Search for the decay $\mu^+ \to e^+ + e^+ + e^-$

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A cylindrical magnetic spark chamber has been used to carry out a search for the decay $\mu^+ \to e^+ + e^+ + e^-$. It is found that an upper limit of the probability of this decay at the 90% confidence level is $W(\mu^+ \to e^+ + e^+ + e^-)/W(\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu) \leq 1.9 \times 10^{-9}$.

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The results of experiments in neutrino beams[1] have shown that two kinds of neutrinos exist—electron and muon neutrinos. At the same time it was experimentally established that there is conservation of a new quantum number—muon leptonic charge. Suggestions of the existence of such a law had been made previously[2,3] in connection with the need to explain the absence of such decays as $\mu \to e\gamma$ (Refs. 4 and 5) and $\mu \to eee$ (Refs. 6–8). The problem of the difference in the physical properties of the electron and the muon is apparently one of the fundamental problems in contemporary elementary particle physics. The experimental determination of the degree of validity of the conservation of muon charge is in this light of undoubted interest. We report below an experiment on the search for the decay $\mu^+ \to e^+ + e^+ + e^-$, whose existence would indicate violation of this law.[1)]

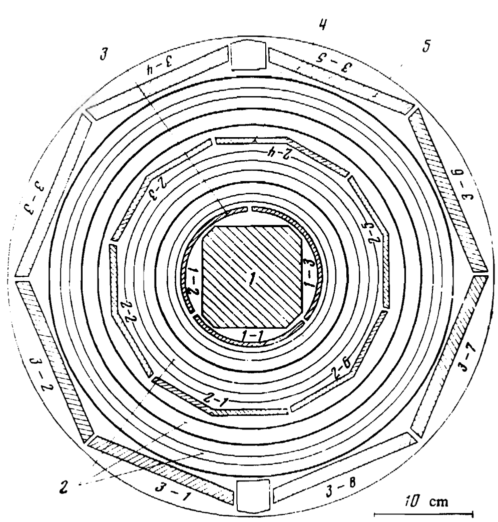
The search for the decay $\mu^+ \to e^+ + e^+ + e^-$ was carried out by means of a cylindrical magnetic spark chamber which has been described in detail elsewhere.[9] The spectrometer consists of a cylindrical spark chamber placed in a magnetic field and triggered by a hodoscopic system of scintillation counters located around and inside the chamber. The geometry of the apparatus is shown in the figure.

The spark chamber consists of a set of concentric cylinders of aluminum foil 0.05-mm thick with a 5-mm gap between them. There are altogether 18 working gaps in the chamber. The outer and inner cylinders which enclose the chamber volume are made of Dural. The outer cylinder has a working diameter of 382 mm. The diameter of the inner cylinder is 135 mm and its wall thickness is 0.25 mm. The volume enclosed between these cylinders is sealed by clear plastic ends. The height of the chamber is 325 mm. The coordinates of depth in the chamber are determined by means of a special prismatic device which has been described separately.[10]

The electronic system that produced the pulse triggering the apparatus utilized semiconductor coincidence circuits that made possible a resolution of ~6 nsec when operating in particle beams.[11] For higher reliability the chosen length of the shaped pulses was 10 nsec. In addition to the fast electronic circuits, the pulses from the photomultipliers are fed also to a high speed five-beam oscilloscope[12] whose sweep was triggered simultaneously with triggering of the chamber. The oscilloscope screen and the spark chamber were photographed by means of an RFK-5 camera. Oscillograms of the pulses from the photomultipliers permit analysis of the signals for time, logical, and pulse-height information.

The spectrometer was placed in a beam of positive pions with energy 80 MeV. Muons were obtained as the result of decay of pions stopped in the target placed inside the chamber. The target of plastic scintillator had the form of a parallelopiped of dimensions 180 × 100 × 22 mm and was placed at an angle of 37° to the beam direction, so that its projection on the plane perpendicular to the beam had dimensions 100 × 100 mm. The fast electronic logic system produced a pulse which controlled the triggering of the apparatus in the case of a coincidence within the resolution of the electronics (~10 nsec) of nine pulses arising in the target and in any two scintillation counters of the first row, three scintillation counters of the second row, and three counters of the third row (see the figure).

In a total of 620 hours of exposure, 4.1×10^{10} pions were stopped and we obtained 588 000 pairs of chamber and oscilloscope photographs in which $\mu^+ \to e^+ + e^+ + e^-$ decays could be recorded. About 64% of the run was carried out at a field strength of 0.45 T (0.45×10^4 Oe).



Cross section of spectrometer in plane perpendicular to pion beam direction: 1—target, 2—spark chamber gaps, 3—three scintillators of first row, 4—six scintillators of second row, 5—eight scintillators of third row.

Analysis of the data obtained in this run showed that the backgrounds are small. Therefore, in order to increase the efficiency for detection of this decay in the next run the magnetic field was decreased to 0.3 T, although the accuracy in determination of the momenta of the particles in this case drops (on the average from ~12% to ~17%).

Preliminary selection of the events was carried out on the basis of the following criteria:

1) there are two positron tracks and one electron track;

2) all tracks reach the third row of scintillation counters;

3) all tracks pass through different scintillation counters of the second and third rows;

4) in each track there are at least five sparks;

5) in the oscillogram of an event there are pulses from those scintillation counters through which the particles passed.

As the result of two scannings of the entire material we selected 2064 photographs of events for subsequent analysis. The coordinates of the tracks of these events were measured in microscopes with automated data readout (PUOS). The data obtained were then analyzed by computer. The χ^2 criterion was used to establish whether all three tracks originate from one point located in the target. Events with a χ^2 value whose probability was less than 5% were discarded. As a result 307 events remained. The same criterion was then used to determine whether the observed decay kinematics are consistent with the hypothesis that this was a $\mu^+ \to e^+ + e^+ + e^-$ decay. Events with a χ^2 value whose probability was less than 10% were assumed to be background. After this analysis, two events remained which could be considered further as possible candidates for cases of $\mu^+ \to e^+ + e^+ + e^-$ decay.

In the search for rare decays, in addition to the beam intensity and the apparatus efficiency, the presence of background and the possibility of separating it from the desired process is of decisive importance. It is obvious that the main method for separation of the effect from the background is the most accurate possible determination of the kinematics of the event. In order to retain the accuracy in determination of the kinematic parameters at a sufficiently high level, we decided not to consider events with a configuration such that more than 25% of the energy of all particles was lost in the target (~25 MeV). In such cases the scattering and the inaccuracy in determination of the energy of the individual particles and the point of decay lead to anomalously large errors. In turn this significantly increases the probability of obtaining a low value of χ^2, i.e., simulation of the desired decay. Introduction of the criterion described above reduces the efficiency for detection of $\mu^+ \to e^+ + e^+ + e^-$ decays only by 7%. It turned out that both remaining candidates should be discarded on the basis of this criterion.

The loss of energy in the target by all particles for one event amounted to 28 MeV. Here the accuracy in determination of the momenta of the individual particles from the track curvature was 10–15%, and the final uncertainty in determination of the particle energy, as the result of the factors enumerated above, reached ~60%. In the other case the particles lost 40 MeV in the target, the momenta were determined from the curvature with an accuracy of 10–20%, and the error in determination of the particle energy in the worse case amounted to 80%.

In spite of the fact that as the result of the analysis we found no $\mu^+ \to e^+ + e^+ + e^-$ decay event, it is necessary to discuss the probable source of the background. Possible sources are:

1) the decay $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu + e^+ + e^-$;

2) the decay $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu + \gamma$ with subsequent conversion of the γ ray in the target near the point of decay;

3) accidental coincidences of emission in opposite directions of two positrons from muon decay, where both positrons have an energy close to the maximum and one of them is scattered by an electron of the target material, transferring to it an exceptionally large energy ($\gtrsim$10–15 MeV);

4) accidental coincidence between emission of a positron from muon decay and passage through the chamber and target of a charged particle from the region outside the chamber, since such a particle simulates a positron and an electron.

The possible contribution from the decays $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu + e^+ + e^-$ and $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu + \gamma$ was calculated by the Monte Carlo method. Here we took into account the geometry and resolution of the spectrometer, the triggering logic, the magnetic field strength, the ionization loss in the target, and the design of the chamber. It turned out that the number of such decays which could be interpreted as a $\mu^+ \to e^+ + e^+ + e^-$ decay for the statistics obtained in the experiment is negligible (< 0.1 event). This is due to the fact that for simulation of the $\mu^+ \to e^+ + e^+ + e^-$ decay it is necessary that, within the resolution of the spectrometer, the sum of the energies of the particles equal the muon mass and the sum of the projections of the particle momenta on any coordinate axis equal zero. This is possible only when both neutrinos in the background processes have an energy close to zero. The probability of this, according to Ref. 13, is very small.

In order to clarify the correctness of the assumptions made regarding the sources of background, the 307 events in which tracks could be associated with one point of the target were checked for the presence of an electron-positron pair with invariant mass < 20 MeV or, by means of the χ^2 test, for the presence of a straight-through particle. It turned out that in ~90% of the events there is a pair or a straight-through particle. The remaining events can be interpreted as cases of the decay $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu + e^+ + e^-$ with a large angle between the directions of emission of the particles.

It should be noted that in the two candidates there were electron-positron pairs with small invariant mass. It is obvious that it would be possible, if necessary, to introduce criteria for rejection of events with straight-through particles or electron-positron pairs. Use of such criteria suppresses all four types of background discussed. The loss in detection efficiency for the $\mu^+ \to e^+ + e^+ + e^-$ decay in this case amounts to ~30% if the matrix element for the process is constant. At the same time the exposure could be increased by at least a factor of ten before the background discussed would reach the order of unity.

Of course, in the case where the process $\mu^+ \to e^+ + e^+ + e^-$ occurs as a result of internal conversion of the γ ray in the decay $\mu^+ \to e^+ + \gamma$, use of the selection criteria described above leads to a significantly greater loss in detection efficiency. However, in this case, generally speaking, it is preferable to study the decay $\mu^+ \to e^+ + \gamma$. The detection efficiency for the decay $\mu^+ \to e^+ + e^+ + e^-$ was calculated by the Monte Carlo method on the assumption that the matrix element of the decay is constant. Here we took into account the spectrometer geometry, the ionization loss in the target, the triggering logic, the magnetic field strength, and the loss due to the criterion of rejection of events in which the combined energy loss by the particles was greater than 25 MeV. The efficiency turned out to be 5% for a field of 0.45 T and 7.8% for a field of 0.3 T. These values were then corrected for the efficiency of the scintillation counters, the shower efficiency of the spark chamber, the efficiency for scanning of the photographs, and the loss due to the camera dead time and to introduction of confidence levels in χ^2. As a result the final efficiency for detection of events at a field of 0.45 T was found to be $(2.3 \pm 0.4) \times 10^{-2}$ and for a field of 0.3 T, $(4.3 \pm 0.8) \times 10^{-2}$. The number of muon decays for a field of 0.45 T was 2.64×10^{10} and for a field of 0.3 T, 1.46×10^{10}.

Using the Poisson distribution, we obtain an upper limit for the probability of the decay $\mu^+ \to e^+ + e^+ + e^-$ relative to the main muon decay:

$$W(\mu^+ \to e^+ + e^+ + e^-)/W(\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu) \leq 1.9 \cdot 10^{-9}$$

at the 90% confidence level.

According to existing models of the conservation of lepton number the decay $\mu^+ \to e^+ + e^+ + e^-$ is completely forbidden. Suggestions had been made, however, that lepton number may be one of the first candidates for a nonconserved quantum number.[14] Conservation of lepton number is violated also in the model proposed by Primakoff and Rosen.[15] Nikolaev and Shmatikov[16] have discussed gauge models of the weak interaction in which $\mu \to e$ transitions are possible. At the present time there is no generally accepted model, free from theoretical difficulties, of an interaction violating conservation of lepton number.

If we assume that nonconservation of muonic charge is due to the fact that "mixed" states of electron and muon neutrinos take part in the weak interaction, then the combination $\nu_e + F/G \times \nu_\mu$ will enter into the Lagrangian of the weak interaction instead of ν_e. In this case from the probability limit obtained for the $\mu^+ \to e^+ + e^+ + e^-$ decay we can find, using the formula for the probability of this decay given in Ref. 17, that

$$F/G < 10^{-2}$$

for a cutoff parameter $\lambda = 100$ GeV. The same order of magnitude of estimate is obtained also from experiments on the search for the decay $\mu \to e + \gamma$.[4,5]

In Refs. 18 and 19 a phenomenological analysis was made of the amplitude for radiative transition of a muon into an electron. From the probability of decay $\mu^+ \to e^+ + e^+ + e^-$ we can obtain a limit on the form factor $[\xi(m_\mu^2)]^2$ corresponding in this model to radiation of longitudinally polarized photons:

$$[\xi(m_\mu^2)]^2 < 5 \cdot 10^{-21}.$$

This result is inferior only to data from experiments on the search for the process $\mu^- Z \to e^- Z$.[20]

Great interest at the present time is attracted by the problem of neutral currents. Accordingly, if we assume that there exists an anomalous four-fermion interaction of the type $(\bar{e}, e)(\bar{\mu}, e)$ which violates conservation of muonic charge, then the decay $\mu \to eee$ will be a first order process in the constant F_n of this interaction. From the result of the present work we obtain for the value of the constant F_n the estimate

$$F_n/G < 4.4 \cdot 10^{-5}.$$

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1)Preliminary results for this work were reported previously.[8]

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Role of resonances associated with multiphoton transitions in molecules under the influence of an intense light field

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It is shown that electronic resonances, at internuclear distances that differ from the equilibrium value, may play an important role in multiphoton transitions in molecules. In particular, such resonances lead to a delay of the multiphoton dissociation process and to a substantial change in the angular distribution of the spreading fragments.

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The behavior of molecules in an intense electromagnetic field has been investigated in less detail than the behavior of atoms. In particular, the specific role which electronic resonances may play in connection with multiphoton transitions in molecules has still not been analyzed. The point is that, in addition to resonances in intermediate electronic states similar to those which occur in atoms, resonances associated with different values of the internuclear distance R, differing from the equilibrium value R_e, are also possible in the system of a molecule's electronic terms. Certain effects associated with multiphoton transitions in molecules, which may be caused by resonances of a similar type, are discussed in the present article.

For the sake of definiteness let us consider the nonresonant n-photon dissociation of a diatomic molecule under the influence of an intense field of optical frequency ω. The terms of the initial U_1 and final U_2 electronic states for this case are shown schematically in the figure. After a transition to the repulsive term U_2, dissociation of the molecule usually occurs in a time of the order of 10^{-13} to 10^{-14} sec; however, this process may be significantly retarded if one-photon optical transitions between terms 1 and 2 are forbidden. For a sufficiently high intensity of radiation, the one-photon resonance $\hbar\omega = U_2(R) - U_1(R)$, appearing in the region $R_1 > R_e$, leads to a strong interaction between terms 1 and 2, as a result of which a radical rearrangement of the nuclear motion occurs. It is now necessary to determine the motion of the nuclei on the basis of the electronic Hamiltonian, which includes the resonance interaction with the radiation field.[1]

The procedure for separating the electronic and nuclear motion in a molecule located in a strong field is actually equivalent to the use of the Born–Oppenheimer approximation in the representation of "rotating" electronic states, where the resonance interaction of the molecule with the external field $\mathbf{E} = \mathbf{E}_0 \cos\omega t$ becomes time independent, and the potential energy for the nuclear motion in terms 1 and 2 takes the following matrix form:

$$\hat{U} = \begin{pmatrix} U_2-\hbar\omega/2 & V_0 \\ V_0 & U_1+\hbar\omega/2 \end{pmatrix}. \qquad (1)$$

The presence of the nondiagonal elements $V_0 = \mathbf{d}_{12} \cdot \mathbf{E}_0/2$ in Eq. (1) indicates that is is impossible to regard the motion of the nuclei with respect to the terms 1 and 2 as independent in the region $R \approx R_1$. Upon ful-