MUONIUM TO ANTIMUONIUM CONVERSION

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Introduction

The standard model is today the generally accepted theory of the electroweak interaction, and it describes well all the existing experimental data. However, this theory is far from the completion yet, and there are some properties of the electroweak interaction which cannot be explained on its basis. We shall mention some of them.

Nature of chiral asymmetry of weak interaction. The standard model assumes – on the base of experimental data only – that all fundamental fermions are left-spiral particles (antifermions are right-spiral antiparticles), the symmetry of their interaction is $SU_L(2) \times U(1)$, and the carrier of the weak interaction is the left-handed W_L boson. It can happen actually (and from the theoretical point of view it looks reasonable) that the chiral asymmetry of the weak interaction is the result of spontaneous breaking of the global $SU_L(2) \times SU_R(2) \times U(1)$ symmetry, which arises due to the large mass difference of the right-handed W_R boson and the left-handed W_L boson (experimental data give today a restriction on the mass of W_R boson: $W_R > 406$ GeV/c^2).

Properties of Higgs particles. As it is known, in the Standard model all fundamental fermions are massless particles, and the observable masses of leptons and quarks arise through the Higgs mechanism due to their interaction with the Higgs scalar field. The Higgs mechanism requires existence of scalar Higgs bosons in nature. Experimental observation of the Higgs bosons (direct or indirect), determination of their charge, mass, and other properties is one of the most important goals of the modern elementary particle physics.

Neutrino properties. Is the neutrino a particle of the Dirac type (neutrinos and antineutrinos are different particles) or of the Majorana type (neutrinos and antineutrinos are identical particles)? Is there any mixing between neutrinos of different generations? What are the masses of the neutrinos? So far there are no answers to these questions.

Lepton numbers conservation. The allowed muon decays $\mu \to e\nu\tilde{\nu}$, $\mu \to e\nu\tilde{\nu}\gamma$ assume the lepton numbers conservation. No experimental evidence have been found so far for violation of this conservation low. Though one expects that the nonconservation of the lepton numbers could be observed with increasing the sensitivity of the rare decay experiments. The search for the muonium ($M = \mu^+e^-$) to antimuonium ($\bar{M} = \mu^-e^+$) conversion might be one of such experiments.

The possibility of the transition $M \to \bar{M}$ was pointed out for the first time by Pontecorvo (1957). The detailed analysis of the process has been accomplished by Feinberg and Weinberg (1961). Assuming, following Feinberg and Weinberg, the standard V–A structure of the Hamiltonian responsible for the $M \to \bar{M}$ transition one can obtain the following relation:

$$W_{M\bar{M}} = 2 \cdot 10^{-5} (G_{M\bar{M}}/G_F)^2,$$

where $W_{M\bar{M}}$ and $G_{M\bar{M}}$ are the branching ratio and the weak interaction constant for the $M \rightarrow \bar{M}$ conversion, respectively, and G_F is the Fermi constant of the weak interaction.

One model allowing the transition $M \rightarrow \bar{M}$ assumes that the neutrino is the Majorana particle. In the $SU(2)$ symmetry models with the Majorana neutrino a double charged Higgs boson exists inevitably. Exchanging by such boson results in the process represented in Fig. 1 and in the value of $G_{M\bar{M}}/G_F$ given by the expression:

$$\frac{G_{M\bar{M}}}{G_F} = \frac{f_{ee} f^*_{\mu\mu}}{g^2_W} \left(\frac{M_W}{M_{++}} \right)^2, \tag{3}$$

where f_{ee}, $f_{\mu\mu}$ are the coupling constants; $g^2_W = 8 G_F M^2_W / \sqrt{2}$ is the dimensionless constant of the weak interaction; M_W is the mass of the W boson; M_{++} is the mass of the double charged Higgs boson.

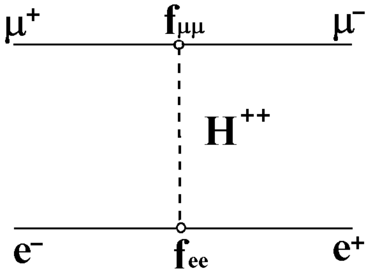

Fig. 1. Transition $M \rightarrow \bar{M}$ in the model with the Majorana neutrino.

The experimental situation in studying the conversion $M \rightarrow \bar{M}$ is presented in Table 1.

Table 1
Results of experimental study of $M \rightarrow \bar{M}$ transition (published in the 90s)

Experiment		Research method	$G_{M\bar{M}}$
TRIUMF	1990	$\beta + \gamma$ from reaction $\mu^- +^{184}$ W $\rightarrow^{184}$ Ta $\rightarrow^{184}$ W	$< 0.29\ G_F$
LAMPF	1991	e^- from μ^- decay and nuclear e^+	$< 0.16\ G_F$
PNPI–JINR [1]	1992	e^- from μ^- decay $44 \leq E_e \leq 53$ MeV	$< 0.38\ G_F$
PNPI–JINR [2]	1993 *)	e^- from μ^- decay $46.5 \leq E_e \leq 53$ MeV	$< 0.13\ G_F$
LAMPF	1993	L_α and K_α X-rays of mesoatom Bi	$< 6.9\ G_F$
PNPI - JINR [3]	1994 **)	e^- from μ^- decay $46.5 \leq E_e \leq 53$ MeV	$\leq 0.14\ G_F$
PSI	1996	e^- from μ^- decay and nuclear e^+	$\leq 0.02\ G_F$

*) – preliminary results; **) – one candidate event is observed.

As one can see from Table 1, the lowest limits on the $M\bar{M}$ conversion have been obtained in the PSI experiment (1996). However, an important remark should be noted. The PSI experiment was carried out in the conditions when the target area was in the strong magnetic field (~1 kGs). As we can show, within the $(V-A)\times(V-A)$ theory the $M\bar{M}$ transition is suppressed in the magnetic field for any spin state of the muonium atom. Indeed, in the $M\bar{M}$ transition the sign of the magnetic moment of the atom changes (the particles become antiparticles). But if the spin state of the system is not changed (this is in accordance with the $(V-A)\times(V-A)$ interaction), then the energy difference between the initial and the final states in the magnetic field H is equal to $\sim 2\mu_B H$, where μ_B is the Bohr magneton. This gives rise to the strong suppression of the conversion process even in the small magnetic fields (~1 Gs).

Fujii et al. (1993) and Horikawa and Sasaki (1996) have considered the $M\bar{M}$ conversion models within $(V-A)\times(V+A)$ interaction. In this case it is possible to observe the $M\bar{M}$ transition even in the strong magnetic field. Thus, the PSI experiment gives the limitations on the probability of the $M\bar{M}$ conversion process for the hypothetical case of the $(V-A)\times(V+A)$ interaction and the lower limit on the mass of the double charged boson (dilepton) which carries this interaction. Within the $(V\mp A)\times(V\mp A)$ theory the $M\bar{M}$ transition is forbidden in the conditions of the PSI experiment.

PNPI–JINR experiment

A new direct and independent method of studying the muonium to antimuonium conversion ($M \rightarrow \bar{M}$) was proposed and realized at PNPI, and the necessary equipment to perform the experiment was created [4,5]. In 1989–90 a new setup was installed in the muon channel of the PNPI synchrocyclotron, and the background conditions for the proposed experiment were studied.

The main experiment was carried out by a joint PNPI–JINR group using the beam of "surface" muons at the JINR phasotron. The first physical run at the JINR phasotron was performed in May–June of 1991. In the beginning, the parameters of the muon beam, the background conditions, and the muonium yield from SiO_2 powder into vacuum were investigated. After that the first series of physical measurements of the conversion process was made and the first estimation of $W_{M\bar{M}}$ and $G_{M\bar{M}}$ was obtained [1]: $W_{M\bar{M}} < 3.6 \cdot 10^{-6}$, $G_{M\bar{M}} < 0.38\ G_F$ (90%CL).

This result proved to be comparable with that obtained earlier at meson factories. The intensity of the "surface" muons ($\sim 1.8 \cdot 10^5$ s^{-1} at the proton current of 2μA), the geometrical and time parameters of the experimental setup existed at that time were obviously insufficient to get the experimental data of the quality better than the world's level.

The modernization of the existing equipment and the muon channel was completed by the end of 1991. The solid angle of the spectrometer and the speed of read-out from proportional chambers were increased. The intensity of the "surface" muons was increased almost by a factor of three owing to replacing quadrupole lenses in the channel by solenoidal lenses which were developed at JINR specially for this experiment. The main parameters of the beam were as follows: momentum $P_\mu = 21.5$ MeV/c; $\Delta P_\mu / P_\mu \simeq 7.7\%$; intensity of the surface muons (at the proton current of 2.0 μA) $I_\mu = 4.8 \cdot 10^5$ s^{-1}; the positron contamination in the beam $N_{e^+}/N_{\mu^+} \simeq 2$; the beam size (full width at half-maximum) of 7×8 cm^2; the duty factor of 75%.

In 1991–92 two new series of physical measurements of the conversion $M \rightarrow \bar{M}$ were carried out at the JINR phasotron. The results of this research and comparison with the world's data are given in Table 1.

The experimental setup and the data analysis are described in Refs. [2,3]. Only one event satisfying the selection criteria for the search of the conversion $M \rightarrow \bar{M}$ process was registered.

The technique used in the PNPI–JINR experiment was based on registration of high energy electrons from the muon decay with a wide aperture magnetic spectrometer. The identification of the physical and background events was performed by comparative analysis of spatial, amplitude, and time distributions of the positrons (from the μ^+ decays) and electrons (from the μ^- decays). When the spectrometer is tuned to detect the positrons from the μ^+ decays, the main part of information belongs to the physical events. In this case the principal parameters of the distributions mentioned above (mean values and dispersions) can be determined. Then these values were used to reject the background events while detecting the electrons from the μ^- decay; in this case the overwhelming majority of the registered events belongs to the background.

The complete list of the parameters and the corridors of their possible variations are given in Table 2. The values of the parameters for the event, which has been registered in the experiment and can be attributed to the muonium to antimuonium conversion, are also shown.

Table 2
Parameters used for selection of physical events

Type	Parameter	min	max	Event	Parameter	min	max	Event
I	X1	210	1130	516	Z1	240	850	796
	X2	40	1520	476	Z2	20	1100	884
	X3	60	1130	700	Z3	180	1320	988
	X4	30	1340	972	Z4	40	1380	996
	$\Delta T1$	110	500	190	$\Delta T2$	140	500	220
	$\Delta T3$	180	400	260				
	A1	25	120	41	A2	25	150	69
	A3	50	550	511	A4	50	550	349
II	Angle X-12	–13	18	3	Angle Z-12	–5	8	3
	Angle T-12	–16	20	3	Angle N-12	–13	10	–1
	Angle X-34	131	177	161	Angle Z-34	–13	11	–1
	Angle R	80	150	104				
	Target X	–85	65	5	Target Z	–35	32	31
	Target T	–90	80	–7	Target N	–20	42	31
	Radius F	0	80	36	Radius S	0	68	47
III	Quality	1	2	1	Energy	46.5	53	48.6
	ΔXY	–34	45	11	ΔZ	–60	45	9
	Normal	85	95	90	$\Delta\beta_z$	–8	9	2
	Calculated X	–80	66	9	Calculated Z	–35	32	31
	Calculated T	–85	79	–3	Calculated N	–60	60	33
	Calculated F	0	80	36	Calculated S	0	68	47
	Centre	–30	22	–7	Sector	114	130	125
	Length	103	154	115	Pole Z	0	125	67

I – parameters measured during the experiment: X1–X4, Z1–Z4 are the coordinates in 8 planes of PCs (channels of TDC); $\Delta T1$–$\Delta T3$ is the time difference of arrival of strobe-signals from the scintillation counter and from the cathodes of three PCs (channels of TDC); A1–A2 are the amplitudes of signals from scintillation counters of spectrometer (channels of CDC); A3–A4 are the amplitudes of signals from cathode preamplifiers of PCs (channels of CDC); PC is the proportional chamber; TDC is the time-to-digital converter; CDC is the charge-to-digital converter.

II – parameters calculated in the course of the experiment (on-line mode): Angle X-12 – Angle Z-34 are the angular characteristics of the event (degrees); Angle R is the angle of particle deflection in the spectrometer (degrees); Target X – Target N are the characteristics of the point where the muon decay has taken place (mm); Radius F – Radius S are the location of the electron trajectory relatively to the centre of external collimators of the equipment (mm).

III – parameters calculated during the subsequent events processing (off-line mode): Quality is the characteristic of the event (1 – the trajectory of the electron in the spectrometer is far from its poles, 2 – close to the poles), Energy is the electron energy (MeV); ΔXY, ΔZ, Normal, $\Delta\beta_z$ are the calculated parameters (see Ref. 3 for more details); Calculated X – Calculated S are the parameters of the initial event trajectory for inverse processing (calculated trajectory in the opposite direction); Centre, Pole Z are the characteristics of location of the electron trajectory relatively to the spectrometer geometry.

The results of all measurement series of the PNPI–JINR experiment are summarized in Table 3.

Table 3
Results of experimental study
of the $M \rightarrow \bar{M}$ conversion in the PNPI–JINR experiment

Series	N_μ	$W(\Delta E)$	W_M	$N_{M\bar{M}}$	$W_{M\bar{M}}$	$G_{M\bar{M}}$
I [1]	$4.5 \cdot 10^{10}$	$1.05 \cdot 10^{-3}$	0.027	0	$< 3.6 \cdot 10^{-6}$	$< 0.38\ G_F$
II + III [3]	$3.44 \cdot 10^{11}$	$1.51 \cdot 10^{-3}$	0.029	1	$\leq 5.1 \cdot 10^{-7}$	$\leq 0.14\ G_F$
I + II + III	$3.89 \cdot 10^{11}$			1	$\leq 4.7 \cdot 10^{-7}$	$\leq 0.14\ G_F$

N_μ is the total number of muons passed through the target; $W(\Delta E)$ is the probability of electron registration by the spectrometer in the energy interval ΔE [5]; W_M is the value used for the probability for muonium to get out of the SiO_2 powder into vacuum [5]; $N_{M\bar{M}}$ is the number of registered candidate events; $W_{M\bar{M}}$ – the measured branching ratio for the conversion $M \rightarrow \bar{M}$; $G_{M\bar{M}}$ is the measured upper limit of the coupling constant for this process.

Using our experimental result and the expression (3) (following from the theoretical model of the $M \rightarrow \bar{M}$ transition via Majorana neutrino) and assuming that the constants f_{ee} and $f*_{\mu\mu}$ are equal to g_w, it is possible to get an estimation of the mass of the double charged Higgs boson H^{++} responsible for the process of the $M \rightarrow \bar{M}$ conversion: $M_{++} \geq 210$ GeV/c^2.

Further plans

The preparations for new measurements of the conversion process $M \rightarrow \bar{M}$ are now under way at PNPI and JINR. The new experiment is designed to improve the $M \rightarrow \bar{M}$ conversion probability limit by a factor of 8–10. To reach this goal, it is necessary to change the geometry of the target unit to accommodate the full intensity of the muon beam (2-fold gain), to reduce the magnetic field in the target region to 20 mGs (2-fold gain), to increase the spectrometer aperture (1.5-fold gain), to increase the muon beam intensity and the net data-taking time (2-fold gain).

The work to meet these requirements has been partly accomplished already. The measurements will be performed practically without external magnetic field in the conversion region and with strongly suppressed background.

The new $M \rightarrow \bar{M}$ conversion experiment is planned to be carried out at the JINR Phasotron by joint efforts of PNPI, JINR, Kurchatov Institute, and ITEP.

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