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June 1994

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June 14, 1994

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Abstract:

We have measured the momentum of muons from the decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ at rest to be $p_{\mu^+} = 29.79207 \pm 0.00012$ MeV/c. This result leads to a laboratory upper limit of 0.16 MeV (CL=0.9) for the muon-neutrino mass. The cosmological upper limit of the neutrino mass, the muon mass and the new p_{μ^+} -value yield the pion mass $m_{\pi^+} = 139.57031 \pm 0.00016$ MeV. The mean kinetic energy of the pions stopped in the isotropic-graphite production target immediately before their decay is found to be $\overline{T_{\pi^+}} = 0.415 \pm 0.027$ eV.

The most precise method so far to determine the muon-neutrino mass is the measurement of three quantities, namely the momentum $p_{\mu+}$ of the muons from the decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ of stopped pions [1,2], and the rest masses of the muon $m_{\mu+}$ and the pion $m_{\pi-}$. We have measured the momentum $p_{\mu+}$ by a new technique, involving the momentum analysis of muons in a surface muon beam, i.e. a beam of muons originating from the decay of π^+ -mesons stopped at the surface of a pion production target. The magnetic spectrometer used to analyze the muon momenta has a homogeneous magnetic field, three copper collimators with rectangular openings, and a muon detector system composed of a silicon microstrip detector and a single silicon surface barrier counter.

In our previous $p_{\mu+}$ -measurements [1,2], a π^+ -beam was used; the stopped pion decays were made to occur in a scintillator placed in the homogeneous magnetic field of the spectrometer. The main advantage of using a surface muon beam is that the density of muons in phase space is four orders of magnitude higher than in the older method. Thus the openings of the collimators in the spectrometer can be made much smaller than before without causing the event rate to be too low; this leads to a better momentum resolution and enables one to improve upon the precision of the previous $p_{\mu+}$ -result in only a few days of beam time.

The layout of the experiment is shown in Fig. 1. Protons with a kinetic energy of 590 MeV from the PSI isochronous cyclotron produce π^+ -mesons in the production target E, a rotating-wheel device made of isotropic graphite (type EK90 from Ringsdorff-Werke, Bonn, Germany). The target is 6 cm long in the proton beam direction, and is electrically grounded. Its temperature during the data-taking runs was ~ 990 – 1270 K, depending on the proton beam current (200 – $550 \mu A$). A fraction of the pions are stopped in the production target and decay nearly at rest. If the decay occurs close to the surface of the production target, the decay muons

can exit from the latter. A part of these ‘surface muons’ are transported in vacuum by the π E1 beam line, composed of dipole and quadrupole magnets and a Wien filter separator, to the muon spectrometer.

The muons which leave the target with an appropriate momentum vector first pass the standard part of the π E1-channel, which was set to select positively charged particles in a ~ 1 percent wide momentum band, ranging from ~ 29.6 to ~ 29.9 MeV/c. The separator was set to transmit muons and suppress the positron contamination. The muons enter the spectrometer through the copper collimator A (thickness 0.3 mm, width 0.12 mm, height 10 mm) located inside the homogeneous magnetic field. Collimator B (width=height=10 mm) defines the horizontal angular acceptance of the spectrometer, and collimator C (width 14 mm, height 10 mm) defines the vertical angular acceptance. These openings are chosen such that the spectrometer accepts only the central, almost uniformly populated part of the (x, Θ, y, Φ) -space [3] of the beam. The angular distribution of the muons entering the spectrometer was derived from measurements of the rate in a small scintillator near collimator A as a function of the positions of the four jaws of a remotely movable horizontal and vertical collimator system (item 11 of Fig. 1), located 1.5 m upstream of collimator A. After passing collimator C, the muons traverse a silicon microstrip detector (thickness 0.28 mm, 384 vertical 0.05 mm wide strips) [4], and are stopped in a large single silicon surface-barrier detector (diameter 20 mm, thickness 1 mm) directly behind the microstrip detector. The muons lose about 0.9 MeV in the microstrip detector, and the remaining energy (~ 3.2 MeV) in the single silicon detector. These large energy losses were used to separate the muons from background events, primarily due to beta particles from the decay of radioactive nuclei present in the residual gas (pressure ≈ 1 mPa).

Between runs, the relative positions of the collimators and detectors were mea-

sured by use of a laser interferometer and a coordinate table with a microscope. The collimators A, B, C and the silicon detectors were mounted on a support made of titanium, selected from among the materials fulfilling the magnetic and mechanical requirements because of its small thermal expansion coefficient. The temperature of the titanium support was kept between 293.1 K and 293.5 K both during the runs and the distance measurements, and was continuously recorded. The magnetic field of the spectrometer was stabilized, and mapped between runs, by NMR-probes [1].

One of the resulting muon spectra, recorded at a spectrometer field of 276.0 mT, is shown in Fig. 2. For this spectrum, the central momenta of the π E1-channel and of the spectrometer were set close to the initial decay momentum of 29.79 MeV/c. We recorded 40 spectra similar to that of Fig. 2, at six different magnetic fields (275.4, 275.6, ..., 276.4 mT).

The cut-off around strip 180 in Fig. 2 corresponds to decay muons which originated at the surface of the graphite production target. The distribution in strips 180–280 contains muons from stopped pion decays inside the production target. The peak at strip 190 originates from energy loss straggling of the muons in the production target; see e.g. Fig. 12 of Ref. [2]. The momentum band transmitted by the π E1-channel corresponds to strips $\sim$ 120–280, and the horizontal opening of collimator C, just upstream of the microstrip detector, extends from strip $\sim$ 40 to strip $\sim$ 320. The background due to muons scattered in the collimator jaws, visible in strips 280–320, was found in a Monte-Carlo study [5] to drop approximately linearly to zero from strip 320 to strip 180 of Fig. 2. The background distribution to the left of the cut-off, e.g. in strips 120–170 in Fig. 2, is due to muons from the decay in flight of π^+ mesons in the secondary beam channel.

Of the 40 spectra, 21 were made to contain muons from the side surface of

the production target ($x=0.3$ cm, $z\approx 0$; cf. Fig. 1) while the remaining 19 spectra contained muons from the downstream surface ($x \approx 0$, $z = 3$ cm). The two surface regions were selected by use of the dipole magnets of the beam line [6]. In these two regions, the muons cross the surface layer of a few nanometers, in which the π^+ stopping density was calculated to be smaller than further inside, at very different angles ($\sim 10^\circ$ or $\sim 80^\circ$, respectively). The comparison of the two groups of spectra gave results consistent, within uncertainties, with the Monte-Carlo calculations of the ‘surface correction’ related to the reduced π^+ stopping density near the target surface [6,7].

We also recorded μ^+ -spectra at reduced momenta, at which the muon momentum distribution was nearly uniform. From these spectra, it followed that the relative efficiency of the microstrips was 1.000 ± 0.014 , except for a few faulty strips (*e.g.* strips 212–216; see Fig. 2). In addition, μ^- -spectra were obtained by inverting the polarities of the beam magnets and the spectrometer. Since stopped π^- decay is very improbable, the μ^- -spectra are almost entirely due to pion decay in flight and have no significant cut-off at 29.79 MeV/c. The almost uniform shape of the experimental μ^- -spectra agrees with predictions based on π^- -production cross-sections [8,9]. This confirms the reliability of the calculations of the background due to π^+ -decay in flight for μ^+ -momenta below the cut-off (where the experimental μ^+ -spectra are dominated by stopped π^+ decay) [5].

In the data analysis, the experimental spectra taken at ~ 29.79 MeV/c (*e.g.* Fig. 2) were compared with spectra generated by a Monte-Carlo program. The spatial distribution of pion stops in the production target was generated from experimental pion-production cross sections [8,9]. The pions prior to their decay were assumed to have a Maxwell-Boltzmann type kinetic-energy distribution, the mean energy of which was treated as a free parameter. Such a distribution is

valid if the pions are trapped in a spherical harmonic-oscillator potential [6]. This leads to a gaussian distribution of the initial muon momenta. For the Monte-Carlo program, the muon momentum for pions decaying exactly at rest was assumed to be 29.792 MeV/c. The energy loss of the muons on the way out of the production target was generated according to the theory of Bichsel [10].

If the kinetic energy of the decaying pions is assumed to be zero, the extension of the cut-off (10–90 percent) of the resulting Monte-Carlo distribution is ~ 2 microstrips, predominantly due to the finite openings of the collimators A and B in the spectrometer, and also to muon scattering in the residual gas in the vacuum chamber of the spectrometer and in the microstrip detector. The extension of the experimental cut-off in all 40 spectra, e.g. at strip ~ 180 in Fig. 2, is significantly larger, namely ~ 6 microstrips. This implies that the motion of the decaying pions trapped in the production target dominates the extension of the cut-off.

The Monte-Carlo microstrip distribution was fitted to a 40 strips wide part of the experimental spectra, selected in the region of the cut-off, e.g. strips 166–205 of Fig. 2, using the computer program MINUIT [11], with five free parameters, namely 1) a shift of the abscissa due to the difference between the true muon momentum for pion decay at rest and the value of 29.792 MeV/c assumed for the Monte-Carlo calculation, 2) a normalization factor for the ordinate (number of events per microstrip) at the center of the region of the fit, 3) a parameter defining the slight linear dependence of the normalization factor on the strip number, related to the momentum dependence of the acceptance [5], 4) the height of the background distribution due to pion decay in flight, and 5) the standard deviation of the muon momentum distribution due to pion motion.

Our final p_{μ^+} -result is based on the 19 downstream-surface spectra, for which the ‘surface correction’ of p_{μ^+} is only (51 ± 51) eV/c, much smaller than for the

side-surface spectra [7]. The mean χ^2 -value of the 19 fits is 36.9 for 35 degrees of freedom. The change of the extension of the fit region from 40 to 30 or 50 strips did not lead to significant changes of the results. The $p_{\mu+}$ -values resulting from the 19 fits are compatible; their χ^2 -value with respect to their weighted mean is 20.4 for 18 degrees of freedom.

The standard deviation of the gaussian muon-momentum distribution attributed to the motion of the decaying pions obtained by our analysis is

$$\sigma(p_{\mu+}) = 0.00489 \pm 0.00016 \text{ MeV}/c. \quad (1)$$

The mean kinetic energy of the pions corresponding to Eq. (1) is [6]

$$\overline{T_{\pi^+}} = 0.415 \pm 0.027 \text{ eV}. \quad (2)$$

The energy of Eq. (2) is significantly higher than the mean energy of 0.128–0.164 eV valid for a Maxwell-Boltzmann distribution of free (π^+e^-) -atoms at temperatures of 990–1270 K. On the other hand, Eq. (2) agrees with the assumption that the stopped pions (treated here as a light hydrogen isotope) are trapped in the potential well of a spherical harmonic oscillator as derived by Shirasu et al. [12] from their measurements of the solubility of low-pressure hydrogen and deuterium in isotropic graphite. The data of Ref. [12] were also used to derive that the muons have to overcome an atomic potential of 15.6 eV in leaving the site of their creation in the graphite target [6]. The corresponding correction, which we applied in order to obtain the muon momentum for free pions at rest, amounted to $(57 \pm 7) \text{ eV}/c$. This uncertainty ($\pm 7 \text{ eV}/c$) was chosen to include the value of 50 eV/c, obtained under the assumption of a free (π^+e^-) -atom.

The resulting momentum of muons from pion decay at rest is

$$p_{\mu+} = 29.79207 \pm 0.00012 \text{ MeV}/c. \quad (3)$$

The significant contributions to the uncertainty in Eq. (3) are listed in Table 1. The result of Eq. (3) agrees with the best previous value, $p_{\mu^+} = 29.79179 \pm 0.00053 \text{ MeV}/c$ [1].

The p_{μ^+} -value of Eq. (3), together with measurements of the μ^+ - and π^- -masses and the CPT-theorem ($m_{\pi^+} = m_{\pi^-}$), was used to derive a new value of the squared muon-neutrino mass. The μ^+ -mass was taken from Ref. [13]:

$$m_{\mu^+} = 105.658389 \pm 0.000034 \text{ MeV} . \quad (4)$$

For the π^- -mass, we used each of the two possible values derived in the recent re-analysis [14] of the pionic X-ray spectrum of Jeckelmann et al. [15], i.e.

$$m_{\pi^-}(A) = 139.56782 \pm 0.00037 \text{ MeV} , \quad (5)$$

or

$$m_{\pi^-}(B) = 139.56995 \pm 0.00035 \text{ MeV} . \quad (6)$$

The value $m_{\pi^-}(A)$ of Eq. (5) is obtained if the strongest component in the pionic magnesium ($4f \rightarrow 3d$) X-ray line of Ref. [15] is assumed to correspond to the presence of one K-electron, whereas the value $m_{\pi^-}(B)$ of Eq. (6) results if the strongest component is assumed to correspond to the presence of two K-electrons.

For the smaller of the two π^- -mass values, i.e. for Eqs. (3,4,5), four-momentum conservation in the decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ leads to the squared muon-neutrino mass

$$m_{\nu_\mu}^2(A) = -0.148 \pm 0.024 \text{ MeV}^2 , \quad (7)$$

whereas the larger of the two π^- -mass values [Eqs. (3,4,6)] leads to

$$m_{\nu_\mu}^2(B) = -0.022 \pm 0.023 \text{ MeV}^2 . \quad (8)$$

The first of the two $m_{\nu_\mu}^2$ -values [Eq. (7)], negative by 6.2 standard deviations, can be considered as unphysical and thus excludes the smaller of the two π^- -mass

values [Eq. (5)]. The second $m_{\nu_\mu}^2$ -value [Eq. (8)], on the other hand, is compatible with zero, and hence implies that the larger of the two π^- -mass values [Eq. (6)] is consistent with our new p_{μ^+} -result.

Our experiment thus leads to the following conclusions:

1) The squared muon-neutrino mass is as given by Eq. (8) above. According to the method recommended by the Particle Data Group (page III.39 of Ref. [13]; probability density set to zero for $m_{\nu_\mu}^2 < 0$), Eq. (8) corresponds to the new upper limit

$$m_{\nu_\mu} < 0.16 \text{ MeV} \quad (\text{CL} = 0.9). \quad (9)$$

This is the lowest ‘laboratory’ limit on m_{ν_μ} published to date.

2) The following π^+ -mass results are derived from the p_{μ^+} -value of Eq. (3), the μ^+ -mass of Eq. (4) and three different assumptions on the ν_μ -mass:

a) For $m_{\nu_\mu}=0$ one obtains

$$m_{\pi^+} = 139.57031 \pm 0.00016 \text{ MeV}. \quad (10)$$

b) For muon-neutrino masses below the cosmological upper limit, $m_{\nu_\mu} < 65 \text{ eV}$ [16], the resulting π^+ -mass is equal to that of Eq. (10).

c) For any real value of m_{ν_μ} , the resulting π^+ -mass is equal to or larger than that in Eq. (10).

In comparison with the recent re-analysis by Jeckelmann *et al.* [14], the π^+ -mass of Eq. (10) agrees with the $m_{\pi^-(B)}$ -value of Eq. (6), but excludes the $m_{\pi^-(A)}$ -value of Eq. (5) by 6.2 standard deviations.

Considering the older $m_{\pi^\pm}$ -results compiled in the Meson Full Listings of the 1992 Review of Particle Properties [13], the pion mass of Eq. (10) agrees with the value DAUM 91, but is larger by several standard deviations than the values JECKELMANN 86 and LU 80. The discrepancy between Eq. (10) and JECKELMANN 86 can be explained by the fact that the latter value was based on ‘solution A’ (one K-electron), which according to the re-analysis [14] is no longer preferred over solution B.

3) The mean kinetic energy of π^+ -mesons stopped in isotropic graphite at temperatures of 990–1270 K immediately before their decay is 0.415 ± 0.027 eV; this agrees with the assumption that the pions are trapped in the potential well of a spherical harmonic oscillator, $V(r) = V_0 + \frac{1}{2}k_s r^2$, with $k_s = (1.09 \pm 0.15) \cdot 10^{17}$ eV/cm² [6]. This potential is consistent with that derived from measurements of the solubility of hydrogen and deuterium in isotropic graphite [6,12].

We wish to thank Dr. P.F.A. Goudsmit and Prof. P.F. Meier for discussions, Mr. H. Oesch for collaboration in the distance measurements, Miss E. Barthazy, Mr. B. Henrich and Mr. J. Löffler for participation in the data-taking and analysis, Mr. P. Dick for work on electronics problems, Mr. D.C. George for help with the magnetic spectrometer, and many other PSI staff members for their support.

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Source of uncertainty	Uncertainty [eV/c]
1) ‘Statistical’ uncertainties:	
1.1. MINUIT error (counting statistics and microstrip efficiencies)	± 53
1.2. Scatter of position measurements	± 26
1.3. Scatter of magnetic field maps	± 50
1.4. Monte-Carlo statistics	± 10
Quadratic sum (1)	± 78
2) Systematic uncertainties:	
2.1. Position measurement device	± 19
2.2. Magnetic-field measurement device	± 60
2.3. Muon energy loss in graphite target	± 30
2.4. Graphite-target surface correction	± 51
2.5. Charge drift in microstrip detector	± 30
2.6. Atomic potential at μ^+ -creation	± 7
Quadratic sum (2)	± 92
Quadratic sum (1,2)	± 120

Table 1: Contributions to the uncertainty of the muon momentum p_{μ^+} .

Figure captions:

Fig. 1. Experimental set-up. 1) Central trajectory of 590 MeV proton beam; 2) graphite production target; 3) central trajectory of muon beam; 4) half-quadrupole magnets; 5) dipole magnets; 6) quadrupole magnets; 7) collimator defining the beam momentum acceptance; 8) concrete shielding of proton channel; 9) crossed-field particle separator; 10) lead collimator; 11) remotely movable collimator system (normally open); 12) magnetic spectrometer; 13) pole of spectrometer; 14) muon detectors (silicon microstrip and single surface-barrier detectors); A,B,C: copper collimators.

Fig. 2. Distribution of muons over the 384 strips of the silicon microstrip detector, measured at a central muon-beam momentum setting of 29.75 MeV/c and a spectrometer field of 276.0 mT. One microstrip width (0.05 mm) corresponds to $\Delta p_{\mu^+} \approx 0.0021$ MeV/c. The muon momentum increases to the left. For details, see text.

Fig.1.

Fig. 2.