Experimental study of muonium-antimuonium conversion at the phasotron of the Joint Institute for Nuclear Research

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An experimental search has been made for muonium-antimuonium conversion ($M \rightarrow \bar{M}$) in an intense beam of surface muons produced at the phasotron of the Joint Institute for Nuclear Research. A wide-angle magnetic lens was used. This experiment was carried out as a collaboration between St. Petersburg Institute of Nuclear Physics and the JINR. A new method was used. It is based on the detection of high-energy electrons from the decay of the muon of the antimuonium by a wide-aperture magnetic spectrometer. This method provides a high luminosity for the detection of the conversion process, along with a low background. No events associated with the $M \rightarrow \bar{M}$ conversion were detected. A limit $W_{M\bar{M}} < 3.9 \times 10^{-7}$ (at a 90% confidence level) was established on the probability for the conversion process, with respect to ordinary muon decay. This limit is better than the limit which previously existed by a factor of 1.7 The new value for the muonium-antimuonium conversion constant is $G_{M\bar{M}} < 0.13 \cdot G_F$ (90% CL).

The conversion of muonium ($M = \mu^+ e^-$) into antimuonium ($\bar{M} = \mu^- e^+$) has attracted interest in connection with the problem of lepton-number nonconservation. The $M \rightarrow \bar{M}$ conversion requires nonconservation of lepton quantum numbers: $\Delta L_e = -2$, $\Delta L_\mu = 2$. If we assume that an interaction $\mathscr{H}$ which converts M and $\bar{M}$ does exist, then states with definite masses become linear combinations of the M and $\bar{M}$ states: $M_{1,2} = (M \pm \bar{M})/2$. If the system is pure muonium at the time $t_0 = 0$, then at time t it has gone into the state

$$M_1 \exp(-m_1 t - \Gamma_\mu t/2) + M_2 \exp(-m_2 t - \Gamma_\mu t/2)],$$

where Γ_μ is the decay probability, and $m_{1,2}$ are the masses of particles $M_{1,2}$. The system thus has M–$\bar{M}$ oscillations with a period $T = 2\pi/|\delta|$ ($\delta = 2\langle \bar{M} | \mathscr{H} | M \rangle$), and the probability $W_{M\bar{M}}$, that the muonium will decay as antimuonium (the conversion probability),[1] is $|\delta|^2/2\Gamma_\mu^2$. If we assign $\mathscr{H}$ an ordinary V–A structure with a constant $G_{M\bar{M}} = G_F f$, we find the probability $W_{M\bar{M}} = 2.5 \times 10^{-5} f^2$.

Various models and mechanisms for the violation of lepton number, among which processes with $|\Delta L|=2$ are more likely than processes with $|\Delta L|=1$, determine the range for studying the constant f: $10^{-2}<f<10^{-6}$ (Refs. 2–4).

Some TRIUMF[5,6] and LAMPF[7] experiments have yielded upper estimates of the constant $G_{M\bar{M}}$: $G_{M\bar{M}}<0.29G_F$ (Ref. 6) and $G_{M\bar{M}}<0.16G_F$ (Ref. 7). These figures indicate that the M–$\bar{M}$ conversion process requires further experimental study. These new experiments require high-luminosity installations and low-background procedures. One such method is to detect the electrons from μ–e decay at the high-energy end of the Michel spectrum through the use of a wide-aperture magnetic β spectrometer. The possibilities of this method were discussed in Refs. 8 and 9, and the background processes were estimated. A distinctive feature of this method is that the probability for the background processes is lower than the current experimental estimate of $W_{M\bar{M}}$, and a mechanism is available for suppressing these processes: by cutting off the energy range of the electrons from μ–e decay which are detected.

In 1991 and 1992, the St. Petersburg Institute of Nuclear Physics and the Joint Institute for Nuclear Research jointly undertook an effort to devise an experiment for searching for muonium–antimuonium conversion and for measuring the probability for this process, using the beam of "surface" muons of the JINR phasotron.[10] 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 $I_\mu=4.8\times10^5$ s^{-1}, the positron impurity in the beam was $N_{e+}/N_{\mu+}\approx 2$, the size of the beam (the 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 the 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 forms here (in the SiO_2) and diffuses at thermal velocities into the vacuum region, in which the $M\rightarrow\bar{M}$ conversion is observed (the interaction region; section A–A in Fig. 1). After they pass through the window of the vacuum chamber (100 μm of a material equivalent to Mylar), the positrons or electrons from μ–e decay, with energies in the interval 36–53 MeV, are observed by means of four proportional chambers with delay-line recording of data.[11] 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 at the center of the magnet deflects the electrons and the positrons from muon decay in opposite directions. Scintillation counter C_5, behind chamber PC4, generates a temporal signal of the detected event. An event is said to be detected in the spectrometer if signals from three cathodes of 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 $\epsilon=0.98$; the spatial resolution of 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 measured the coordinates of the particle (eight planes) and the time at which the particle passed between different elements of the apparatus. For each event we worked from the measured parameters to determine the point at which the

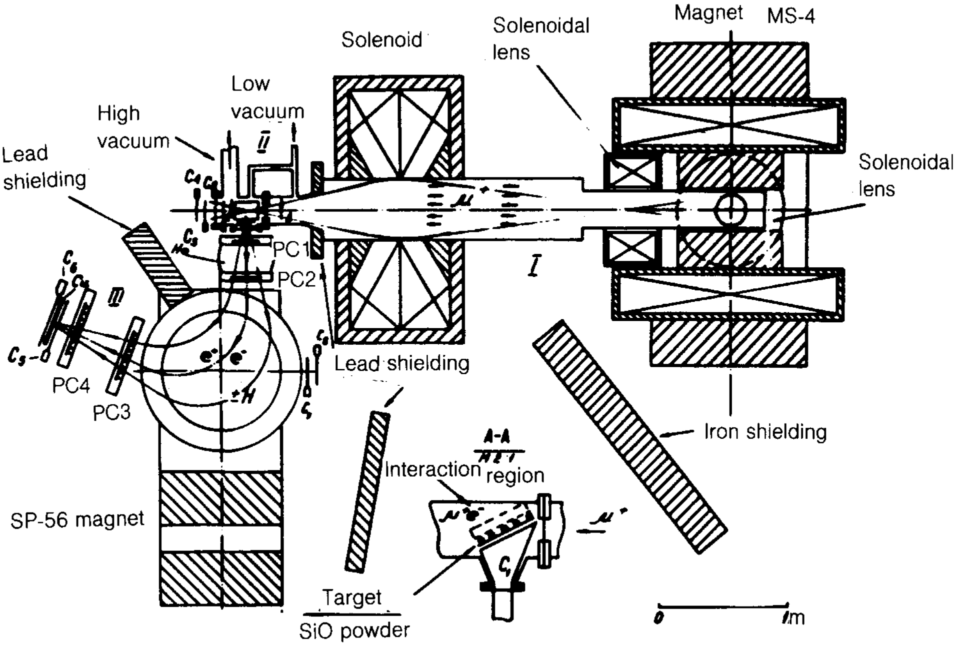

FIG. 1. Experimental layout of the search for the conversion of muonium into antimuonium. C_1, C_2—Monitor counters for detecting positrons; C_5, C_6—counters for detecting useful events; PC1, PC2, PC3, PC4—proportional chambers; Cu—copper filter.

muon decayed and the angles at which the positron (or electron) entered and left the spectrometer, and we calculated the energy of the particle which was detected. We constructed one- or two-dimensional distributions with respect to the measured and calculated parameters for the given statistical base of positrons and electrons. In the analysis we also used pulse-height distributions from the analog outputs of the scintillation detectors and the cathode amplifiers of the proportional chambers.

Figure 2 shows the raw experimental spectra from the detection of positrons and electrons by the spectrometer. Figure 3a shows a detailed distribution of the raw electron spectrum near the surface of the SiO_2 target.

Earlier studies[7,12] have shown that after muonium forms in SiO_2 powder it diffuses a distance up to 40 mm from the plane of the target over the lifetime of the muon. The arrow in Fig. 3a shows the spatial region with respect to the normal to the target (at distances of 8–40 mm from the central plane of the target) in which events of $M \rightarrow \bar{M}$ conversion were sought.

In detection by a positron spectrometer, most of the detected particles are evidently associated with real positrons from the decay of μ^+ particles which have been stopped in the SiO_2 target, and the distributions found experimentally with respect to the parameters specified above are associated with physical particles. For these particles, we can specify precisely the ranges over which these parameters can vary. In the

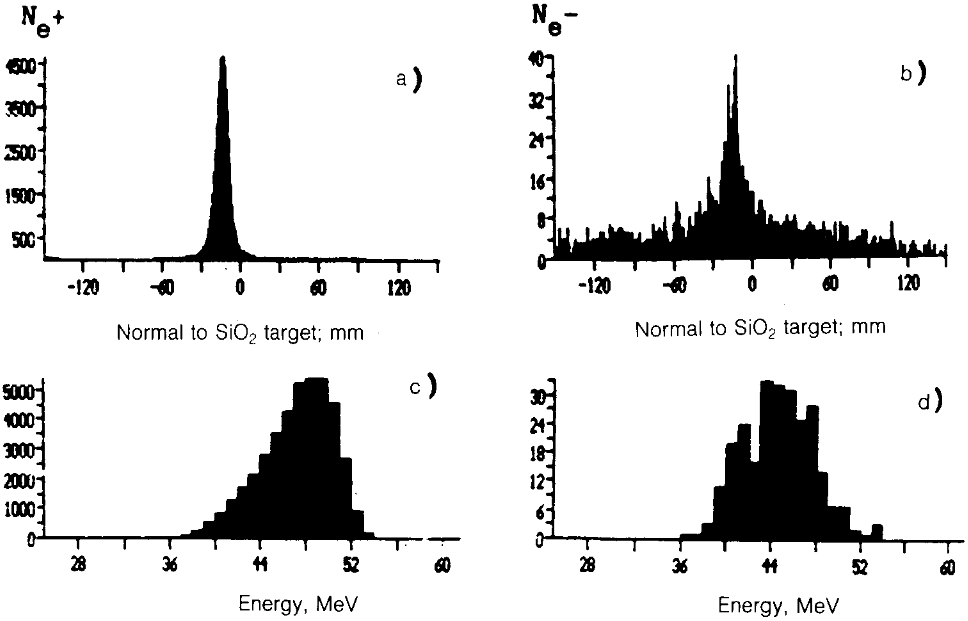

FIG. 2. Experimental distributions of the detected particles with respect to the normal to the surface of the SiO_2 target (top) and their energy distributions (bottom) for positrons (at the left, $N_{\mu^+} = 3.9 \times 10^7$) and for electrons (at the right, $N_{\mu^+} = 8.3 \times 10^{10}$). The center of the target has the coordinate 14 mm; 0 is the center of the window of the vacuum chamber.

detection of electrons, in contrast, most of the events stem not from real particles but from noise of the apparatus or from random triggerings upon a superposition of events, so there are naturally random distributions with respect to the measured parameters. The distributions for all the measured and calculated parameters for the electrons and positrons can be the same only for events associated with the $M \rightarrow \bar{M}$ conversion or for events associated with the physical background. Figures 3b and 3c show how the experimental spectrum for the electrons is changed when limits are imposed on the ranges of values for the parameters of the events. The primary selection criteria were determined through analysis of the experimental spectrum for positrons. Figures 2 and 3 correspond to one of the data files. The spectra for the other files are similar.

Over the entire time devoted to measuring the muonium-antimuonium conversion at the JINR phasotron ($\approx$640 h), 3.5×10^{11} muons passed through the target. In the present study, $\approx$80% of the total statistical base ($N_{\mu^+} = 2.9 \times 10^{11}$) was analyzed. No electrons in the energy interval 46.5–53 MeV, which simultaneously satisfied all the selection criteria imposed, were observed in the interaction region specified above.

The number of positrons from the decay of the muon in the muonium atom from

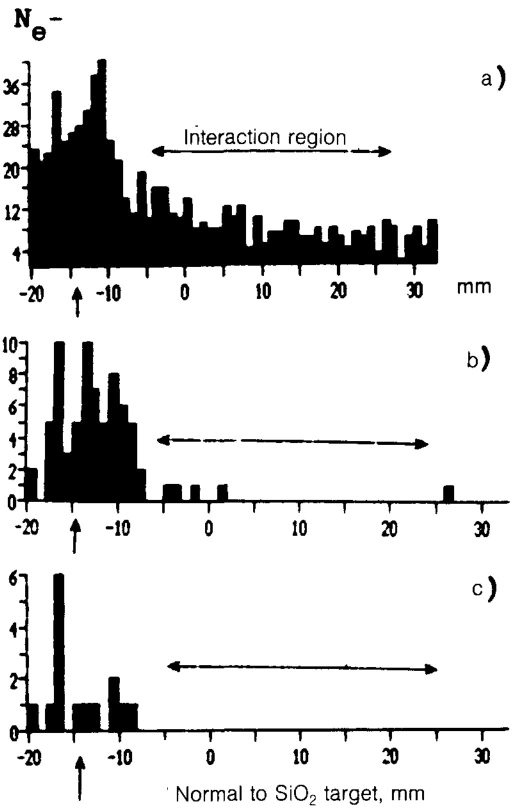

FIG. 3. Detailed distribution of the electron spectrum in Fig. 2b near the surface of the SiO_2 target. *a*—Raw spectrum; *b*—spectrum of electrons after the imposition of limits on the ranges of the measured and calculated parameters for the total width of the energy spectrum; *c*—the same, in the energy interval 46.5–53 MeV.

the interaction region which are detected by the apparatus is given by the expression $(N_{e^+})_{Mu} = N_{\mu^+} W(\epsilon,\Delta E) W_{M\mu}$, where N_{μ^+} is the number of muons incident on the target, $W(\epsilon,\Delta E)$ is the probability that the spectrometer will detect positrons with an energy in the interval ΔE which satisfy the given selection criteria, and W_{Mu} is the probability for observing muonium in vacuum in the interaction region per incident muon.

The probability $W(\epsilon,\Delta E)$ was found by simulating the process by the Monte Carlo method. Under the conditions of the present experiments, this probability was 1.51×10^{-3} for the positron energy interval 46.5–53 MeV. The probability $W_{M\mu}$ was studied by the method of Ref. 12. The muons of the beam were detected by scintillation counter C_1, with a 60-μm thickness of plastic, and were stopped in the SiO_2 powder (section *A–A* in Fig. 1). For each event, we identified the spatial point in the vacuum region near the target to which the muonium diffused before the muon decayed. The time interval between the instant at which the muon stopped and the instant at which the positron was detected in the spectrometer was also determined. The escape of muonium into vacuum was found by analyzing the temporal distribution of positrons from μ–e decay for various parts of the vacuum region. For the probability for the escape of muonium into the interaction region shown in Fig. 3, we found a value of 0.030 ± 0.003 per incident muon, which agrees with the data of Refs. 7 and 12. In an effort to improve the reliability of the result, we used a lower value of W_{Mu}, specifically, 0.027, in calculating the probability for the $M \to \bar{M}$ conversion.

In summary, as 2.9×10^{11} muons passed through the working target, the apparatus detected 1.18×10^{7} positrons from the decay of the muon of a muonium atom which was in the interaction region and which satisfied the given selection rules. Half of them were in the $I=1$ spin state and did not participate in the conversion process (the suppression stemmed from fringing magnetic fields near the target[1]).

The probability for muonium-antimuonium conversion (at a 90% confidence level) in accordance with a Poisson distribution, is found from the relation $W_{M\bar{M}} < \ln 10/[(N_{e^+})_{Mu} \cdot 0.5] = 3.9 \times 10^{-7}$, which corresponds to a value $G_{M\bar{M}} < 0.13 \cdot G_F$ for the muonium–antimuonium conversion constant (90% CL).

The new value found for the probability for the conversion process in the present study is better by a factor of 1.7 than the current estimate ($W_{M\bar{M}} < 6.5 \times 10^{-7}$, 90% CL; LAMPF, 1991).

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