# EXPERIMENT “FAMILON”: SEARCH FOR MUON NEUTRINOLESS DECAY

**V.A. Gordeev, V.S. Demidov$^{1)}$, V.N. Duginov$^{2)}$, Yu.V. Elkin**

$^{1)}$ *Institute for Theoretical and Experimental Physics, Moscow*

$^{2)}$ *Joint Institute for Nuclear Research, Dubna*

The experimental test of possible expansion of the Higgs sector is under study. The standard model of particle interactions is based on the principle of gauge symmetry, offering the theoretically esthetical way to introduce the intermediate bosons of fundamental particle interactions and to explain the difference between weak and electromagnetic forces *via* the Higgs mechanism of symmetry breaking. After the discovery of $W^{\pm}$ and $Z^0$ bosons at LEP (CERN) there were only few doubts about the content of that part of the Glashow-Weinberg-Salam theory which concerns the interaction of vector bosons with quarks and leptons. It seems that the next and probably the decisive checkout of this theory would be the detection of Higgs bosons. Really, the major property of the Glashow-Weinberg-Salam theory is renormalizability. Nobody has managed to construct a renormalized theory containing massive vector bosons without introducing Higgs fields until now. In a simple version of the theory there is only one elementary Higgs doublet. It means that after the implication of Goldstone degrees of freedom to construct massive charged $W^{\pm}$ and neutral $Z^0$ bosons, only one observable neutral Higgs boson remains. However, there are no grounds to assume that the Higgs sector is so poor. Contrariwise, there are theoretical reasons to extend the symmetry beyond the Standard Model and to suppose that if scalar particles exist in general, their number can be significant.

Spontaneous breaking of the global family symmetry results in the prediction of Goldstone boson called familon. In the case of global $SU(3)_H$ family symmetry breaking, the octet of massless familons is predicted. In the model of singlet familon (Anselm and Uraltzev, 1983) the family symmetry breaking results in the prediction of a single familon state. The familon exchange leads to effective flavor changing neutral current processes, such as $\mu \to 3e$ or $K \to \mu e$. However, for small familon coupling constant $f$ the probability of such processes is of the order of $f^4$, whereas decays with free familon emission are much less suppressed being of the order of $f^2$. Thus the familon model can find much more sensitive test in the searches for the free familon emission in decays of charged leptons, such as $\mu \to e\alpha$. In hardronic decays the search for familon decay modes is complicated by the necessity to account for the structure of hadrons and is restricted by the selection rules in the hadron transitions. It is important that familon decays of charged leptons take place both for scalar and pseudoscalar couplings and are much easier interpreted in the terms of bare familon interaction.

Anselm, Uraltsev and Khlopov has estimated the scale of family symmetry breaking from the unstable neutrino models of structure formation and predicted the rate of $\mu \to e\alpha$ decay close to the level of sensitivity reached in experiments. The increase of an experimental level of the sensitivity to the lepton family violation decays could play the role of “experimentum cruces” for dark matter cosmological scenarios and familon models underlying them. This aspect of searches for rare lepton decays was strongly evolved in the successive development of cosmoparticle physics, studying fundamental relationship between cosmology and particle physics.

The experimental method of the search for $\mu^+ \to e^+\alpha$ decay based on the dependence between the differential rate of the decay and electron energy, muon polarization and angle between electron and muon. The vector of positron momentum and muon polarization has to be measured.

The main components of the experimental setup such as the spectrometer magnet, tracking system and beam channel have been installed earlier. The “FAMILON” setup is mounted at the surface muon beam of the phasotron at LNP JINR (Dubna). It is the precision spectrometer for measuring momentum of positrons with energy near 50 MeV. The tracking system consists of 4 proportional chambers in front of and behind the magnet for measuring positron directions. For $\mu$SR-analysis two pairs of Helmholtz coils are used.

In the period 2002–2006 the results were taken in four fields of activity: **the computer support**, **simulation of the proposed experiment, development of the software and appropriate apparatus.**

**The computer support** of the experiment "FAMILON" represents the combination of INTERNET connected computers of the institutes – members of the experiment, while the information is concentrated at PNPI. Each individual computer should have the same set of special programs for processing of the experimental information.

The aim of **the simulation** [1, 2] is to evaluate the influence of the substance (air, wires, scintillators and so on) on the precision of the measured positron momentum and to optimize the position of detectors in the setup in order to reach maximum energy accuracy and positron registration efficiency. The magnet sizes, the map of the magnetic field, the construction of the proportional chambers sets, the relative position of the magnet and the target – those are the basic initial data having been introduced into the simulation program.

The uncertainty in the positron momentum $p$ is defined mainly by the uncertainty in the reconstruction of its direction according to hit wires in the proportional chambers in front of the magnet and behind it. It depends on the wire spacing $h$ in the coordinate planes and on the distance $x$ between chamber planes. The value $\sigma_p/p$ is used as the relative uncertainty, where $\sigma_p$ is the r.m.s. deviation. The $x$-distance dependence of the direction uncertainty $\sigma_\theta$ for 52.83 MeV positron in vacuum and for $h$ = 2 mm is shown in Fig. 1 by falling dotted line. In the real experiment, the positron multiple scattering in the substance of the setup is the main factor which increases errors. The average multiple scattering angle is shown in Fig. 1 as a function of the path length for positrons in air by asterisks connected by growing line. The summary error calculated as the mean geometrical value of these two components is shown by solid line with a wide minimum at 10–18 cm. The distance between sets of proportional chambers in air in front of the magnet and behind it should be obviously equal to ~20 cm to obtain the maximal precision of momentum measurements.

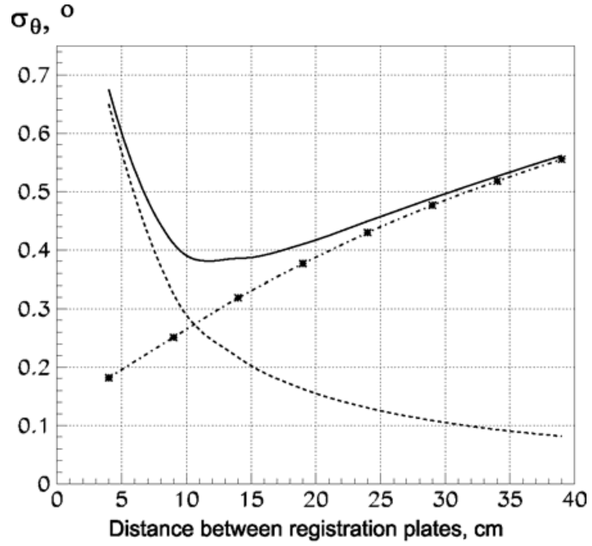

**Fig. 1.** The dependence of the uncertainty in the positron direction on the distance $x$ (in cm) between registration planes for positron energy of $E$ = 52.8 MeV. Dashed line – the measurement precision in vacuum; dashed-dotted line – the uncertainty due to the multiple scattering; solid line – the error in the real experiment

To evaluate the highest precision of the positron momentum measurement the simulation of the monochromatic positron registration in chambers was carried out without any substance on the positron path: for 52.8 MeV (maximum in the Mishel-spectrum) and 51.8 MeV (1 MeV less). The difference in Y-coordinates at the PC4-plane (see Fig. 2 in Ref. [1]) for the above two energies is 37 mm. From this the transition coefficient from the coordinate error to the energy error follows, it is equal to 0.027 MeV/mm.

To evaluate the influence of substance on the momentum uncertainty, the registration models were simulated for monochromatic positrons with the maximum energy in the Mishel-spectrum and various setup configurations. Fig. 2 shows the Y-coordinate distributions at the PC4-plane for three cases: a) only the construction materials of the proportional chambers are taken into account and the setup is in vacuum (solid line); b) vacuum is only inside the magnet (dots); c) the whole setup is in air (dashed line). One can see that air gives the main contribution to the coordinate dispersion.

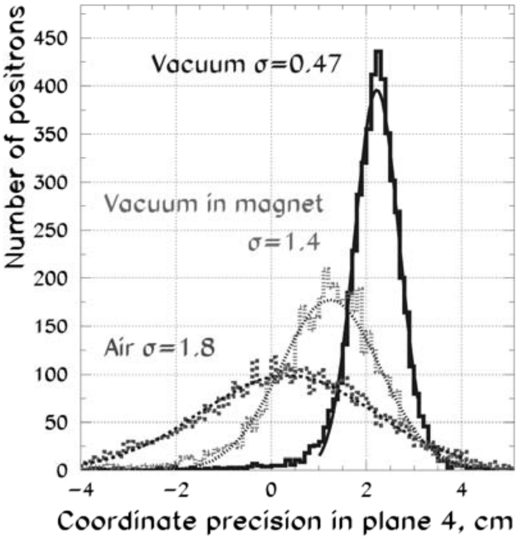

**Fig. 2**. Y-coordinate distributions at the PC4-plane for 3 cases: a) only construction materials of the proportional chambers are taken into account and the setup is in vacuum (solid line); b) vacuum is only inside the magnet (dots); c) the whole setup is in air (dashes)

Analogous calculations were carried out for another two cases: all space between chambers is filled with helium; vacuum is inside the magnet while the rest space of the setup is in helium.

Analyzing the simulation results one can get the evaluations of the accuracy of momentum measurements for various configurations of the setup. The scale of this accuracy is defined by the r.m.s. deviation in the Y-coordinate distribution at the PC4-plane (the horizontal coordinate of point where positron hits the chamber PC4). The most important results are presented below.

The highest precision of momentum measurements with $h = 2$ mm in the ideal case (positron in vacuum) is $\sigma_p = 0.025$ MeV or $\sigma_p/p \approx 5\times10^{-4}$ for the maximum of Mishel-spectrum.

The maximal attainable precision for the proportional chambers of given construction (a quantity of substance along the positron path) is $\sigma_p/p \approx 2.5\times10^{-3}$ if the whole setup is placed in vacuum.

If vacuum is only inside the magnet, then the momentum uncertainty rises up to $\sigma_p/p \approx 5\times10^{-3}$.

If the whole apparatus of the setup is placed in helium, the precision improves up to $\sigma_p/p \approx 3\times10^{-3}$.

In the case when the whole apparatus is in air $\sigma_p/p \approx 9\times10^{-3}$.

The configuration with vacuum inside the magnet while the rest space is filled with helium seems to be optimal. In this case $\sigma_p/p \approx 2.6\times10^{-3}$. Figure 3 demonstrates the trajectories of 50 positrons with energy of 52.8 MeV for this configuration.

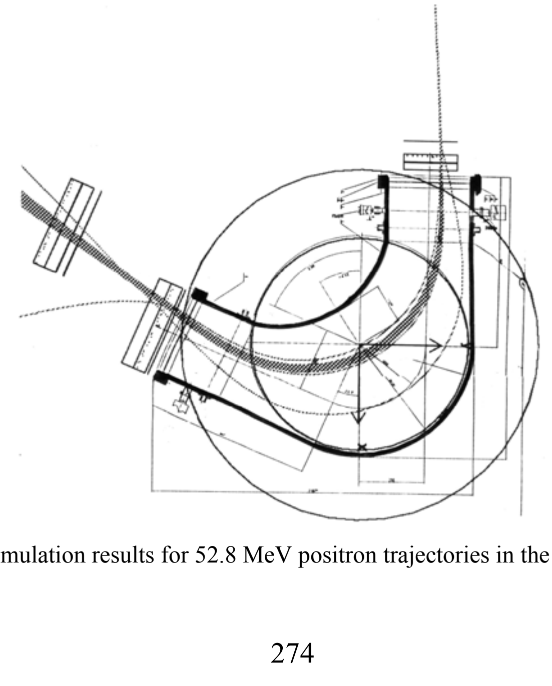

**Fig. 3.** The simulation results for 52.8 MeV positron trajectories in the setup “FAMILON”

Note that the real precision of momentum measurements will be slightly higher because coordinates of only one chamber have been used in the above evaluations, but for the momentum reconstruction at least two chambers are used.

The further improvement of the precision of momentum measurements may be obtained only if the constructive improvement of the coordinate detectors will decrease the quantity of substance on the positron path.

The important parameter of the experiment is the efficiency of the positron registration as a function of the positron energy and exit angle. This efficiency was also calculated by means of Monte Carlo method for the optimal setup configuration. It was assumed that positrons go isotropically out of the target at the exit angle up to 8° and the positron spectrum is described by the Mishel function. The spectrum in the interval 35–52.8 MeV was considered. The efficiency as a function of two parameters – the positron momentum and the exit angle – was determined as the ratio of two-dimensional histograms: one for registered positrons in chambers PC1–PC4 (see Fig. 2 in Ref. [1]), another – for positrons going out of the target. Figure 4 demonstrates the efficiency dependence on the positron momentum for various exit angles. It can be seen in Fig. 4 that the registration efficiency for positrons in the energy interval from 45 MeV up to maximal value does not fall less than 0.5 at exit angles up to 6°.

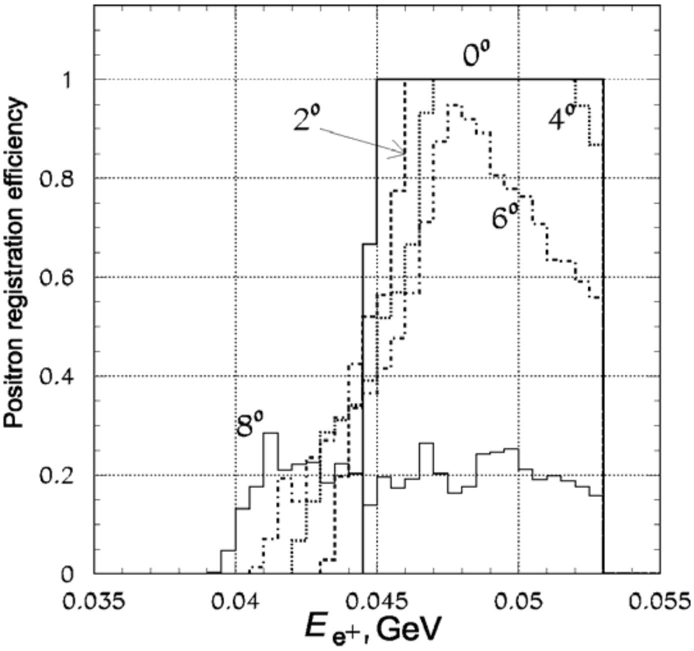

**Fig. 4.** The dependence of the positron registration efficiency on its energy for five exit angles

**The software** [3-5] was developed as two packages "alfa-ONL", "alfa-REC".

Software ON-LINE is realized in the system WINDOWS as the package **"alfa-ONL"**. All technologies of the object-oriented programming are maintained. Software ON-LINE functions are as follows [3, 4, 6]:

- test of subsystems of the setup and of the whole system;
- operation of information accumulation in experiments;
- management of on-line processing in experiments;
- parameter selection and the display of experimental information and on-line results;
- viewing of tracks and of the processing results in on-line and off-line regimes.

The resultant rate of apparatus and software is 300–1000 event/s and depends on the number of hit wires.

The main functions of the **"alfa-REC"** package are to reconstruct the positron trajectory in the magnetic field using the data from proportional chambers, to restore the positron energy and to create data array in the NTUPLE format [4]. For the elaboration of the reconstruction algorithm the methods used in another experiments have been analyzed [5]. As a result, the two-level (on-line and off-line) procedure was chosen.

In **on-line** processing two problems are being solved:

- the inspection of a quality of the setup operation, the control of background tracks and false chamber hits, the control of the field where particles going from the target are registered;
- the rough acquisition of the momentum distribution for positrons.

In **off-line** processing the maximum accuracy is required for track parameters. The convergence rate of the solutions of Lorentz equation while the momentum is calculated by the method of successive approximations depends on the choice of the initial approximation $p_0$.

- At the first stage the initial approximation of momentum is calculated (by the same method that is used in the on-line process).
- At the next stage the track parameter fitting is carried out using the error matrix which includes correlations of the coordinate measurement errors.

Because of non-uniform magnetic field ("end effects") and of the strong change of the field integral along the trajectory it is necessary to determine the initial approximation of the momentum $p_0$ much more exactly.

The algorithm was elaborated for the determination of parameter errors and for the momentum reconstruction with track hit coordinates in three chambers. This algorithm is used when events are processing in the **on-line** regime. The contribution of the multiple Coulomb scattering to parameter errors of the trajectories depends on the number of chambers in the setup, their position, particle path length in air and in vacuum. If the setup geometry is changed, it is necessary to modify the processing algorithm in the **off-line** regime. The correct evaluation of measurement errors and of the multiple scattering influence will allow to minimize errors of trajectory parameters under real conditions of the experiment.

**Apparatus.** The precision of measurement of positron energy is determined both by the energy resolution of the magnetic spectrometer and the uncertainty of the positron energy loss in the working target in which muons stop [6]. It is proposed to use in the experiment aluminum with thickness from 150 mg/cm$^2$ up to 250 mg/cm$^2$ (the average thickness is 200 mg/cm$^2$) as the working target. If the target is a single Al plate, then we cannot define the muon stopping point in the target and therefore cannot define the energy loss for positron from muon decay. The average energy loss in substance for relativistic positrons is 2 MeV/g/cm$^2$. Then the uncertainty in determination of the positron energy is 0.4 MeV and the relative precision for the high-energy region of Mishel-spectrum is not better than $8\times10^{-3}$. The obvious way to remove the above-mentioned uncertainty is to use an active target which consists of several thin metal foils working as plane-parallel avalanche counter.

The prototype of the active target for the "FAMILON" experiment has been worked out and produced at PNPI [7, 8]. Investigations at the surface muon beam of the LNP JINR phasotron show the high registration efficiency for muon passage through the gas gap of the avalanche detector (99% for 1 mm $CO_2$ gap at the atmosphere pressure). Also they show the high enough ability for the selection of muons and electrons by means of measuring the detector signal amplitude.

The electronics of the setup "FAMILON" is carried out in the CAMAC standard and has program manipulation through the personal computer. The used interface means – controllers of A2-type, branch drivers and the direct connection of the computer interface with K16 controller – permit to work with crates distant up to 100 m. At the same time the single operation takes 30 $\mu$s; this does not limit in our experiment the rate of the statistics accumulation because the maximum anticipated intensity of useful events is 100 s$^{-1}$.

At present the **new system (CROS3)** is being elaborated at PNPI for the readout of information from coordinate detectors in the experiment "FAMILON". The system CROS3 is the third generation of the data readout systems for coordinate detectors. The CROS3 takes into account all particularities of the previous systems and develops them on the basis of new technologies. The use of special micro-schemes (ASIC) and large micro-schemes with programmed logical connections (FPGA) lets to decrease essentially the system sizes and consumed power and to rise the rate of the information processing. New standards (LVDS, PCI, Optical Link) let to reach high integration not only for the readout system but for the whole experiment electronics. The main characteristics of the system CROS3 are as follows:

- program regulation of the threshold, of the delay time and of the duration of "window" in which signals are registered;
- small system sizes and low dissipated power;

- interfaces in standards LVDS, Optical Link, PCI, Ethernet;
- data readout rate up to 160 Mbite/s;
- reduction of the number of cables;
- small dead time;
- the measurement of the hit channel time distribution inside the registration "window".

**The methodical run** was carried out with a purpose to check the working capacity of hard- and software, to evaluate the trigger system efficiency and to verify the validity of simulation [4, 9]. 94148 triggers were registered that have been worked out by the system of scintillation counters when muon decays were displayed in the setup. Events were treated with the program "alfa-REC". As a result the reliability of proportional chambers and electronics readout system [4] was fixed .

The processing of information provided by the electronics readout system allows $\mu$SR-analysis of the registered events including those in which positrons were not registered. Fig. 5 presents the $\mu$-meson lifetime distribution for 49480 events in the range from 0.1 to 4.5 $\mu$s. The distribution is the decay exponent modulated by sinusoid with the amplitude depending on the muon polarization value and with the period in accordance with the muon spin precession frequency in the magnetic field of the Helmholtz coils. The exponential fitting of the distribution gives muon mean lifetime of 2.185 ± 0.008 $\mu$s that coincides within errors with table value. The function correspondent to the experimental value is drawn by smooth line. Damped harmonic oscillations reflect the time dependence of muon polarization. It is possible to obtain from this fitting curve the precession frequency $f = 2.20 \pm 0.15$ MHz.

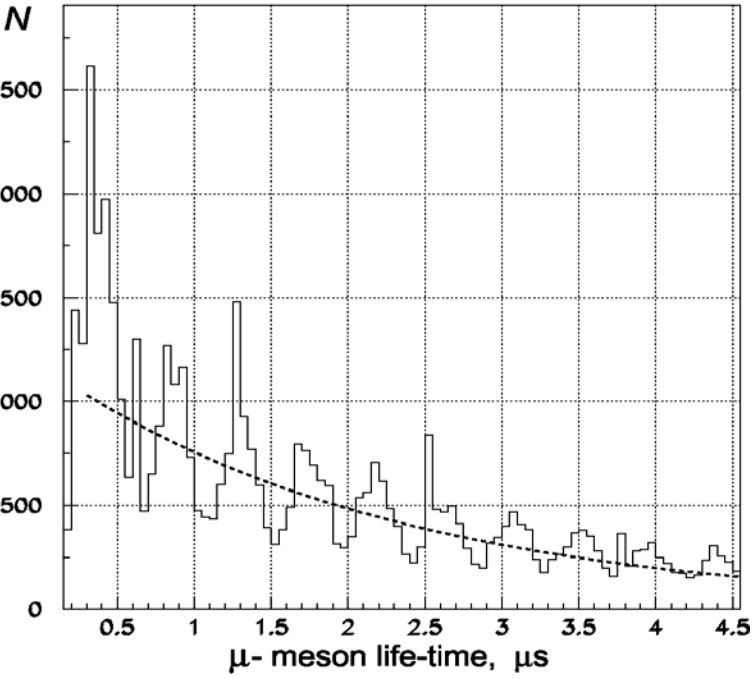

**Fig. 5.** $\mu$-meson lifetime distribution for 49480 events. The dotted line – the result of the approximation by the exponential function with index 2.185 ± 0.008 $\mu$s

Figure 6 presents the positron energy distribution. Let us remind that it was the test run, therefore the spectrometer has not been tuned to register positrons with maximum energy. Nevertheless, the obtained energy spectrum is a good criterion for examination of the simulation program. The spectrum of positrons outgoing from the target was simulated in accordance with the Mishel distribution a part of which is shown by the dotted line. The simulated "measured" positron spectrum is shown by solid line. The coincidence of the calculated spectrum and the experimental one confirms once more that the simulation is correct.

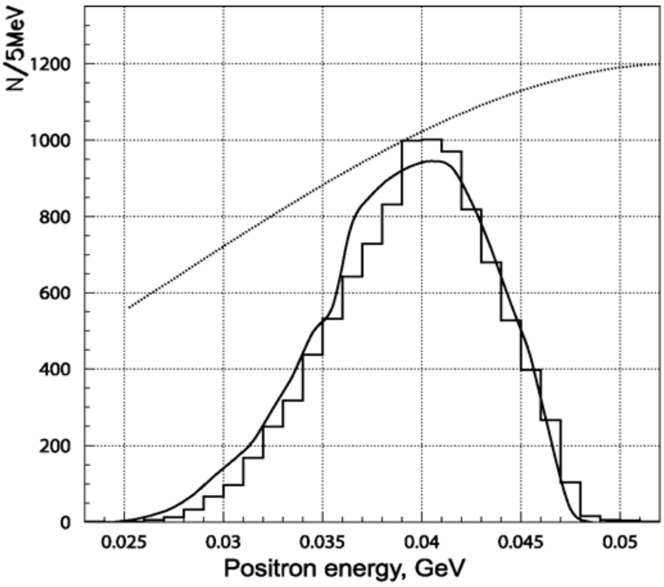

**Fig. 6.** The energy spectrum of positrons registered in the setup "FAMILON"

The list of participants of the experiment "FAMILON":
V.A. Andreev[1], N.F. Bondarev[1], V.S. Demidov[2], E.V. Demidova[2], V.N. Duginov[3], Yu.V. Elkin[1], V.L. Golovtsov[1], V.A. Gordeev[1], K.I .Gritsai[3], S.A. Gustov[3], V.G. Ivochkin[1], E.M. Karasev[1], M.Yu. Khlopov[4], E.N. Komarov[1], S.V. Kosianenko[1], A.G. Krivshich[1], M.P. Levchenko[1], T.N. Mamedov[3], I.V. Mirokhin[3], V.G. Olshevsky[3], Yu.A. Scheglov[1], G.V. Scherbakov[1], A.Yu. Sokolov[2], Yu.P. Schkurenko[2], A.V. Stoykov[3], L.N. Uvarov[1], S.I. Vorobyev[1], A.A. Zhdanov[1], V.A. Zhukov[3].

[1] – Petersburg Nuclear Physics Institute of RAS (Gatchina)
[2] – Institute for Theoretical and Experimental Physics (Moscow)
[3] – Joint Institute for Nuclear Research (Dubna)
[4] – Institute of Applied Mathematics of RAS, Center for Cosmoparticle Physics "COSMION" (Moscow)

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