The FAMILON experiment: conception and simulation

V.A. Andreev, V.S. Demidov, E.V. Demidova, V.N. Duginov,
Yu.V. Elkin, V.A. Gordeev, K.I. Gritsai, K.E. Gusev, S.A. Gustov,
V.V. Ianovski, V.G. Ivochkin, E.M. Karasev, N.A. Khaldeeva,
M.Yu. Khlopov, E.N. Komarov, S.V.Kosianenko, A.G. Krivshich,
T.N. Mamedov, I.V. Mirochin, V.G. Ol’shevski, A.N. Ponomarev, G.I.Savel’ev,
Yu.A. Scheglov, G.V. Scherbakov, Yu.P. Shkurenko, A.Yu. Sokolov, A.V. Stoikov,
S.I.Vorobyov, , A.A. Zhdanov,

The experiment is based on the hypothesis of the existence of the familons – the elementary particles which are responsible for the breaking of the horizontal symmetry of the lepton family. The existence of such particles must result to the 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 LNP JINR phasotron. The FAMILON set-up is installed at the beam of the surface muons; the methodical runs had been carried out. The FAMILON experiment is described and the results of the Monte-Carlo simulation of the positron registration by the magnetic spectrometer are presented.*

INTRODUCTION

In ninetieths one has 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 has been carried out on the intensive surface muon beam of the LNP JINR phasotron when investigating the process of the muonium-to-antimuonium conversion. As a result the new estimations have been obtained for the upper experimental limits of the conversion probability W_{MM} and the corresponding constant of the weak interaction $G_{M\bar{M}}$ in this process:

$$W_{M\bar{M}} \leq 4.7\cdot 10^{-7},\ G_{M\bar{M}} \leq 0,14 G_F (90\%\mathrm{C.L.}).$$

Besides the low limit has been evaluated for the H^{++}- Higgs boson responsible for the $M\bar{M}$ -process [1] ($M_{++}\geq 210$ GeV). The experiment was performed in the framework of the state scientific and technical research program of the Russian Federation «The fundamental nuclear physics» (the project 1.3.5-07) and at the financial support of the

Russian Foundation of the fundamental investigations (the grants 95-02-03780-a, 95-02-07498-b).
In 1999 PNPI, JINR and IETP have taken the program concerning with the further research of the rare and exotic muon and pion decays, making use of the experimental method proposed. As the first stage one has decided to elaborate the apparatus for seeking of the possible muon decay $\mu\to e\alpha$ (α-the scalar particle).

To explain the existence of the fermion generations one has proposed the various horizontal symmetry theories. The P - and CP-violations, the neutral currents changing the flavour can be included into these models and the phenomena in question are suppressed by the huge mass of the corresponding gauge bosons. If the horizontal symmetry is the global one, the spontaneous symmetry breaking results to the existence of the Goldstone bosons [2,3,4]. The search for such decays and the scalar particles is one of the important trends of the contemporary physics. There are the theoretical arguments for such particles – to be massless (the goldstone bosons) or to have the small mass (the pseudogldstone bosons). Besides these particles are also interesting from the experimental point of view: they might be observed at the low energies. In 1985 A.A. Anselm, N.G.Uraltsev (PNPI) and M.Yu.Khlopov (IAM, Moscov) have evaluated the scale of the violation of the generation symmetry, making use of the models of the formation of the Universe structure by the unstable neutrinos; they proposed also the decay rate of muon to the electron and the familon (the Goldstone boson):

$$R_\alpha = \Gamma(\mu\to e\alpha)/\Gamma(\mu\to e\nu\bar{\nu})\cong 10^{-6} \text{ [5].}$$

Some time later in PNPI one proposed the experimental method for the investigation of such process [6]. The last one is based on the measurement of the energy behaviour of the asymmetry of the decay positron near the high energy edge of the Michel spectrum.

During the last years the nonconservation of the lepton number in the neutrino sector is being discussed in the connection with the evidence of the atmosphere neutrino oscillations in the underground experiments. The theoretical models connect the effects of the massive neutrino mixing with the possible existence of the neutrinoless decays of the charged leptons $\mu\to e\gamma$, $\mu\to 3e$ and the μe-conversion on the nuclei. There are the strong experimental limitations for such processes [7]:

$$Br(\mu\to e\gamma)<4.9\times10^{-11},\ Br(\mu\to 3e)<1\times10^{-12},\ Br\ (\mu e\text{-conversion}) <4.4\times10^{-12}.$$

The theoretical estimations are not so strong. The search for these rare processes has the huge advantage from the point of view the models explaining the possible ways of the generation symmetry breaking.

The aim of the experiment is the search for the neutrinoless muon decay $\mu^+\to e^+\alpha$. This investigation will be carried out at the surface muon beam of the LNP-phasotron making use of the FAMILON set-up.

THE DESIGN OF THE EXPERIMENT

The experimental conception has been elaborated at PNPI [8,9]. The search for events of the two-particle decay μ→eα will be realized making use of the $\mu\rightarrow\nu\bar{\nu}$decay data near the high energy edge of the positron spectrum. The direct observation of the monochromatic line resulting from the rare channel μ→eα 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).

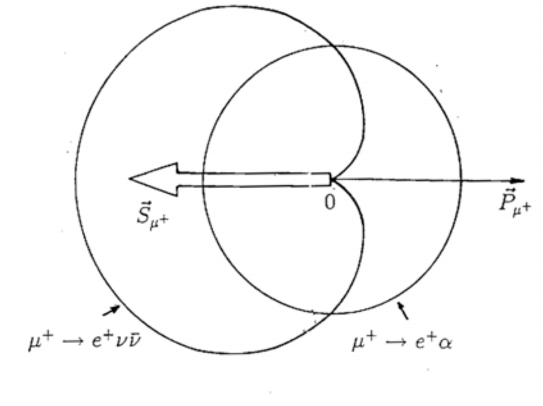

Fig.1. The angular distribution of positrons respectively the muon spin for the decays $\mu\rightarrow e\nu\bar{\nu}$ and μ→eα.

Many difficulties can be avoided when investigating the decay of the polarized muon and analyzing the energy and angular distributions of positrons. Fig.1 demonstrates the angular distribution of positrons for the main decay mode and the mode under investigation (the angle θ is measured between the muon spin and the positron momentum). In the first case the strong asymmetry takes place (relatively the direction of the muon spin); of course this effect is determined by the parity nonconservation. In the second case the distribution is isotropic. As a consequence the μ→background is much less for the positrons moving opposite the muon spin direction, than for any other ones.

Experimentally the idea of the joint analysis of the energy and angular distributions is realized by the way as follows. The positron momentum is measured by the precise magnetic spectrometer with the energy resolution $\Delta\varepsilon/\varepsilon \sim 10^{-3}$ and the standard μSR-technique is used for the analysis of the correlation between the muon spin and the positron momentum [8].The polarized muons stop in the target with the high density of the conductivity electrons to avoid the muon depolarization. The spin precession spectra are analyzed as a function of the positron energy near the high energy edge of the Michel spectrum. If the $\mu \to e\alpha$ events take place, this leads to the sharp decrease of the asymmetry in this range. It should be noted that in such measurements the systematic errors reduce to a minimum as all μSR-spectra collect simultaneously.

The experimental setup FAMILON is represented in fig.2. Its detailed description may be found elsewhere [9]. This arrangement is settled down on the beam line of the surface muons with the kinetic energy 4.2 MeV, which were produced from the decays of π^+-pions stopping in the surface layer of the meson production target.
In the upper part of fig.2 one can see the system of the magnetic elements to measure the μSR-spectra of the $\mu \to e$ - decay events. It consists of the pair of the Helmholz coils to create the crossed magnetic fields ($B_\perp$=0÷500Gs and $B_\parallel$=0÷1000 Gs) and three pairs of the square coils to compensate the scattered magnetic fields in the area of the stop target.

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 coordinate system of spectrometer consists of the scintillation counters C1÷C6 and the proportional chambers PC1÷PC4. The trigger signal is formed by the counters C1÷C6, which are jointed in the fast selection configuration (the time resolution ~ 1ns).The coordinate system was chosen in such way, that the X-axis was directed along the positron momentum, the Z-axis did upward and Y-axis did in the appropriate way to make the right coordinate system.

The Y-and Z-planes of the proportional chambers have the gap 4 mm, the step of wires 2 mm and the different number of channel depending on the size of chambers: the PC1- and PC2- chambers (200 mm×200 mm) have 192 channels and the PC3-and PC4-chambers (350 mm×350 mm) do 352 channels everyone. The chamber are filled by the magic gas mixture Ar(75%)+C_4H_{10}(24.7%)+ hladon 13 B1 (0.3%), which is produced by the gas mixing system, providing up to 200 cm^3 per minute.

The Monte-Carlo simulation finds out that the FAMILON-setup itself is able to determine the positron energy not worse $\sigma_p/p=2.5\times10^{-3}$. However the energy error is due to not only the energy resolution of the magnetic spectrometer but also to the uncertainty of the energy losses of positron in the muon stop target. If the stop-target is the only Al-plate (the thickness 200 mg/cm^2), the uncertainty of the energy loss of positron is ~0.4 MeV. Thus the relative precision of the positron energy near the high energy edge of the Michel spectrum is not better than 8×10^3.

The evident way for removing effect in question is to use the active target which consists of the number of the thin metal foils. This construction may work as the system of the plate parallel avalanche counters [10].

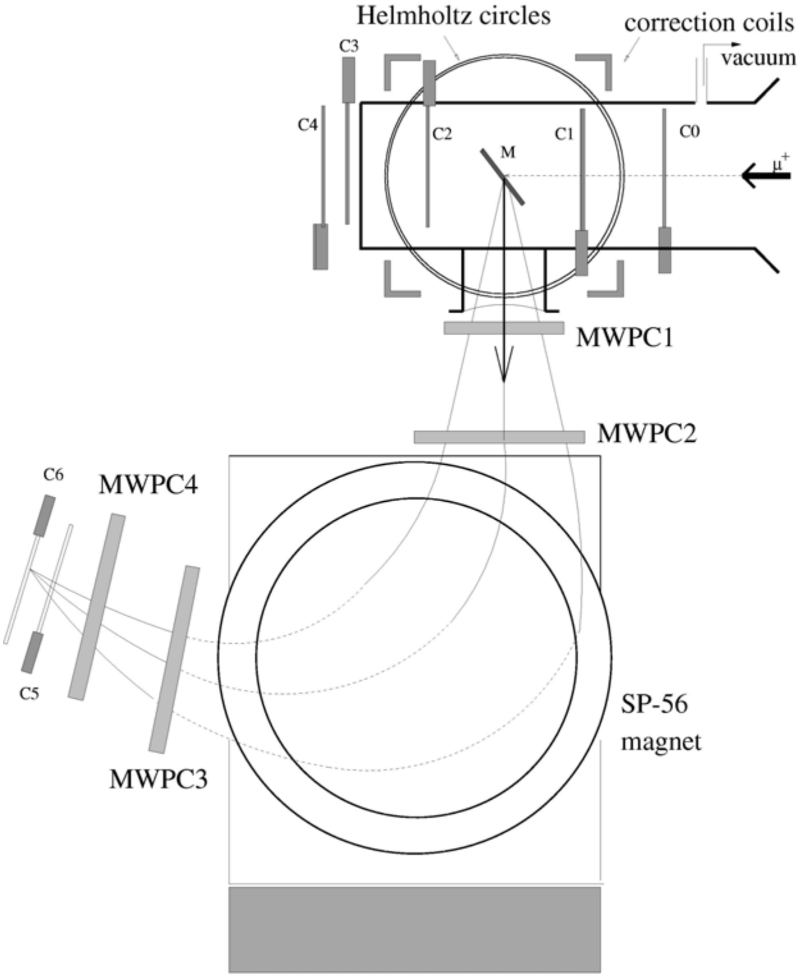

Fig.2. The view of the FAMILON-setup.

The prototype of such active target designed for the FAMILON-experiment is elaborated and produced at PNPI [11]. The tests on the surface muon beam of the JINP LNP-phasotron have shown that the single counter (gap 1 mm; CO_2, 1 atm) has the high efficiency for the slow muons ($\varepsilon \cong 0.98$) and is able to discriminate muons and positrons by means of the amplitude analysis of signals from the detector.

The electronics of the FAMILON-setup (fig.3) is performed in the CAMAC-standard and has the program driving making use of the Pentium-II computer. The interface tools (the A2-controller, the branch driver and the direct involving of interface with the computer) provide the possibility to work with the crates removed up to 100 m. In this case the time for performing one operation is equal to 30 μs; this is does not limit the counting rate of statistic because the maximal intensity of the useful events is not more that 100 ^{1}/s.

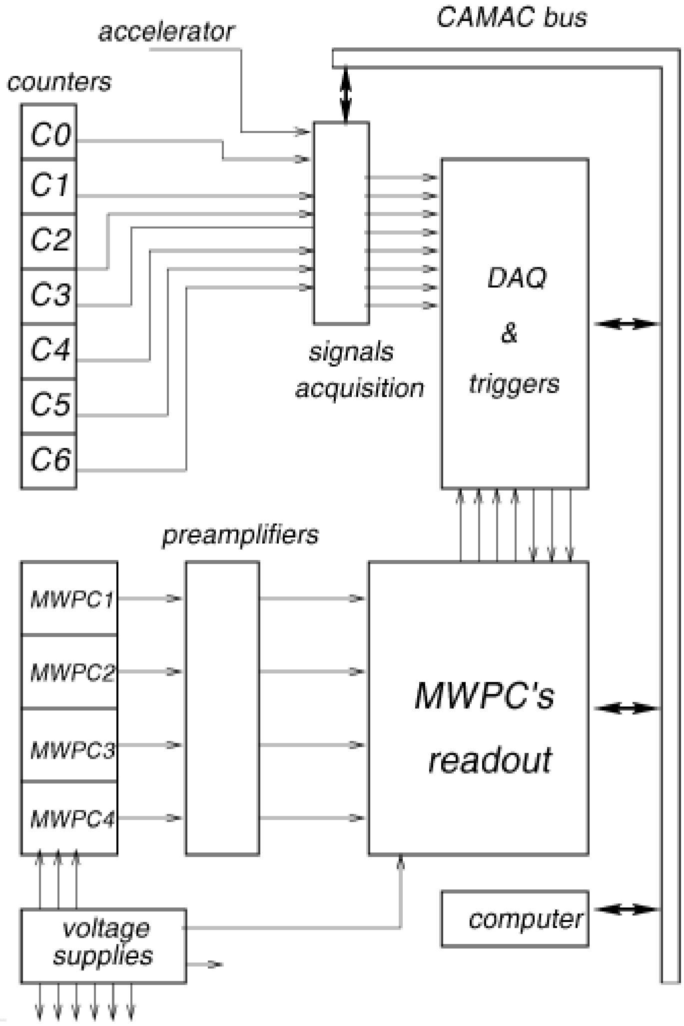

Fig.3. The electronics of the FAMILON-setup.

The read-out system of the proportional chambers is realized of the modules; every module consists of 32 channels of reading the proportional chamber.

The feature of receiving and writing information concludes that after every cycle of registration it works in the uninterrupted way up to the arrival of the next trigger signal. The signal from the every wire goes to the operation memory (16 bits). The memory address changes with the frequency 25 MHz. Thus at every moment the memory system has the information about 16 states of the every wire; such states are separated by the time interval 40 ns and as a result the memory time is equal to 640 ns. The trigger signal stops the cycle writing, then the electronics makes the reading information from the wires of the proportional chambers to the computer; after this the cyclic writing to the memory starts again up to the arrival of the next trigger signal.

The on-line program providing is realized in the MS WINDOWS-system making use of the technology of the object-oriented programming. It performs the functions as follows:

- the test of the individual systems and the system as a whole;
- the driving of the collection of the experimental information;
- the driving the on-line treatment of the experimental data;
- the parameter selection and the representation of the experimental information and the results of the on-line treatment;
- the parameter selection and the representation of the off-line information measured;
- the representation of the tracks and the results of the on – and off-line treatment.

As a results the apparatus and the program providing are able to accept ~ 300÷1000 events per second (it depends on the number of wires triggered).

The main tasks of the off-line programs are the determination of the positron energy in accordance with the data of the proportional chambers and forming of the output data in the NTUPLE-format for the statistical and physical treatment.

The computer providing of the FAMILON-experiment is the group of computers which are in the different institutes (the FAMILON-collaboration) and connected by the INTERNET with the concentration of information in PNPI. The every computers in the institutes must have the identical program set of the experimental data treatment.

The apparatus as a whole is assembled on the muon beam line and tested in the short accelerator runs. In accordance with these runs [12] and the computer simulation in the frame of the GEANT-3.21 program one has formulated the technical project to provide for the FAMILON-set the additional equipment to achieve the more high accuracy of determining the positron energy.

THE SIMULATION OF THE FAMILON-SETUP

As it was cited above the method of seeking of the neutrinoless muon decay comes down to the measurement of the energy dependence of the asymmetry in the angular distribution of positrons resulting from the muon decay near the upper edge of the Michel spectrum (E_e^{max}=52.83 MeV). The feature of experiment is to measure the momentum of positrons making use of the magnetic spectrometer and this imposes a number of the demands on the setup configuration.

The aim of the simulation is to evaluate the effects of matter along the positron trajectories (air, wires, counters and so on) on the measurement precision of their momentum and optimize the position of detectors to achieve the necessary energy resolution and the high registration efficiency of positrons. As the main initial data one has used the magnet sizes, the topography of the magnetic field, the construction of the proportional chambers and the mutual disposition of a magnet and a target.

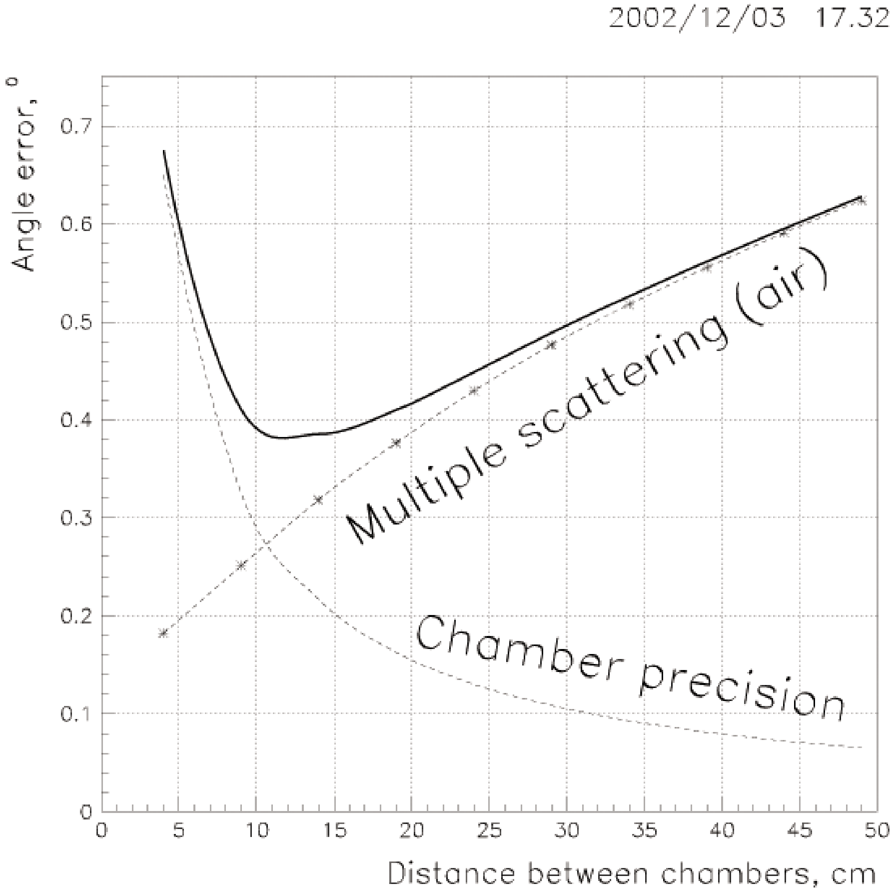

Fig 4. The measurement errors of the positron direction (E=52.8 MeV) depending on the X-distance between the registration planes (the dashed line corresponds to vacuum, the dash-dotted one does to the multiple scattering effect, the solid line does to the real experiment).

The error of measuring the momentum p of positron is mainly due to the uncertainties its directions up-and downstream the magnet accordingly the coordinates of the wires triggered and depends on the step h which the signal wires are in the coordinate planes and on the distance X_n between the chamber planes. One accepted the value σ_p/p as the relative error, where σ_p is the dispersion of the momentum determination. In fig.4 the pointed curve demonstrates how this value changes with the X_n-distance at $h = 2$ mm in vacuum for the positron momentum 52.8 MeV. However the multiple scattering of positrons in the substance of the setup increases the momentum error. The mean angle of the multiple scattering is shown by the stars depending on its range in air. The resulting error may be regarded as the mean geometric of this effects and represented by the solid curve, which has the wide minimum in the range 10-18 sm. Probably to achieve the accuracy demanded in the momentum measurement it should choose the gap between the chambers ~20 cm (when the positrons travel in air).

To estimate the best accuracy of the momentum determination one has carried out the simulation of passing the monochromatic positrons with momentum 52.8 MeV/c (the high energy edge of the Michel spectrum) and 51.8 MeV, provided the matter is absent along the positron trajectory. Both trajectories have crossed the plane of the PC4-chamber and the distance between the points of crossing in the PC4-plane is equal to 37 mm. This gives result the momentum dispersion of setup ~0.027 MeV/mm.

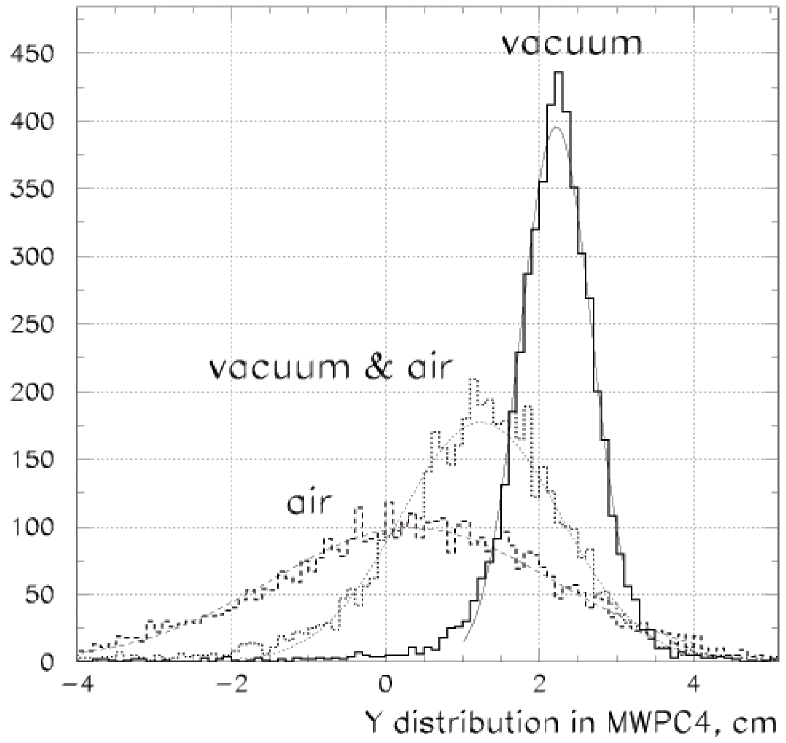

Fig.5. The Y-distribution of positrons in the PC4-chamber:

- 3 chambers (PC2-4) are in vacuum (the solid line);
- a vacuum is only inside the magnet (the dotted line);
- the chambers are in air (the dashed line).

To evaluate the effect of matter in the setup on the accuracy of the momentum determination one has simulated the passing the monochromatic positrons (P=52.8 MeV/c) for the various cases, when it was taken into account (fig.5):

- only the construction materials of the proportional chambers , (the rest is vacuum, the solid curve);
- the vacuum only inside the magnet (the dotted curve);
- all setup is in air (the dashed curve).

Evidently, the main contribution is due to the air. The same investigations have been performed for two versions:

- all space between the chambers is filled by helium;
- in addition the vacuum is inside the magnet.

The dispersion σ_y for coordinate Y of the crossing point of the PC4-plane was taken as a criterion of the momentum accuracy. Of course the best accuracy was obtained when there are no any matter along the positron trajectories:

$$\sigma_p/p = 0.025 \text{ MeV}, \quad \sigma_p/p \cong 5\text{x}10^{-4}.$$

When all setup is in vacuum the value σ_p/p is equal to $2.5\text{x}10^{-3}$. If vacuum is only inside the magnet, the error increases ($\sigma_p/p = 5\text{x}10^{-3}$). But if the air is exchanged by helium one has $\sigma_p/p = 3\text{x}10^{-3}$. When all setup is in air the last one is $\sigma_p/p = 9\text{x}10^{-3}$.

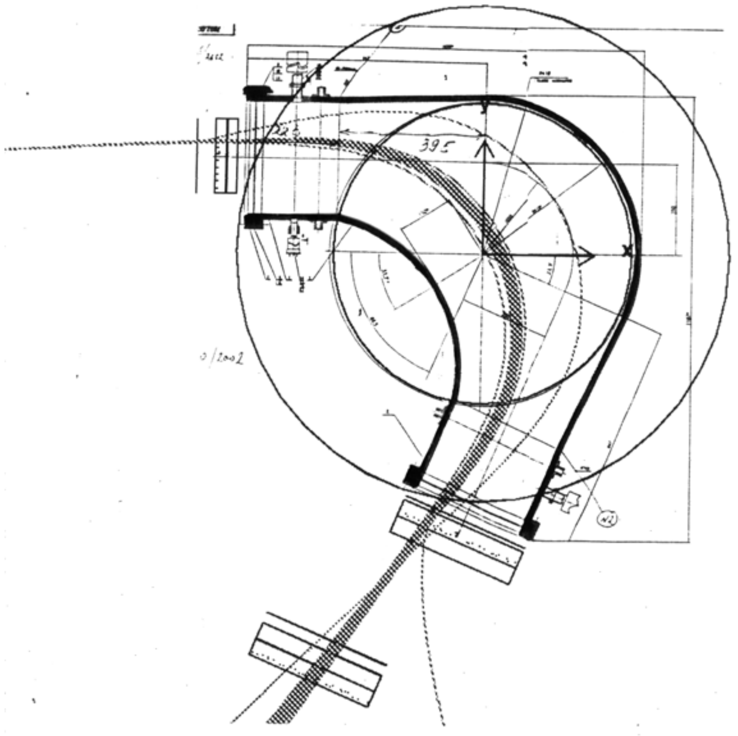

Fig.6. The results of the trajectory simulation of positrons (52.8 MeV) in the FAMILON - setup.

The optimal version is the case, when the air is removed out of the vacuum chamber between the magnet poles and the rest space is filled by helium $\sigma_p/p = 2.6\text{x}10^{-3}$. The fig.6 demonstrates 50 trajectories of positrons (52.8 MeV) for this configuration.

It should be noted that the real accuracy will by better, because these estimations have been made making use of the coordinates only of one chamber (two chambers will be taken into account during the track reconstruction). The further progress is possible when the coordinate detectors is designed with the much less quantity of matter.

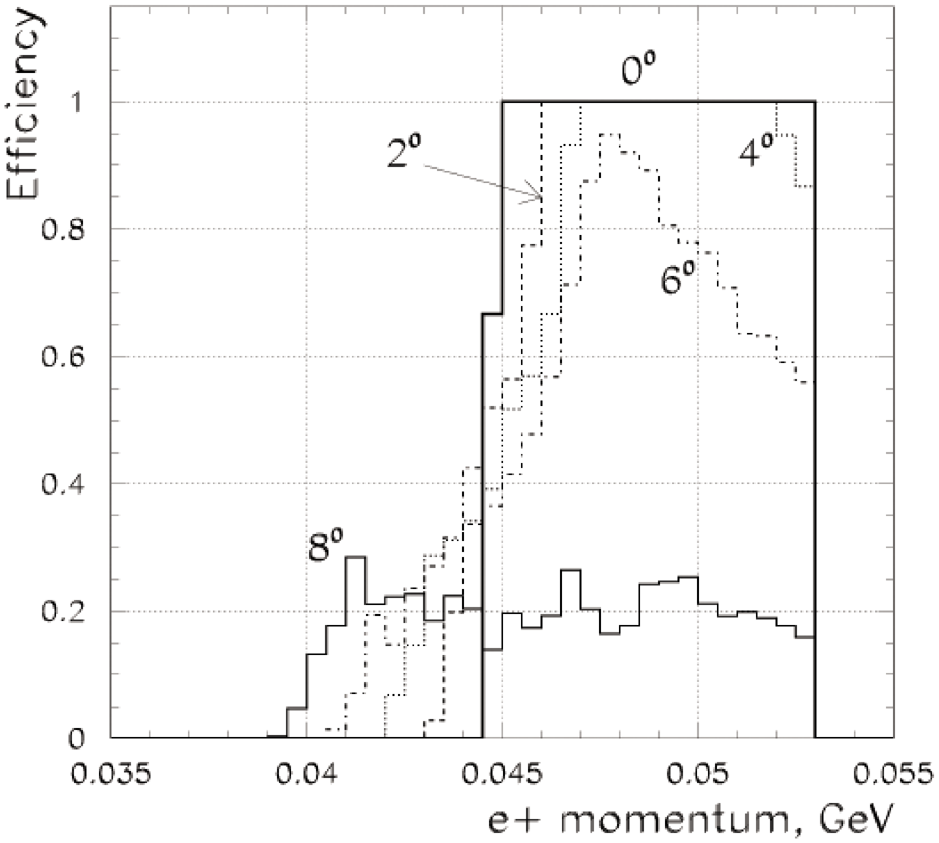

Fig.7. The momentum dependence of the registration efficiency of positrons (0°-the solid line; 2°-the dashed line; 4°-the dotted line; 6°-the dash-dotted line; 8°-the solid line).

The important parameter of experiment is the acceptance of setup. It was determined by the Monte-Carlo method. One supposed that the positrons go out of the target isotropically (up to 8°) and the positron spectrum has the Michel form. One has considered only the energy interval 35.0-52.8 MeV. The acceptance is the function of two variables (the momentum and angle of positron). The efficiency of setup was defined as the ratio of the number of events of two 2-dimensional histograms (angle - energy): one of them is built up for positrons detected by the PC2-PC4-chambers, the other one does for positrons coming out of target. In fig.7 the efficiency is shown for the different angles (0°-the solid line; 2°-the dashed line; 4°-the dotted line; 6°-the dash-dotted line; 8°-the solid line).One can see, that the registration efficiency for the positron momentum more than 45MeV exceeds always the level 0.5 up to the angle 6^o.

CONCLUSION

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 $R_\alpha=\Gamma(\mu\to ea)/(e\nu\bar{\nu})<10^{-5}$ (~300 hour accelerator run, making use of the surface muon beam of the LNP JINR –phasotron).

The further progress of investigation is connected with the design of the magnetic spectrometer with the high energy ($\sim10^{-4}$) and time (~0.25ns) resolution. The possible project of such setup is proposed in [12]. The main parts of this arrangement are the active target based on the parallel plate avalanche detectors (to detect the stop point of muon) and the time projection chamber in the magnetic field (to measure the coordinates of the positron track). As it was shown such apparatus would allow to investigate the $\mu\to ea$-process at the level $R_a\leq 3\text{x}10^{-8}$.

The FAMILON-experiment is performed in the framework of the scientific and technical program of Russia «The researches and the developments on the priority directions of the development of science and technique of the 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) and the support program of the leading scientific schools of Russia (the project 99-02-18540-a).

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