Measurement of the mass of the neutral kaon

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The momenta and emission angles of the pions in the reaction $e^+e^- \to K_L K_{S_{\pi^+\pi^-}}$ have been measured with a cryogenic magnetic detector at the VÉPP-2M storage ring. The energy of the particles in the storage ring is found by resonant depolarization. The mass found for the neutral kaon is 497.742 ± 0.085 MeV.

This experiment was carried out with a cryogenic magnetic detector[1] at the VÉPP-2M storage ring at $2E = 1018.73 \pm 0.03$ MeV energy of the beams, near the peak of the ϕ resonance. At this energy of the beams the kinetic energy of the kaons is 11.7 MeV, and the momentum of the nonrelativistic kaons and also the limiting angle at which the pions fly apart during the decay are sensitive to relatively small variations of the mass of the neutral kaon.

The decay pions are detected, and their momenta measured, by a cylindrical optical spark chamber inside a superconducting solenoid. The magnetic field in the volume of the detector was 15 kG in the present experiments. Because of the magnetic field, the low temperature, and the elevated pressure of the gas mixture in the spark chamber, we achieved a spatial resolution of about 100 μm in the XY plane, which is perpendicular to the axis of the beams. The spatial resolution along the Z axis, parallel to the axis of the beams, was 2.5 mm. The effect of multiple scattering of pions on the accuracy at which the momenta are reconstructed is comparable to the effect of the spatial resolution of the detector. The accuracy at which the angle at which the pions resulting from the decay of the kaon fly apart is 2°. At these characteristics of the detector, the angles and momenta of the detected pions make it possible to achieve a momentum resolution of about 10.5 MeV/c for the K_S mesons. The adjustment of the optical system is monitored with the help of reference marks on the front and rear walls of the spark chamber. The programs for reconstructing the particle trajectories take into account the optical characteristics of the detector, the displacement of the sparks in the crossed magnetic and electric fields, and the nonuniformity of the magnetic field.

The selected luminosity integral is 10 nb^{-1} at an average luminosity of 1.3×10^{29} cm$^{-2} \cdot$ s^{-1} of the VÉPP-2M storage ring during the accumulation of a statistical base. The trigger conditions involve the detection of two-particle events in which the angular deviation from collinearity in the XY plane lies between 0° and 90°. The efficiency at which the reaction $e^+e^- \to K_L K_{S_{\pi^+\pi^-}}$ is detected is about 20%. In the experiments, 58 000 photographs were recorded, on about 2000 of which candidate kaon decays were subjected to measurements.

The primary criterion for the selection of useful events is the sum of the pion momenta, $(P1 + P2)$, since this sum lies in a narrow interval of values near 416 MeV/c for the decay of the kaon into two pions. Taking into account the radiation corrections and the momentum resolution of the detector, we selected events with 340 MeV/$c < (P1 + P2) < 500$ MeV/c.

To reduce the contribution from the electroproduction $e^+e^- \to e^+e^-e^+e^-$, we discarded events in which the angular deviation from collinearity of the two tracks in the XY plane did not exceed 10°, since the events in this process are distributed with a peak near zero. We also discarded events with few measured points on a track and with a spatial resolution three times worse than the average resolution. In addition, we selected events in which the distance in the XY plane from the kaon decay point to the axis of the beams was less than the radius of the vacuum tube of the accelerator. The coordinates of the region of the interaction of the electron and positron beams were found through an analysis of electron-positron scattering events and events of the process $e^+e^- \to 3\pi$. Applying these criteria, we identified 780 events.

Analysis of a possible contribution of background processes to the statistical base selected in this manner shows that the greatest contribution would come from the process involving the production of neutral kaons, in which one of the decay pions in turn decays into a muon and a neutrino inside the detector. Estimates show that these events should constitute about 1% of the total number, and this circumstance was taken into account in the analysis of the statistical base.

Using the method of resonant depolarization[2,3] along with a system for stabilizing the average energy of the beams,[4] we were able to determine the energy, and to keep it constant throughout the experiment (within 15 keV), for each of the colliding electron and positron beams in the VÉPP-2M storage ring. To reduce the effect of radiation corrections on the accuracy with which the mass of the neutral kaon is determined, we place the energy of the colliding electron and positron beams during the experiment on the left-hand slope of the resonance curve of the ϕ meson. Since the energy of the kaons after the radiation corrections can be assumed known, we can work from the momentum distribution of these particles to determine the mass of the neutral kaon. There is a further possibility of comparing the total energy of the pions measured in the detector with the known energy of the kaon and thereby determine the absolute value of the magnetic field in the apparatus. The resulting uncertainty of 0.1% in the magnitude of the magnetic field contributes 27 keV to the error of the determination of the mass by this method. The same uncertainty in the magnetic field leads to a change of 320 keV in the invariant mass of the pions constructed under the assumption that the energy of these pions is unknown.

The mass of the kaon can be determined not only from the momentum distribution of the K_S mesons but also by measuring the limiting angle between the emitted pions in the case in which the pions are emitted perpendicular to the direction in which the kaon is moving in the rest frame of the kaon.

To determine the mass of the kaon, we divided the selected events into two groups. The first contained 614 events, in which the momenta of the pions differed by more than 10%. In the second group of 166 events, this difference was less than 10%.

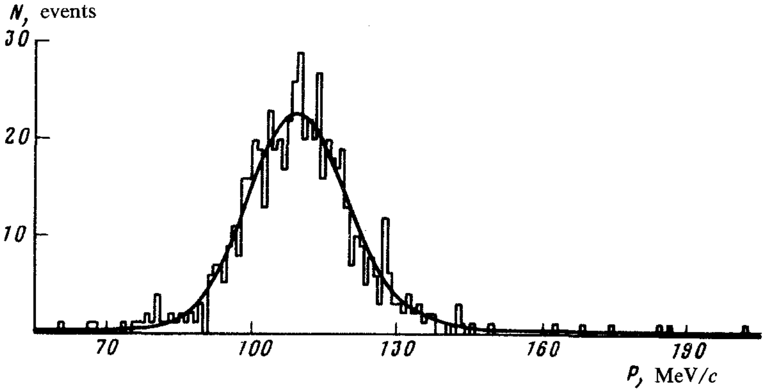

FIG. 1. Distribution of events of the first group in the momentum of the K_S meson. Solid line—Calculated with $M = 497.762$ MeV.

Working by the maximum-likelihood method from the momentum distribution of the kaons in the events of the first group (Fig. 1), we determined the mass of the neutral kaon: $M = 497.762 \pm 0.116$ MeV. The radiation corrections are made in accordance with Ref. 5. The error specified here consists of the error due to the resolution of the detector and the limited statistical base (100 keV) and the errors which result from the optical distortions and the displacement of the sparks in the electric and magnetic fields, the imperfect calibration of the magnetic field and the detector, and the uncertainty in the energy of the beam and in the momentum distribution generated by the Monte Carlo method.

The angles between the pion emission directions in the events of the second group must lie in a narrow interval of 0.6° near the limiting value of this angle, which is about 150°, but processes involving the emission of soft photons and the finite angular resolution of the detector broaden this region. Comparison of the experimental distribution in the angle between the pion emission directions for the events of the second group (Fig. 2) by the maximum-likelihood method yields $M = 497.720 \pm 0.122$ MeV.

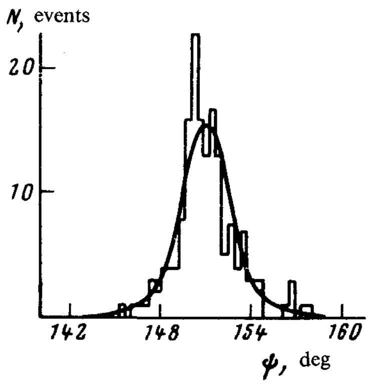

FIG. 2. Distribution of events of the second group in the angle (ψ) between the emission directions of the pions. Solid line—Calculated with $M = 947.720$ MeV.

The error indicated here consists of the error due to the resolution of the detector and the limited statistical base (115 keV) and the errors due to the optical distortions and displacement of the sparks in the electric and magnetic fields, the uncertainty in the determination of the beam energy, and the uncertainty in the expected distribution in the angle between the pion emission directions which was generated by the Monte Carlo method.

Since the results obtained by the two methods agree with each other, within the experimental errors, which are mostly statistical, we can average these results. We then find the final value for the mass of the kaon to be $M = 497.742 \pm 0.085$ MeV.

This value differs by 0.097 MeV from the preliminary result which we reported in Ref. 6. The difference stems from the more accurate allowance for the effect of the spatial resolution of the detector on the shape of the distributions in kaon momentum and in the angle at which the pions are scattered.

The error of this study is 1.5 times smaller than the error cited by the Paticle Data Group[7] in the neutral-kaon mass of 497.67 ± 0.13 MeV, which they find by taking an average over the available data.

We are indebted to the VÉPP-2M staff for maintaining the accelerator facility in good operation during the experiment.

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