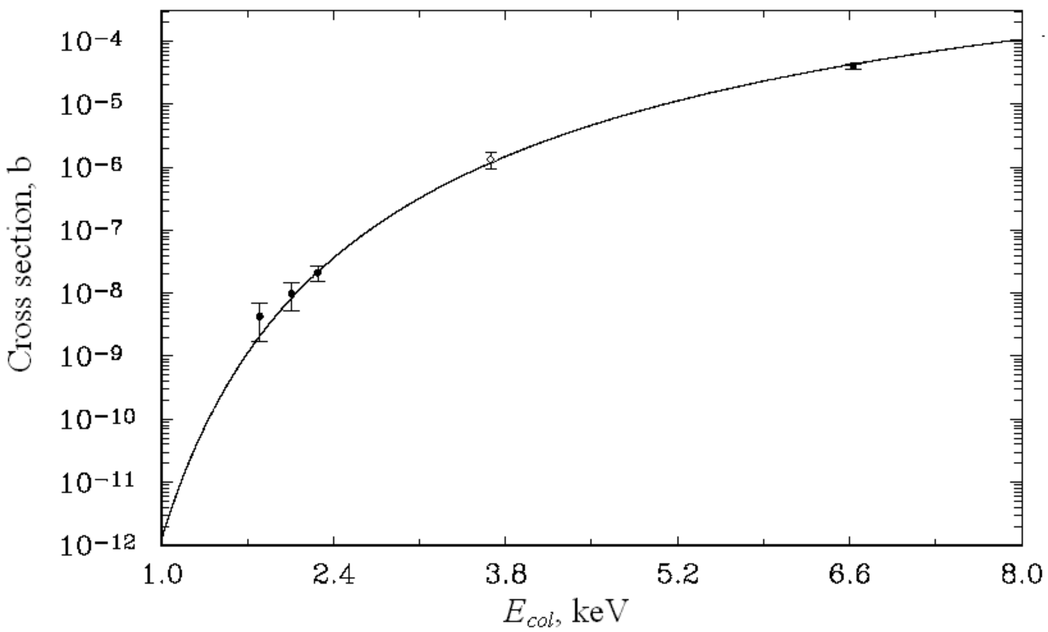

Fig.2. Dependence of cross section of the dd reaction on the deuteron collision energy: •, ○ are the results obtained by the "LESI" collaboration; ■ is the data from the paper by A.Krauss, H.W.Becker, H.P.Trautvetter et al., Nucl. Phys. A465 (1987) 150; the solid curve is the dependence calculated with the S-factor value S = 53.8 keV·b, found in the "LESI" investigations.

05-2-1039-2003/2006

Priority of the project:

Status: New

Dark Matter Search with Germanium Detectors
Project DM-GTF

Leader from JINR: V. Bednyakov

Participating countries and international organizations: Germany, JINR, Slovak Republic.

The project is aimed at direct measurements of dark matter particle elastic interaction with Ge isotopes. The design, development and construction of a new setup (with "naked" high purity Ge detectors directly in liquid nitrogen) are finished in the Gran Sasso (Italy) underground laboratory. The setup is a pilot experiment for the future highly new-generation experiments with full-scale GENIUS (GErmanium in liquid Nitrogen Underground Setup). With this pilot setup (Fig.1) assuming a final target mass of 40 kg, an energy threshold of 12 keV and a background index of 4 counts/ (kg keV y) corresponding to ~ 0.01 counts/(kg keV d) in the energy region 11–100 keV one would need a significance of 190 kg y to see the claimed DAMA annual modulation (Fig.2) with 95% probability and 90%C.L. This corresponds to an overall measuring time of approximately five years which would correspond to the life time of this experiment. Another application will be to test the prerequisites necessary to realize the GENIUS-type full-scale project (measure impurities in materials and nitrogen; develop and test a holder system for detectors; test long term stability of operating HPGe detectors in LiN; and develop new data acquisition system and electronics). In order to achieve a dramatic step forward, background reduction, the GENIUS concept is based on the application of standard detection techniques while removing all dangerous contaminations from the direct vicinity of the detectors. The concept has the great advantage no individual cryostat system is needed. Instead, the HPGe crystals (2.5 kg each with threshold of 500 eV and resolution of 700 eV at 100 keV) are surrounded by liquid nitrogen of much higher radiopurity which in addition provides ideal cooling and shielding against external radiation.

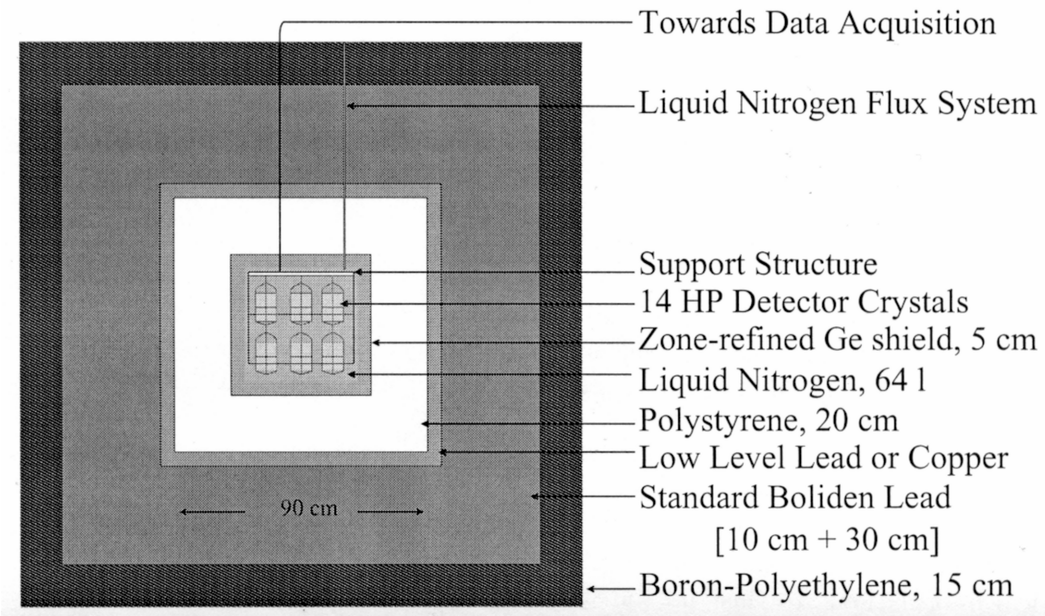

Fig.1. GENIUS-TF.

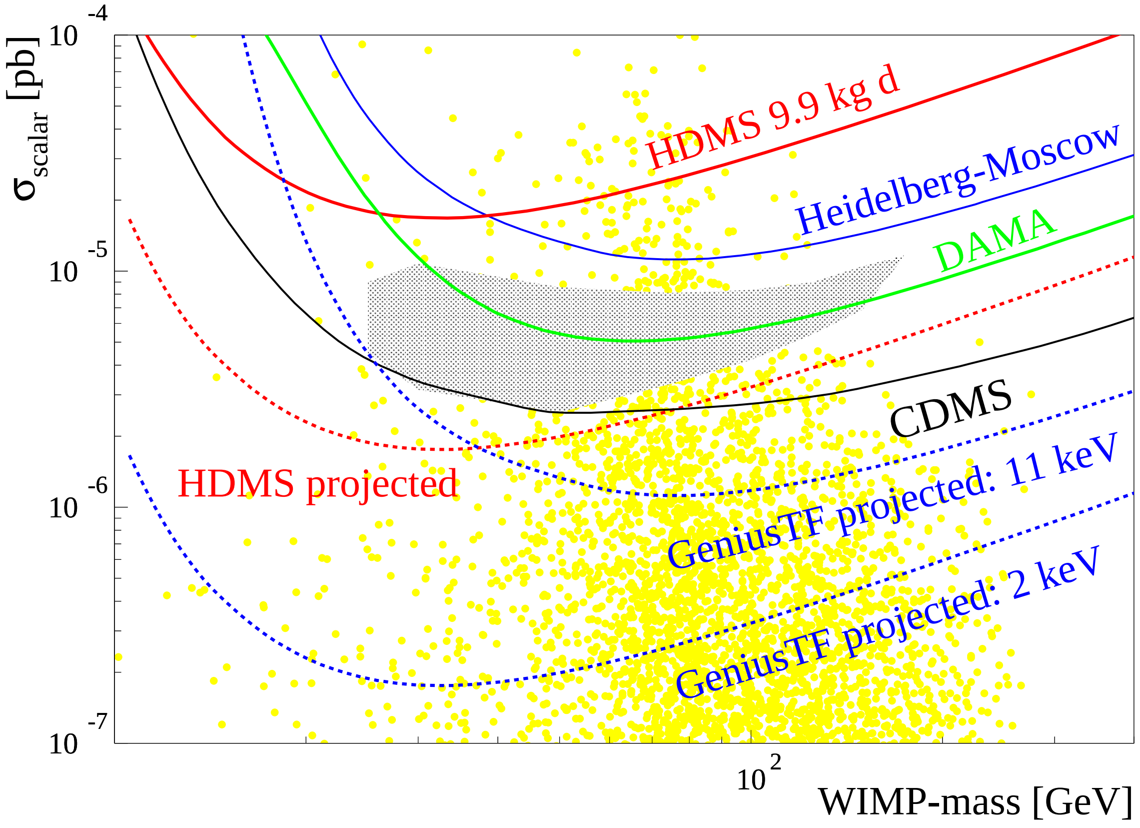

Fig.2. Exclusion plot of the scalar WIMP-nucleon elastic scattering cross-section as a function of the WIMP mass. The small shaded area represents the 2σ evidence region from the DAMA experiment. The dashed curves are the expectation for GENIUS-TF.

The JINR team is already involved in hardware and relevant software development as well as detector simulation. Due to the fact that one should search for very rare events, and on the way one needs to obtain convincing evidence of dark matter it is very important to stay on the basis of all available experimental, cosmological and theoretical information. To this end, the theoretical support will include creation of numerical codes for data development and analysis (seasonal modulation, etc.) together with interpretation of the experimental data on the basis of modern supersymmetric extensions of the Standard Model.

The main physical goal of GENIUS-TF is to prove or disprove the DAMA evidence region using both, the WIMP-nuclear recoil signal and the annual modulation signature, within a time scale of about 5 years. At the second step (if any) the GENIUS-TF has potential to improve the limit on the effective Majorana neutrino mass down to about 0.1 eV.

05-2-1039-2001/2006

Priority of the project:

Status: Data taking

Project ANKE COSY

Leader from JINR: V. Komarov

Participating countries and international organizations: JINR, Germany, Poland, Russia.

A Problem under investigation and the main goal of study

The investigated problem concerns the proton-nucleus interaction at high momentum transfers. At the transfers higher than ~ 0.4 GeV/c the nuclear structure is probed at short distances

in a range of the nucleon overlapping, and energy transfers to few-nucleon groups in a range of ~0.3–0.7 GeV lead to local high excitations of the nuclear matter. Features of the few-nucleon systems in such conditions are a poorly investigated field of nuclear physics. To know them it is necessary to comprehend the transfer from the nucleon systems to the quark-gluon ones. In particular, the obtained information is need for persuasive and profound interpretation of the cumulative processes. The immediate goal of the project is a study of the deuteron breakup induced by protons of 0.5–2.8 GeV energy in kinematics close to that of the backward elastic pd-scattering:

$$p + d \rightarrow (pp)_s + n(180°) \qquad (1)$$

$$p + d \rightarrow (pn)_s + p(180°) \qquad (2)$$

($(pp)_s$ and $(pn)_s$ denote here the forward emitted nucleon pair with a small relative energy.)

Breakup through the channels (1) and (2) is studied with a complete reconstruction of the event kinematics and use of the polarized protons and deuterons. Therefore, this simplest cumulative process may be investigated in the most informative way.

Current importance of the problem, information about recent studies of it, already obtained results of the Collaboration in the topic.

Nuclear short range structure is one of the fundamental problems of nuclear physics. Recently it has been studied especially intensively in electron-nucleus interactions at the Jefferson Laboratory (USA). The experiments on proton-nucleus interactions give independent information for the problem solution since the energy-momentum transfer in the latter is provided by quanta of not the electromagnetic but the strong interacting field. The accelerators admitting effective research of such kind are nowadays the JINR Nuclotron and the proton synchrotron COSY (Jülich).

The present project is based on the use of a wide purpose magnetic spectrometer ANKE implemented at the internal beam of COSY. It is in the frame of the international collaboration ANKE of physicists from 7 scientific centers of Germany, JINR, 4 scientific centers of Russia, 3 institutes of Poland and also of Georgia and Great Britain. The immediate participation in the experiments of the present project hold the colleagues from JINR, FZ-Jülich, FZ-Rossendorf , the universities of Muenster, Koeln, Erlangen, Tbilisy, MGU (Moscow), ITHEP and SPINP (Gatchina).

The physicists of DLNP JINR have proposed and realized together with the ANKE collaboration colleagues a program of the experiments COSY EXP.20, which is the dominant part of the project. Two detector groups providing record of processes (1) and (2) are developed and commissioned in the experiments. A software support of the experiments has been also developed. In the beam-time runs of 2001 and 2003 the energy dependence of the cross section of the breakup (1) and vector analyzing power of the process have been measured. The first results of this study are already published.

The expected results

At completing of the project the spin-averaged differential cross sections of the deuteron breakup in channels (1) and (2), vector and tensor analyzing power and spin-spin correlations will be measured. Processing of the already taken data for determination of cross sections and vector analyzing power will be completed until 2005. A polarized deuterium target, developed in the collaboration for the ANKE spectrometer should be installed in it in 2004. The measurements are planned for 2005–2007 with data processing and analysis until 2009. Besides the main task, a study of the charge exchange proton-neutron scattering will be performed in the frames of the project.

It will be done by an investigation of the deuteron breakup at momentum transfers close to zero:

$$d + p \to (pp)_s + n(0°) \quad (3)$$

At the deuteron beam, the process requires about the same conditions of the proton pair detection as processes (1) and (2).

Use in the collaboration of the detector systems and the software support , developed by the JINR physicists, expects their participation in several experiments on the study of omega, φ and a(zero)-meson production at energies from the thresholds up to 2.8 GeV.

Scientific significance of the results

Fulfilling of the program in full amount of the planned investigations will create an experimental database for a systematic analysis of the simplest cumulative process. Such analysis may serve as a foundation for understanding transition from the nucleon systems to the hadron/quarkgluon ones (conditions of the transition, its characteristics, approaches of the description).

Required resources in 2004–2009 years

Total amount of financing:

JINR budget expenses by the theme 1040 — 22 K$/year · 6 =132 K$
BDR BMBF grant — 25 KEuro/year · 6=150 KEuro

Computer net resources :

Use of computers purchased at the project means and use of the computing-information net of DLNP JINR.

Employed personal:

Main executors (100% employed) — 9 persons
Partly employed (30%–60%) — 3 persons

05-2-1040-2001/2006

Priority of the project:

Status: Data taking

Investigation of the Muon Properties and the Muon Interactions with Matter (Project MUON)

Leader from JINR: V. Duginov

Participating countries and international organizations: Russia, Switzerland.

Main goals of the project are study of the properties of muon and muonium, measurements of the magnetic moment of negative muon in 1S-state and μSR (Muon Spin Rotation, Relaxation, Resonance) investigations of muon behavior in matter and its application to the physics of condensed matter.

Muons are high-sensitive microprobes wich allow one to examine the processes leading to their depolarization in the interior of matter. Muons can also detect defects in crystals or provide the information, for example, on how hydrogen would behave within semiconductors, insulators, or organic molecules.

We will continue the study of the phenomenon of the change of the magnetic moment of a Dirac particle bound to a nucleus. The change of the magnetic moment of electron is due to its relativistic motion on Bohr orbital and is called the relativistic correction. But measurement of the magnetic moment of a deeply bounded electron can't be done in practice. This phenomenon can be studied for negative muon in the 1S-state of different atoms. We suppose to measure the magnetic moment of negative muon in the 1S-state both in light and heavy atoms.

Investigations of the behavior of the shallow acceptor centers in diamond structure semiconductors are being performed on the JINR phasotron and on the meson factory PSI (Switzerland).

This interest is connected with the wide discussion of the quantum computers also. Application of the traditional methods for investigation of the acceptor centers in these semiconductors (EPR) is limited by a high spin-lattice relaxation rate of the magnetic moment of the acceptor and by random crystal strains.

In 2004–2007 we suppose to study the interaction of the acceptor impurity in:

- Si(Al) at the one axis pressure;
- boron in the artificial diamond;
- boron and aluminum in the silicon carbide (SiC).

The results on the electronic structure of acceptor centers in the diamond and silicon carbide have both the independent scientific interest and the importance forte application of the heterostructural semiconductors.

Muonic technique is a reliable and generally accepted method to study magnetic phenomena in metals and alloys. We plan to continue the study of materials with “heavy electrons”, i.e. materials with effective electron mass which exceeds the free electron mass more than a hundred times, that leads to unusual magnetic properties differences from classic dia- or paramagnetic ones. The main goal will be the study of the magnetic ordering type in these compounds at low temperatures.

We started the study of Ce-compound - one of the heaviest-electron systems.

Below 0.4 K the increase of the muon spin depolarization rate represents the development of quasi-static ordering of magnetic moments of electronic origin supposedly random-oriented.

The clear frequency shift of muon spin precession at external transverse field was seen. We plan to continue the study of these phenomena.

We propose to perform the study of anomalous muonium Mu^* ($\mu^+ e^-$) signal temperature dependence with the aim to investigate a possible Mu^* diffusion. The muon spin precession and relaxation in the Mu^* state may be described when the energy of Zeeman interaction of a muonium electron in the external magnetic field is much greater than energy of the hyperfine interaction in muonium atom. In anisotropic muonium atom the magnetic field produced by electron doesn't coincide in direction with the external field. So, in a strong longitudinal field the muon spin of Mu^* state is influenced also by transversal component of a local field.

Status of the experimental setup

Temperature range	4,2–300 K
Magnetic field range	0–0,6 T
Resolution time	1.2 ns
Dead time	20 ns
Width of the channel	5,5 ns (1,1 ns convert.)
Signal/background ratio	10^3

At the present time, a new μSR spectrometer on the surface muon beam is being put into operation. The application of this setup will allow increasing the field of the solvable problems, because of the possibility to work with very thin samples (films, foils) and with the powder samples.

But the possibility of the application of this set-up is limited due to the absence of the spin rotator on the surface muon beam. The JINR phasotron and its beams are quite suitable for many problems of the cited program.

The experimental complex MUSPIN on the muon beams of the phasotron allows solving the wide circle of problems in the field of muon behavior in matter. The experiments with small samples (single crystals, powders) are planed to perform at PSI (Switzerland).

Cost and resources estimation.

Budget expenditures

The equipment and materials (photomultipliers, CAMAC modules etc) — 5000 $/year

International collaboration (visits to PSI and intern. conferences) — 5000 $/year

Phasotron beam — 300 h/year

Additional sources of financing

The RFBR Grant N02-02-16881 supports this work and new proposal for the Grant is prepared.

Paul Sherrer Institute provides the beam-time and pays the living expenses during the experiments.

Staff i includes 6 scientists, 1 engineer and 2 workers. Young specialists are welcomed.

05-2-1040-2001/2006	Priority of the project:
	Status: Data taking

Precise Measurement of the Pion Beta-decay Rate (Project PIBETA)

Leader from JINR: S. Korenchenko

Participating countries and international organizations: Croatia, Georgia, JINR, Poland, Poland, Switzerland, the USA.

2001–2003 Main Results

In 2001 data taking for the pion beta-decay was finished at the unique PIBETA spectrometer constructed during previous years in the frame of the PIBETA project. In 2002-2003 the analysis of the experimental data was continued.

By now the PIBETA collaboration have recorded about two orders of magnitude rarer pion and muon decay than was available in the entire world data sets on the $\pi^+\to\pi^0 e^+\nu$, $\pi^+\to e^+\nu$, $\pi^+\to e^+\nu\gamma$ and $\mu^+ \to e^+\nu\bar{\nu}\gamma$ channels. The event statistics are summarized in the following table:

Decay	PIBETA data set	World data set
$\pi^+\to\pi^0 e^+\nu$	> 50 k events	1.77 k events
$\pi^+\to e^+\nu$	> 580 M events	0.35 M events
$\pi^+\to e^+\nu\gamma$	> 60 k events	1.35 k events
$\mu^+ \to e^+\nu\bar{\nu}\gamma$	> 500 k events	8.5 k events

Our current preliminary working result for the pion beta decay branching ratio is $BR \approx 1.044 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.})\cdot 10^{-8}$. The data set acquired in 1999 and 2000 was used. The Standard Model (SM) prediction according to PDG data is BR = 1.038–1.041 (90% C.L.).
The quality of our data is best illustrated in Figures 1.

We are currently well on our way to achieve the stated goal to measure pion beta branching ratio with accuracy ~ 0.5 %. The work is continued to examine more precisely the background processes, registration efficiency and other factors.

The data set of ~15000 radiative pion decays ($\pi^+\to e^+\nu\gamma$) was analysed in 2002. This set was recorded in parallel with the beta-decay data taking. A part of radiative pion decay (RPD) statistics was taken with the trigger proposed earlier by the Dubna group. The results of the preliminary analysis of the RPD data set turned out to be quite unexpected, while certain indications of such possibility already existed. Theoretically RPD is defined by two electroweak formfactors, axial (F_A) and vector (F_V). In the Standard Model (SM) in accordance with the CVC hypothesis F_V is defined by π^0 lifetime and equals 0.0259(5). We obtained F_V = 0.0139(10) which fitted experimental data by both formfactors. Discrepancy with the SM value is about 12 standard deviations. It is possible to obtain a satisfactory fit to our data assuming that there is a small contribution of a tensor interaction to the RPD defined by tensor formfactor $F_T \approx$ -0.0017(1). It is well known that tensor interaction is absent in the SM, however.
So a phenomenon beyond the SM has been discovered. The experimental results and results of different fits are shown in Fig.2.

Proposal for the continuation of the PIBETA Project in 2004–2007

The discovery of a possible limitation of the Standard Model (SM), namely, impossibility to interpret the experimental data on the radiative pion decay $\pi^+\to e^+\ \nu\ \gamma$ (RPD) obliges us to do new measurements of this decay. By now the authors have found no reasonable sources of errors in the results. On the other hand, the analysis of the obtained experimental data shows that the random

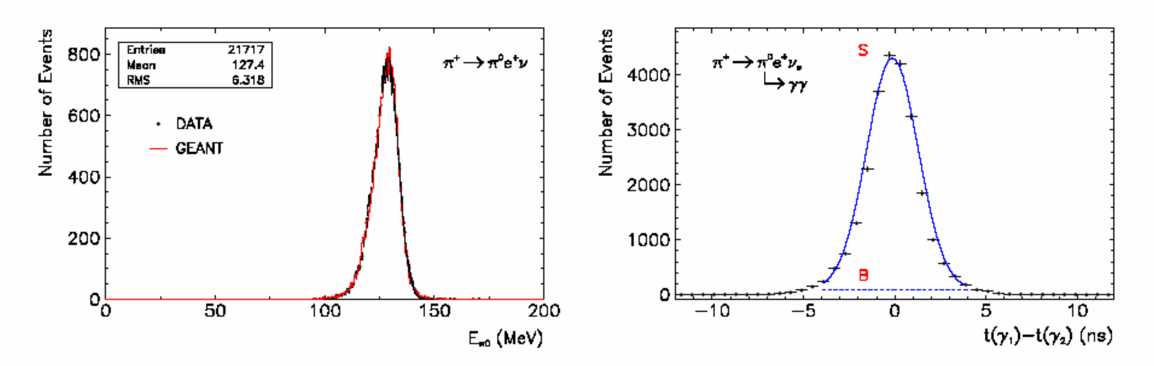

Fig.1. Left: energy spectrum of the measured pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of data; solid curve: GEANT simulation (preliminary). Right: γ-γ time difference for the same set of πβ data events (dots); curve: fit. Signal to background ratio exceeds 250. Priliminary.

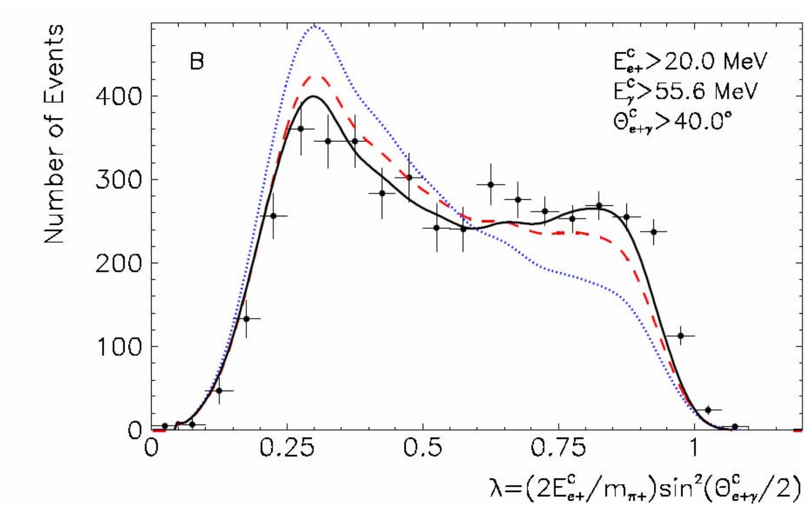

Figure 2. Measured spectrum of the kinematic variable $\lambda = (2E_{e+}/_{m\pi+}) \sin^2 (\theta_{e\gamma}/2)$ in $\pi^+ \to e^+ \nu\gamma$ decay for the kinematic region B, with limits noted in the figure. Dotted (blue) curve: fit with the pion form factor F_V fixed by the CVC hypothesis, and F_A taken from the PDG 2002 compilation, Dashed (red) curve: fit with F_V and F_A released of all constraints, and $F_T \equiv 0$. Solid (black) curve: it with Fy constrained by CVC, and F_A and F_T unconstrained. The resulting value for F_T is -0.0017± 0.0001. Preliminary results — work in progress.

coincidence background equals 20–40% (depending on the specific procedure used for the analysis) of the total number of RPD events. The nature of the background and the procedure used for its subtraction give us no reasons to consider the obtained result as a mistake. However, taking into account the fundamental importance of the obtained result it is absolutely necessary to make new measurements under conditions that will allow a random coincidence background reduction by a factor of 5–10.

That is why the authors propose to do new investigations of the RPD using the beam with the intensity lower by a factor of 5–10 than the one used to measure the beta-decay of pion. So the beam rate would be 0.1–0.2 MHz. We are going to use the “One-Arm HT” trigger designed previously for registration of the $\pi^+ \to e^+ \nu$ decay in the PIBETA experiment. The trigger requires that the energy deposited in one of the calorimeter super-clusters should be equal or greater than 52 MeV. Obviously, that trigger would provide also maximum efficiency for registration of the $\pi^+ \to \pi^0 e^+ \nu$ and $\pi^+ \to e^+ \nu$ decays. Branching ratios of these decays are already known with a precision of 1% and 0.3%, respectively.

The data on the $\pi^+ \to e^+ \nu$ decay in a low intensity beam that will be recorded in parallel with the main task would allow improving of the experimental accuracy of the decay branching ratio by a factor of 2–3. This would be very valuable for future improvement of the estimate of the $\pi^+ \to \pi^0 e^+ \nu$ decay branching ratio. It should be also noticed that the $\pi^+ \to e^+ \nu$ decay branching ratio is directly coupled to the fundamental aspects of weak interaction physics, in particular to a possible existence of the tensor interaction.

05-2-1039-2001/2006

Priority of the project:

Status: New

Measurement of the Magnetic Moment of the Neutrino with the Low-Background Germanium Spectrometer GEMMA (Project GEMMA)

Leader from JINR: V. Brudanin

Participating countries and international organizations: JINR, Russia.

The magnetic moment is the fundamental parameter of the neutrino and its measurement in a laboratory experiment and has high importance for the modern concept of elementary particle physics, astrophysics and the model of the Sun. Current experimentally achieved limitation on the magnetic moment of the neutrino (MMN) is $3 \cdot 10^{-10} \mu_B$, where μ_B is the Bohr magneton ($\mu_B = e \cdot h/2m_e$). It is very important to improve sensitivity of laboratory MMN measurements by an order of magnitude, which would allow one to verify some important hypotheses including one which concerns the anomalously large neutrino magnetic moment, which is beyond the Standard Model and some others. A laboratory measurement of the MMN, μ_ν, is based on its contribution to the (anti)neutrino-electron scattering. At small recoil electron energy ($T \ll E_\nu$, E_ν is the neutrino energy), the electromagnetic cross section increases as 1/T while weak interaction component of the cross section is virtually constant with decreasing energy. Therefore, the most effective way to improve sensitivity to μ_ν is to decrease the energy threshold of the detector. The basic challenge of the experiment on measurement MMN with the use of low background germanium spectrometer is to decrease the level of background for shallow setup down to the level 0.3 events/kg·KeV·d, comparable with the background achieved for deep underground setups.

The spectrometer GEMMA (**G**ermanium **E**xperiment on the measurement of **M**agnetic **M**oment of **A**ntineutrino) includes (see Fig.) an array of four Ge(Li) detectors (1) of total mass above 2 kg within NaI (Tl) (2) active shielding (AS). The Ge(Li) detectors are arranged in one cryostat, all parts of which are made of highly pure materials: oxygen — free copper, titanium and teflon. The assembly consists of eight light isolated sections in the same copper vessel. The assembly is viewed by nine photomultiplying tubes (PMT) through bent light guides. This design allows PMTs, dividers, and cables to be kept outside the passive shielding and thus the intrinsic radiation background of the spectrum to be considerably decreased. The cryostat and NaI AS are surrounded with combined multilayer passive shielding consisting of 8 cm borated polyethylene (4), 5 cm oxygen-free copper (3), 15 cm lead (5), and another borated polyethylene layer. At the top the spectrometer is closed with a $120 \cdot 120 \cdot 4$ cm^3 plastic scintillator counter (6). To protect the spectrometer against ^{222}Rn, a radioactive gas of the uranium series, nitrogen is blown through the air-tight cavity around the detector, and forced ventilation with outside air is provided in the laboratory. CAMAC and NIM electronic modules are used to control the spectrometer and accumulate information. The entire information selection and accumulation process is controlled by special programs. Analogue signals from each of four germanium detectors can be written as a separate energy spectrum if they are not accompanied by inhibit signals from the active shielding or other detectors. In addition, signals are selected according to frequency characteristics, which allows microphone and electron noise and mains interference to be isolated and eliminated.

At the Kalinin Nuclear Power Plant a hall is prepared for installation of the GEMMA facility at a distance of 14.5 m from the centre of the core of one of the 3-GW reactors. The radiation, neutron, and cosmic — ray background was measured at the site of the future experiment.
The experiment GEMMA could indeed allow an order of magnitude improvement of the sensitivity to magnetic neutrino moment compared with one measured so far.