EXPERIMENTAL STUDY OF MUONIUM-ANTIMUONIUM CONVERSION AT PHASOTRON OF JOINT INSTITUTE FOR NUCLEAR RESEARCH

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The muonium [$M = \mu^+e^-$] to antimuonium [$\overline{M} = \mu^-e^+$] transition is of interest in connection with a leptonic number nonconservation problem. In this process both electron and muon lepton quantum numbers change by two units. An existence of processes with $\mid \Delta L \mid = 2$ is predicted by a number of theoretical models considering various mechanisms of leptonic number violation. One of the most interesting ones is that in which leptonic $U(1)$ symmetry of the standard model is broken by finite value of Majoran mass of electronic neutrino. In this model neutrinoless double β-decay should take place. This process is looked for. The $SU(2)$ symmetry yields the double charged Higgs bosons carring $\mid \Delta L \mid = 2$. This causes $M \rightarrow \overline{M}$ as the lower order process. Thus investigation of the conversion gives information about the Higgs sector of the very model responsible for neutrinoless double β-decay. Note that this is the gauge version of the Pontecorvo interaction [1] with $\mid \Delta L \mid = 2$.

To estimate quantitatively the probability of the investigated process, it is reasonable to use the coupling constant $f = G_{M\overline{M}}/G_F$ where G_F is the Fermi constant of weak interaction. Different theoretical models predict values laying in the range $10^{-2} > f > 10^{-6}$ [2].

The experimental investigations of TRIUMF [3, 4] and LAMPF [5] give the following restrictions on f : $f < 0.29$ [4] and $f < 0.16$ [5]. Evidently the further progress in the experimental study of the $M \rightarrow \overline{M}$ conversion requires use of low-background methods. In [6] we proposed a technique which enables to identify the $M \rightarrow \overline{M}$ conversion by single acts. The idea is to record the high energy electrons from the decay $\mu^- \rightarrow e^-\overline{\nu}_e\nu_\mu$ by a magnetic spectrometer. The peculiarity of this technique is that the probability of background processes is essentially lower than the existing estimation for $W_{M\overline{M}}$ and, besides, we have an instrument to suppress these processes by cutting a registered interval of electron energy in high-energy end of decay spectrum.

In 1991 and 1992, the Petersburg Nuclear Physics Institute and the Joint Institute for Nuclear Research jointly undertook an effort to devise an experiment searching for the muonium-antimuonium conversion and measuring the probability of this process using a beam of "surface" muons of the JINR phasotron [7]. The momentum of the beam was $p = 21.5$ MeV/c ($\Delta p/p \approx 7.7\%$), the beam intensity (at a proton current of 2.0 μA) was $I_\mu = 4.8 \cdot 10^5$ s^{-1}, the positron admixture in the beam was $N_{e+}/N_{\mu+} \approx 2$, the size of the beam (the full width at half-maximum) was 7×8 cm^2, and the beam duty factor was 75%.

The experimental layout is shown in Fig.1. It consists of a system which provides the beam of "surface" muons (I), a target assembly (II), and a magnetic spectrometer (III). The incident muon beam is slowed and stopped in a finely divided SiO_2 powder with a stopping thickness of 10 mg/cm^2. The muonium is produced here (in the SiO_2) and diffuses at thermal velocities into the vacuum region in which the $M \rightarrow \overline{M}$ conversion is observed through detecting electrons from the decay of the muon in the antimuonium atom. Besides,

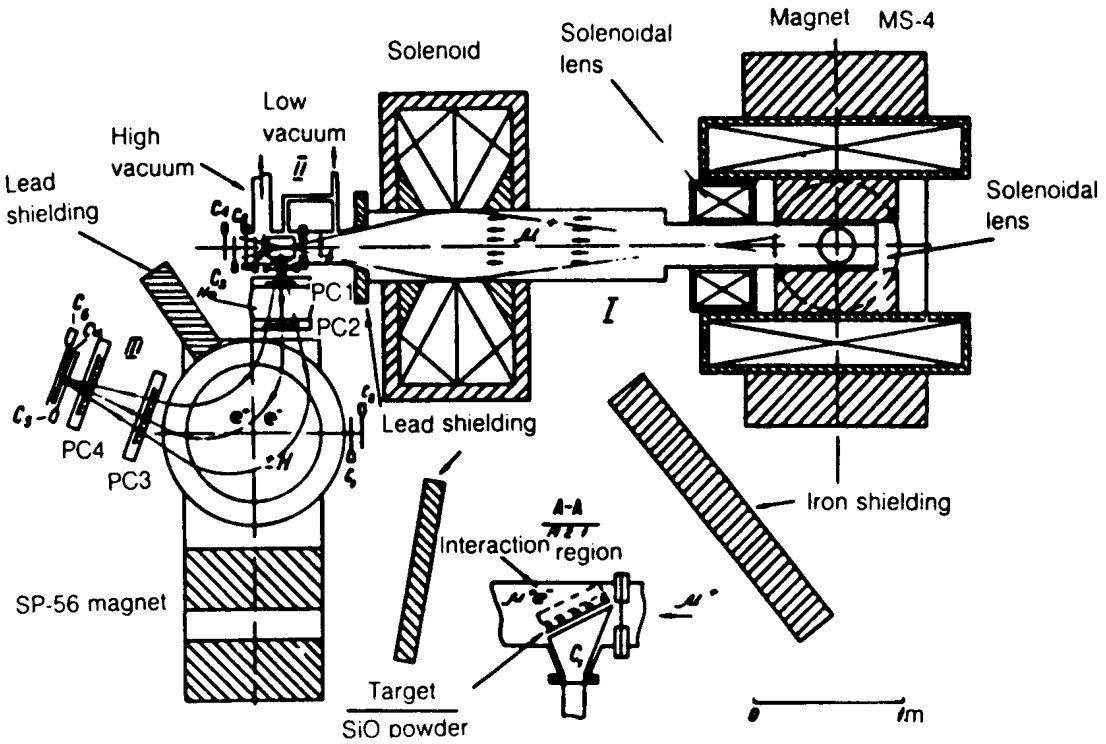

Fig.1. Experimental layout of search for conversion of muonium into antimuonium. C_1, C_2 — monitor counters for detecting positrons; C_5, C_6 — counters for detecting useful events; PC1, PC2, PC3, PC4 — proportional chambers; Cu — copper filter

measurements with reversed field of the spectrometer magnet were performed periodically; in these runs positrons from the μ^+ decay were detected. After crossing the window of the vacuum chamber, the electrons (positrons) from $\mu - e$ decay with energies in the range 36 to 53 MeV were observed by means of four proportional chambers with delay-line read-out [8]. The signals from the cathodes of the first three of these chambers are used to generate a fast trigger. A wide-aperture spectrometer magnet with a field of 3.16 kG in the centre of the magnet deflects the electrons and the positrons from muon decay in opposite directions. A scintillation counter C_5, behind the chamber PC4, generates a timing signal of the detected event. The event is considered to be detected in the spectrometer if signals from three cathodes of the proportional chambers PC1–PC3 and from two scintillation counters C_5 and C_6 arrive simultaneously (quintuple coincidences in a time window of 30 ns). The volume between PC1 and PC2 is filled with helium in order to reduce Coulomb scattering there. The energy resolution of the spectrometer is 1.5%; the efficiency with which electrons or positrons are detected is $\varepsilon = 0.98$; the spatial resolution when determining the point at which the muon decays in the interaction region is ± 3 mm; and the time resolution of the fast electronics is ≈ 1 ns.

For each event we have measured the coordinates of the particle (eight planes) and the time at which the particle passed different elements of the apparatus. The measured parameters were used to determine the point at which the muon decayed and the angles at which the positron (or electron) entered and left the spectrometer and to calculate the energy of the detected particle. We constructed one- or two-dimensional distributions with respect to the measured and calculated parameters for the given statistics of positrons and

electrons. In the analysis we also used pulse height distributions from analogue outputs of scintillation detectors and cathode amplifiers of the proportional chambers.

As earlier studies have shown, the muonium produced in SiO_2 powder diffuses on a distance up to 40 mm from the plane of the target during the lifetime of the muon. That is why a search for events of $M \to \overline{M}$ conversion was made in the region located at distances 8 to 40 mm from the central plane of the target. On the left of Fig.2a the number of electrons detected by the spectrometer is plotted against the distance between the point of their origin and the central plane of the target, on the right the raw energy spectrum of these electrons is presented. When detecting the electrons, most of events are not attributed to real particles but are due to accidentals, so distributions for all the measured and calculated parameters are also random. To choose in these distributions ranges corresponding to the electrons from the μ^- decay, we used similar distributions obtained in the runs in which the positrons were detected by the spectrometer. In the latter case the most part of events is due to positrons from the decay of μ^+, so all the distributions obtained in the course of the experiment arc attributed to real particles and one is able to use them for selecting regions within which the above mentioned parameters should lay. Criteria obtained in such a manner were used later on for analyzing data taken in the experiments with the electrons. Figs.2b–2e demonstrate how the distributions for the electrons vary after imposing restrictions on values of the parameters.

Over the entire time devoted to measuring the muonium-antimuonium conversion at the JINF phasotron (≈640 h), $3.44 \cdot 10^{11}$ muons passed through the target. The number of muonium atoms in vacuum which are involved in $M \to \overline{M}$ conversion process is given by the expression $(N_{e+})_M = N_\mu W(\varepsilon, \Delta E) W_M$, where N_μ is the number of muons incident on the target, $W(\varepsilon, \Delta E)$ is the probability that the spectrometer will detect positrons with energy in the interval ΔE which satisfy the given selection criteria, and W_M is the probability for muonium to be observed in vacuum in the interaction region per incident muon.

The probability $W(\varepsilon, \Delta E)$ was determined by simulating the process by the Monte Carlo method. Under the conditions of the present experiment, this probability was $1.51 \cdot 10^{-3}$ for the positron energy interval 46.5–53 MeV. The probability W_M was studied by the μSR method, it was also extracted by analyzing the time and spatial distributions of positrons from the $\mu - e$ decay for various parts of the vacuum region in comparison with results of Monte Carlo simulation. For the probability of entering muonium into the interaction region we found a value of 0.030 ± 0.001 per incident muon. Trying to improve the reliability of the result, we used a lower value of W_M, specifically 0.029, when calculating the probability for the $M \to \overline{M}$ conversion.

In summary, as $3.44 \cdot 10^{11}$ muons passed through the operating target the apparatus detected electrons due to the process we looked for from $1.51 \cdot 10^7$ muonium atoms in the interaction region which satisfied the given selection rules. In the energy interval 46.5–53 MeV we see one candidate for $M \to \overline{M}$ conversion process at $E = 48.6$ MeV. From this fact we can estimate the upper experimental limit for muonium to antimuonium conversion in accordance with a Poisson distribu tion:

$$W_{M\overline{M}} \leq 3.89/[0.5(N_{e+})_M] = 5.1 \cdot 10^{-7}, \quad f \leq 0.14, \quad (90\%\text{CL}).$$

From Figs.2c–2d we can also estimate the upper experimental limits for background processes in this experiment:

$$W_{bg} \leq 2.81 \cdot 10^{-7}, \quad (90\%\text{CL}) \text{ — for the energy interval 44.5–53 MeV;}$$

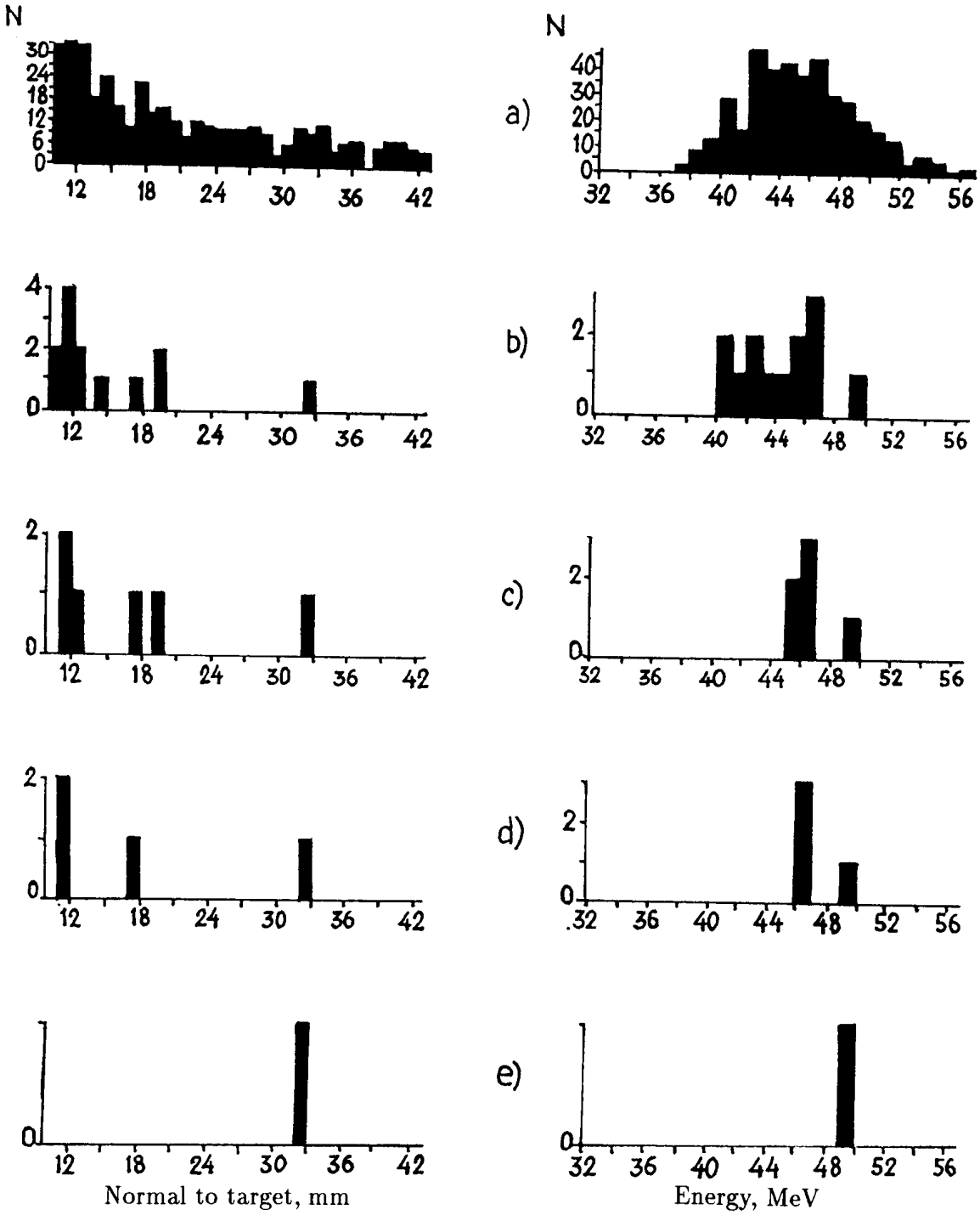

Fig.2. Experimental distributions of detected electrons along the normal to the SiO_2 target in the region where events of $M \rightarrow \overline{M}$ conversion were sought (at the left) and their energy distributions (at the right): *a* — raw spectrum; *b* — spectrum of electrons after imposition of limits on ranges of values for parameters of events; *c* — the same but in the energy interval 44.5–53 MeV; *d* — the same but in the energy interval 45.5–53 MeV; *e* — the same but in the energy interval 46.5–53 MeV

$$W_{bg} \leq 2.18 \cdot 10^{-7}, \quad (90\%\text{CL}) \text{ — for the energy interval 45.5–53 MeV.}$$

Extrapolation of these results to the energy interval 48.5–53 MeV gives the value

$$W_{bg} \leq 8 \cdot 10^{-8}, \quad (90\%\text{CL})$$

for probability to bond the event from Fig.2e with background process.

Of course, the detection of the single event does not mean the discovery of a new phenomenon. But certainly this demands to prolong such investigation aimed either to reduce the experimental upper limit or to registrate many events if the $M \to \overline{M}$ conversion takes place really.

Now the joint PNPI–JINR group prepares the next run of the physical measurements of the $M \to \overline{M}$ conversion and plans to reach the upper limit of the process in question $W_{M\overline{M}} \leq 4 \cdot 10^{-8}$.

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