Analysis of results of an experimental study of the probability for muonium–antimuonium conversion and of background processes in a separated beam of "surface" muons of the phasotron of the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research

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The complete statistical base acquired in the SPINP–JINR joint experimental search for muonium–antimuonium conversion has been analyzed. A total of 3.44×10^{11} muons passed through the target over the two series of physical measurements of the conversion process. One event which qualifies as a muonium–antimuonium conversion was detected. An experimental estimate $W_{M\bar{M}} \leqslant 5.1 \times 10^{-7}$ (90% C.L.) is found for the upper limit on the probability for the conversion process. Results of a study of the probabilities for background processes in the existing formulation of the experiment are reported.

The conversion of muonium $(M = \mu^+ e^-)$ into antimuonium $(\bar{M} = \mu^- e^+)$ has attracted research interest in connection with the problem of nonconservation of lepton number. Both electron and muon lepton quantum numbers change by 2 in this process. The possible occurrence of processes with $|\Delta L = 2|$ has been predicted by several theoretical models, which have examined various mechanisms for nonconservation of lepton number. The most interesting of these is a model in which the $U(1)$ lepton symmetry is broken by the existence of a finite Majorana mass of the neutrino. Another consequence of this effect would be the observation of a double neutrinoless β decay. This decay is presently the goal of an active search. Here $SU(2)$ invariance requires the appearance of doubly charged Higgs bosons in the model. These bosons carry a lepton number $\Delta L = 2$. This circumstance would make the $M \rightarrow \bar{M}$ conversion possible when the interaction is taken into account in first order. A study of this transition would thus provide information on the Higgs sector of the model, supplementing research on double β decay.

For a quantitative estimate of the probability for the process it is convenient to introduce the transition constant[1] $f = G_{M\bar{M}}/G_F$, where G_F is the Fermi weak-

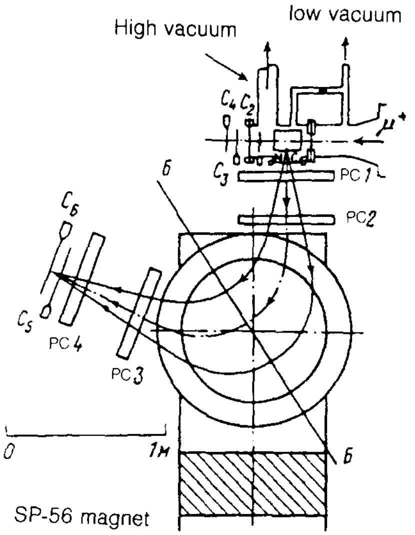

FIG. 1. Schematic diagram of the detector part of the experimental apparatus used to search for the conversion of muonium into antimuonium. C_1,C_2—Thin (≈ 60 μm) counters in vacuum, used to detect "surface" muons; C_3,C_4—monitor counters for detecting positrons; C_5,C_6—counters for detecting useful events; PC1–PC4—proportional chambers.

interaction constant. Different theoretical models predict[2] values for f over the range $10^{-2} > f > 10^{-6}$.

Two series of physical measurements were carried out in 1991–1992 in a search for muonium–antimuonium ($M \rightarrow \bar{M}$) conversion in an intense beam of separated "surface" muons produced at the phasotron of the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research. A wide-angle magnetic lens was used.[3] These measurements were carried out in a collaboration of the St. Petersburg Institute of Nuclear Research and the Joint Institute for Nuclear Research. A new method, offering a high luminosity in the detection of the conversion process and a low background level, was used. The method is based on detecting high-energy electrons from muon–antimuon decay by a wide-angle magnetic spectrometer.[4] A distinctive feature of the method used in this experiment is that the probability for the detection of background processes can be reduced below the existing experimental estimate of the probability for the conversion process ($W_{M\bar{M}}$). Another distinctive feature of the method is that these background processes can be reduced further by cutting off the energy range of the electrons from $\mu - e$ decay which are detected.

The detector part of the apparatus is shown schematically in Fig. 1. The overall experimental apparatus and its basic characteristics, the characteristics of the beam of surface muons, examples of the raw experimental spectra obtained during the accumulation of the statistical base, and a preliminary analysis of the experimental data, based on 80% of the statistical base, are all reported in Ref. 5. Below we report the results of an analysis of the entire statistical base of the experiment. We also report a modeling of the process. We furthermore find an experimental estimate of the probability for background processes under the actual experimental conditions.

Preliminary results of an analysis for the probability muon emission into the interaction observation region in this experiment were also reported in Ref. 5. This

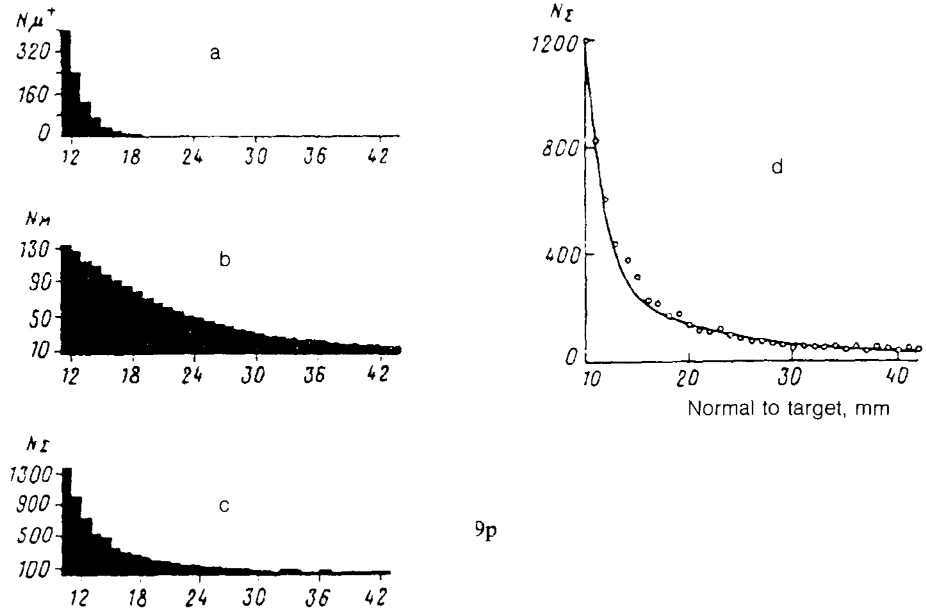

FIG. 2. Results of a comparison of theoretical and experimental data on the probability for muon emission into vacuum. a: Theoretical distribution of the number of positrons from the decay of muons with respect to the normal to the surface of the SiO_2 target in the region in which the muonium–antimuonium conversion is observed (the coordinate of the center of the target is 2). b: Theoretical distribution (analogous to that in part a) of the number of positrons from the decay of muons of muonium atoms in vacuum. c: Experimental distribution of the total number of positrons from the decay of muons stopped in the target and muons of muonium atoms in vacuum. d: Result of a comparison of the experimental distribution of the number of positrons in the region under study (points) and the theoretical distribution (solid curve) for the value $W_M=0.029$, used in the subsequent calculations.

probability is extremely important for normalizing the final result on the probability for the process of interest. The final value of the probability for muon emission from the SiO_2 target into the working region, in which the conversion process is observed, was found through a joint analysis of (a) the data of a μSR study carried out in the course of the experiment and (b) the temporal and spatial distributions of positrons from $\mu-e$ decay for various parts of the observation region—both experimental distributions and distributions calculated by the Monte Carlo method. The result is[6] 0.030 ± 0.001. Figure 2 shows the results of a comparison of the theoretical and experimental data obtained in one series of measurements of the probability for muon emission into vacuum. It can be seen from Fig. 2d that the theoretical and experimental data agree.

As was pointed out in Ref. 5, the coordinates of the particle (eight planes), the times at which the particle passed between different elements of the apparatus, and the amplitude distributions from the analog outputs of the scintillation detectors and the cathode amplifiers of the proportional chambers were measured for each event. From the position of the chambers measured in the selected frame of reference and from the local coordinates in the plane, we found four points (X, Y, Z) which specified the incoming trajectory of the detected particle (chambers PC1 and PC2) and its outgoing trajectory (after deflection in the magnet of the spectrometer; chambers PC3 and PC4). For each event we determined the "meeting plane," which is parallel to the symmetry axis of the magnet and passes through the bisector of the angle through which the particle is deflected in the spectrometer magnet (plane BB in Fig. 1).

The procedure for determining the energy of the detected particle is an integral procedure. It can be summarized as follows:

1. For the particle energy E_0 selected at the level of chamber PC1, one determines the emission angle such that the resulting trajectory between PC1 and the meeting plane passes through the point with the measured coordinates in PC2 (since there is a residual magnetic field between chambers PC1 and PC2, this is not a straight line).

2. Taking into account the average energy losses during the motion of the particle, one estimates the energy (E_0') which the particle should have upon arrival at PC4. The same procedure is used for the pair of chambers PC4, PC3.

Two curvilinear segments of the trajectory are thus obtained for the particle energy E_0, initially chosen arbitrarily. The condition for a joining of these two parts in the meeting plane is tested. For each of the two parts, one calculates two coordinates and two angles at the point of the intersection with the meeting plane. If the energy corresponding to the trajectories in the meeting plane differs by more than 0.1 MeV, step 2 is repeated with a recorrected energy E_0'. Since there are errors in the measurements of the coordinates in PC1–PC4 and the spatial distribution of the magnetic field, and also since there is a Coulomb-scattering component, we cannot expect the two parts of the trajectory to pass through a common point in the meeting plane for each selected energy E_0. However, it is always possible to choose an energy value E_0^* such that the tangents to the trajectories in the dispersion plane (X,Y) at the points of intersection with the meeting plane are parallel. This energy, E_0^*, is taken to be the "actual" energy of the particle. Within the losses in the film of Lavsan (a polyester) at the window of the vacuum chamber, this energy is the energy of the particle which it had as it left the chamber. A discrepancy in the coordinates of the intersection of the meeting plane and in the vertical angles for the two parts of the trajectory (first) provides an estimate of the energy resolution of the spectrometer and (second) serves as a criterion for distinguishing "true" events (in which all the coordinates in the chambers belong to the same physical particle) from background events (in which, for example, the pairs of chambers PC1, PC2 and PC3, PC4 detect two different particles).

Each processed event is characterized by a set of directly measured parameters (such as times and amplitudes) and parameters which are calculated as a result of the analysis. Some of these parameters are physical characteristics of the event (e.g., the coordinate and angle of emission from the target and the energy) and are used in the subsequent analysis. Other parameters, both directly measured parameters (signal amplitudes and transit times in combination with the jitter of the chambers) and parameters found as a result of the analysis of the event (ΔXY, ΔZ, $\Delta\beta_z$, etc.) actually carry no physical information. However, they do make it possible to draw a conclusion about the reliability of the event and thus to eliminate random background events which simulate rare "real" triggerings of the spectrometer tuned to e^- due to a possible conversion process. Since e^+ and e^- ($E \sim 50$ MeV) behave almost identically as they interact with matter, the distributions of these parameters from true events, both e^+ and e^-, should be the same for different orientations of the field in the magnet. By acquiring a sufficient statistical base for e^+ and by determining the parameters of these distributions, one can use the resulting data to analyze the same spectra for e^-.

Figure 3 demonstrates the evolution of the experimental spectrum acquired from the complete statistical base for electrons as limitations for possible ranges of variation of the parameters of the event, both measured and calculated in the course of the analysis, are imposed in succession on this spectrum.

A total of 3.44×10^{11} muons passed through the target over the total duration of the measurements of the muonium–antimuonium conversion at the phasotron (≈ 640 h of accumulation of a statistical base). The number of positrons from the decay of the muon in the muonium atom from the interaction observation region which are detected by the apparatus is given by

$$(N_{e+})_M = N_{\mu+} W(\epsilon,\Delta E) W_M .$$

Here N_{μ^+} is the number of muons incident on the target, $W(\epsilon,\Delta E) = 1.51 \times 10^{-3}$ is the probability for the detection by the spectrometer of positrons which have energies in the interval $\Delta E = 46.5$–53 MeV and which satisfy the selection criteria chosen (this probability was found through a simulation of the process by the Monte Carlo method), and $W_M = 0.029$ is the lower limit on the probability for observation of muonium in vacuum in the interaction observation region, per incident muon.

When 3.44×10^{11} muons pass through the working target, the apparatus thus detects 1.51×10^7 positrons from the decay of the muon of the muonium atom from the interaction observation region which satisfy the selection conditions imposed. Half of these positrons are in a state with a spin $I = 1$ and do not participate in the conversion process. In the energy interval 46.5–53 MeV we find one event, with $E = 48.6$ MeV (Fig. 3), which is not eliminated by the two successive energy cutoffs. This one event can be attributed to either muonium–antimuonium conversion or a background process. From the data obtained in the present experiment we can estimate an upper experimental limit on the probability for the conversion process. According to a Poisson distribution it is

$$W_{M\bar{M}} \leqslant 3.89/[(N_{e+})_M \times 0.5] = 5.1 \times 10^{-7}, \quad f \leqslant 0.14 (90\% \text{ C.L.}).$$

Working from the data in Fig. 3, i and k, we can also estimate an upper experimental limit on the probability for the detection of background processes in the existing formulation of the experiment:[6]

$$W_{\text{bg}} \leqslant 2.81 \times 10^{-7} \text{ (90\% C.L.) for the energy interval 44.5–52.8 MeV,}$$

$$W_{\text{bg}} \leqslant 2.18 \times 10^{-7} \text{ (90\% C.L.) for the energy interval 45.5–52.8 MeV.}$$

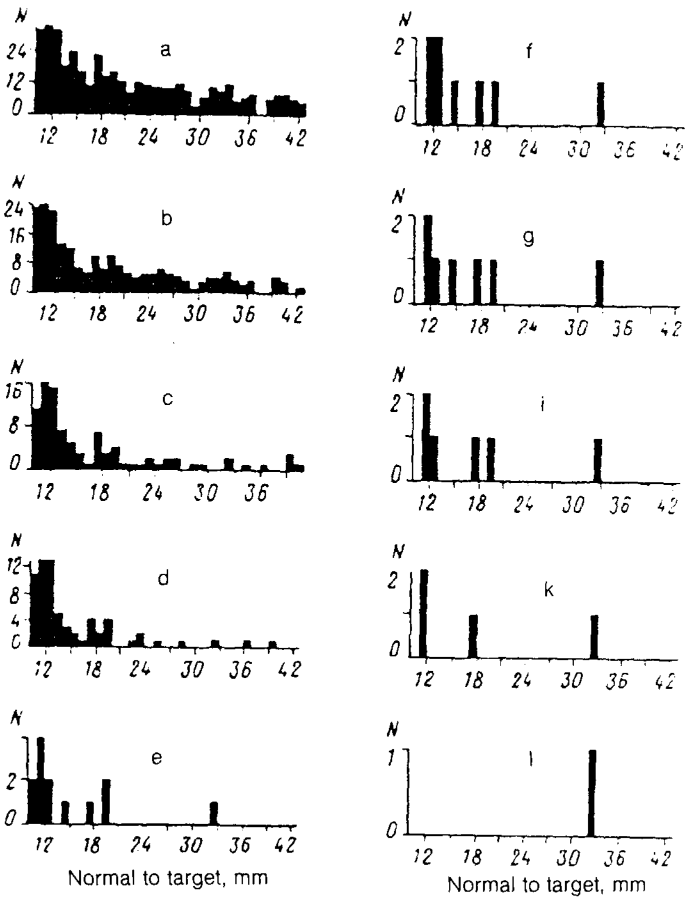

FIG. 3. Nature of the change in the experimental distribution for electrons during the successive imposition of limitations on the range of variation of the measured and calculated parameters. a: Raw electron spectrum. b: After limitations are imposed on the values of the coordinates in eight planes of the proportional chambers and on geometric parameters of the apparatus. c: After limitations are imposed on the parameters of the analysis for the "joining" of the trajectory in the "meeting plane." d: After limitations are imposed on the angular parameters of the event and the region in which events are detected in the target. e: After limitations are imposed on the temporal and amplitude parameters of the events. f–l: After the imposition of limitations on the range of event energies (f—42.5–52.8 MeV; g—43.5–52.8; i—44.5–52.8; k—45.5–52.8; l—46.5–52.8 MeV).

An extrapolation of these data to the energy interval 48.5–52.8 MeV yields $W_{\mathrm{bg}} \leqslant 8 \times 10^{-8}$ (90% C.L.) for the probability for observing a background event in this interval.

The fact that one event is observed does not, of course, mean that we have observed a new effect. However, it clearly emphasizes the importance of continuing this research in order to lower the upper boundary on the experimental limit or to observe many such events, if a conversion of muonium into antimuonium does indeed occur.

Preparations are presently under way at the St. Petersburg Institute of Nuclear Physics and the Joint Institute for Nuclear Research to carry out a new series of physical measurements of muonium–antimuonium conversion. Plans call for lowering the upper experimental limit on the probability for the conversion process to $W_{M\bar{M}} \leqslant 4\times 10^{-8}$.

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[1] G. Feinberg and S. Weinberg, Phys. Rev. **123**, 1439 (1961).
[2] E. G. Drukarev and V. A. Gordeev, Preprint LNPI 1588 (1990).
[3] V. M. Abazov *et al.*, JINR Report R9-93-81 (1993).
[4] E. G. Drukarev *et al.*, Preprint LNPI 1317 (1987).
[5] V. A. Gordeev *et al.*, JETP Lett. **57**, 270 (1993).
[6] V. A. Gordeev *et al.*, Preprint, St. Petersburg Institute of Nuclear Physics, 1970 (1994) (in press).

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