Evidence for the φ-Meson Contribution to Vacuum Polarization Obtained with the Orsay e^+e^- Colliding-Beam Ring

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The absolute cross section for the $e^+e^- \to \mu^+\mu^-$ reaction was measured in a 12-MeV total c.m. energy range centered at the mass of the φ meson. We observe a deviation from the s^{-1} dependence of the cross section predicted by quantum electrodynamics when hadronic modifications are neglected. A good fit to the data requires that one take into account $\gamma \to \varphi \to \gamma$ virtual transitions. Direct evidence for such a vacuum-polarization effect is thus established with a confidence level higher than 0.99.

Cabibbo and Gatto[1] have stressed that e^+e^- colliding beams offer a unique possibility of studying experimentally the Källén-Lehmann representation of the complete photon propagator

$$D_{\mu\nu}'(k) = \frac{\delta_{\mu\nu}}{k^2} + \left(\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}\right)\frac{1}{\pi}\int_0^\infty \frac{da}{a}\,\frac{\mathrm{Im}\Pi(a)}{a+k^2-i\epsilon}\,. \tag{1}$$

On the one hand, the spectral function $\mathrm{Im}\Pi(a)$ which appears in Eq. (1) can be measured with e^+e^- rings since

$$\mathrm{Im}\Pi(4E^2) = (E^2/\pi\alpha)[\textstyle\sum_f \sigma^{(f)}(2E)]\,, \tag{2}$$

where E is the beam energy, and $\sum_f \sigma^{(f)}(2E)$ represents the total annihilation cross section for $e^+e^- \to f$ summed over all final states f which can be produced in the one-photon channel. On the other hand, the modification of the photon propagator implied by the integral on the right-hand side of Eq. (1) can be studied by carrying out accurate measurements on a quantum-electrodynamic (QED) process, such as $e^+e^- \to \mu^+\mu^-$, which involves the propagator of a timelike photon. Such an investigation is precisely the one reported in this Letter. In order to observe a hadronic contribution to the spectral function, we worked at a total c.m. energy equal to the φ-meson mass M_φ, since $\sum_f{}'\sigma^{(f)}(2E)$, the prime indicating that f is limited to hadronic states, exhibits a sharp peak—its highest one—at this energy.

The $e^+e^- \to \mu^+\mu^-$ cross section, which takes into account the modification of the photon propagator due to the φ meson, is obtained[2] by using Eqs. (1) and (2) and a Breit-Wigner formula for $\sigma(e^+e^- \to \varphi)$:

$$\sigma'(e^+e^- \to \mu^+\mu^-) = \left|1 - \frac{3B}{\alpha}\,\frac{M_\varphi \Gamma_\varphi}{M_\varphi^2 - 4E^2 - iM_\varphi\Gamma_\varphi}\right|^2 \sigma(e^+e^- \to \mu^+\mu^-). \tag{3}$$

Γ_φ is the φ full width, B its leptonic branching ratio, and σ' is the cross section corrected for the hadronic effect.[3] Since $B \simeq 3\times10^{-4}$, a 12% deviation is expected when $2E = M_\varphi \pm \Gamma_\varphi/2$. In fact, this effect is somewhat smoothed out by the usual radiative corrections.

We carried out three independent measurements *simultaneously:*

(1) *A luminosity measurement* by detecting double bremsstrahlung and 2γ annihilation events produced at very small angles with the beam line.[4] 800 000 events were recorded. The systematic error attached to the luminosity values is ± 5%.

(2) *An energy calibration* of the ring by detecting the reaction $e^+e^- \to \varphi \to K^+K^-$. In order to fit the corrective factor of Eq. (3) with a minimum number of parameters, we wanted to know within a fraction of 1 MeV the beam energy E relative to $M_\varphi/2$. For this purpose, we measured the excitation curve of the φ resonance. Figure 1(a) shows the apparatus. Thin windows (0.2-mm stainless steel) allowed the kaons, whose kinetic energy ranged between 10 and 15 MeV, to escape the vacuum chamber and be stopped in 3-mm-thick scintillation counters, K_1 and K_2. The very high background originating from the beams was almost completely suppressed by (i) using three anticoincidence counters AC located as shown in Fig. 1(a), (ii) setting high pulse thresholds on K_1 and K_2, (iii) taking advantage of the $K^+ \to \mu^+\nu$ decay. We counted only those K^+K^- events which

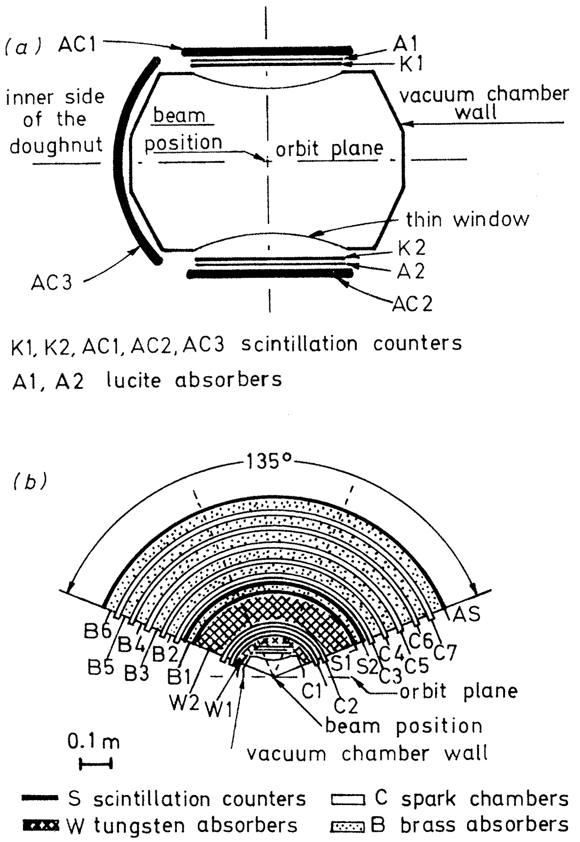

FIG. 1. (a) Projection of the K^+K^- setup on a plane perpendicular to the beams. (b) Upper half of the $\mu^+\mu^-$ detector. The lower half is obtained by symmetry with respect to the orbit plane. Only one of two arrays of scintillation counters AS used to veto cosmic rays is shown in this figure.

generated a muon observed in either AC_1 *or* AC_2 as a delayed signal, and in the innermost spark chambers that surround K_1 and K_2 [see Fig. 1(b)] as a single clean track.

(3) *An absolute measurement of the* $\mu^+\mu^-$ *yield* by detecting 2100 muon pairs in a series of cylindrical optical spark chambers.[5] The upper half of the setup is shown in Fig. 1(b). The chambers were triggered by fourfold coincidences among cylindrical scintillators S sandwiched between the chambers. The positions and thicknesses of the absorbers were chosen in order to assure the identification of muon events on the basis of range measurements. Monte Carlo simulations showed that the efficiency of detection of muon pairs was 0.326 ± 0.004 (statistical error) ± 0.005 (systematic error), and that it did not vary by more than a few 10^{-3} over the energy range explored, while the efficiency of detection of pion pairs was 0.04 ± 0.01 (systematic error; the statistical uncertainty is negligible). All e^+e^-, K^+K^-, $K_S{}^0K_L{}^0$, and $\pi^+\pi^-\pi^0$ events as well as all the particles lost by the beams were eliminated by the 10-cm-thick tungsten absorbers located between the beams and the trigger counters.

In order to carry out our measurements in identical conditions over the whole energy range which we studied, a large fraction[6] of our data were taken while the energy of the ring was continually and linearly varied between $E_{\rm min} = M_\varphi/2 - 3$ MeV and $E_{\rm max} = M_\varphi/2 + 3$ MeV; the period of these cycles was 5 min. Typical intensity and luminosity values at the beginning of a run were, respectively, $I_\pm \simeq 27$ mA and $L \simeq 5\times 10^{28}$ cm^{-2} sec^{-1}. The runs were stopped after 8 to 9 h of data taking when the luminosity was down to about $\frac{2}{5}$ of its initial value. We checked that the beam energy, i.e., $E_{\rm min}$ and $E_{\rm max}$, could be set within less than ± 0.25 MeV during this $2\frac{1}{2}$-month experiment.

Since the ring energy was constantly changed, we used an on-line Varian 620/i computer to record the energy of each detected event ($\mu^+\mu^-$, K^+K^-, double bremsstrahlung, and 2γ annihilation) and to control the development of the experiment.

The trigger rate of the muon detector was about 50/h. We achieved such a low rate by rejecting 99.9% of the cosmic rays with two arrays of veto counters and with a standard timing procedure which takes advantage of the bunching of the stored particles. The luminosity integrated over the 600 h of data taking is 6.9×10^{34} cm^{-2}. 30 000 pictures were taken. Most of the nonvetoed cosmic rays were easily discarded at the scanning of the pictures, which left 3000 events to be measured. The cosmic rays which remained in this set of pictures were all eliminated by setting an upper limit to the range of the tracks. We checked that our cosmic-ray rejection can be considered 100% efficient by applying the same procedure to pictures taken with no stored particles.

The main corrections which come into the analysis of the data are a 5% subtraction of the left-over pion events, and radiative corrections (othe than $\gamma \to \varphi \to \gamma$). The subtraction of pion events was based on the following experimental results[7-10]: $\sigma(e^+e^- \to \pi^+\pi^-, 2E = M_\varphi) = (3.76 \pm 0.51) \times 10^{-32}$ cm^2 (weighted average), $\Gamma(\varphi \to \pi^+\pi^-)/\Gamma_\varphi < 8 \times 10^{-4}$. No constraint was put on the phase of the $\varphi \to \pi^+\pi^-$ amplitude. Our final errors take all these uncertainties into account. As far as radiative corrections are concerned, we used the results of Bonneau and Martin[11] for the $\mu^+\mu^-$ events. We took into account real photons emitted off the peaking approximation. Furthermore, a 1% radiative correction was applied to our double bremsstrahlung measurements according to Baier and Geidt's calculations.[12] The overall uncertainty in these radiative corrections δ was estimated to be $\Delta\delta = 1.5\times10^{-2}$.

Results.—Our first result bears on an eventual polarization of the stored particles with respect to the vertical guide field of the ring. Sokolov and Ternov's analysis[13] predicts an ultimate 92.5% polarization of each beam which builds itself up with a time constant of $3\frac{1}{2}$ h in the conditions of our experiment. Such a transverse polarization would affect the azimuthal distribution of the muons in a well-known way.[14] In order to investigate this point, we considered the ratio $R = (N_{1,2}\times N_{2,1})/(N_{1,1}\times N_{2,2})$, where $N_{1,j}$ ($N_{2,j}$) is the number of muon pairs detected during the first 3 h (after 3 h) of each run, and $N_{i,1}$ ($N_{i,2}$) is the number of events detected with an azimuthal angle ϕ with respect to the horizontal plane such that $25° \leq \phi \leq 45°$ ($67.5° \leq \phi \leq 90°$). One predicts $R = 1.5$ if polarization does take place, and $R = 1$ if it does not. The measured value is $R = 0.99 \pm 0.11$. Therefore, we conclude that the crossing of a resonance did prevent the polarization from taking place in our experiment. This result agrees with the observations of Le Duff *et al.*[15]

We may now check whether Eq. (3) correctly describes our absolute measurements of the muon cross section. Figure 2(a) is the best fit of the right-hand side of Eq. (3) integrated over the detector acceptance to the number of observed $\mu^+\mu^-$ events divided by the time-integrated luminosity for each energy bin. The value of M_φ is set according to our excitation curve of the φ as shown in Fig. 2(b). For Γ_φ, we use a weighted average of more-accurate measurements, $\Gamma_\varphi = 4.00 \pm 0.22$ MeV.[16] Therefore, our fit has two parameters: B, on the one hand, and on the other a scale factor κ by which we multiply the right-hand side of Eq. (3). The χ^2 value of the best fit is 9.6 for thirteen degrees of freedom.

From the best fit, we deduce[17] that $\kappa = 1.12 \pm 0.03$ (statistical) ± 0.11 (systematic); this value is to be compared to unity. This test is nearly independent of the $\gamma\to\varphi\to\gamma$ transition effect. We may use our result on κ to set a lower limit on a cutoff parameter Λ introduced in the usual way[18]: One modifies the cross section for $e^+e^- \to \mu^+\mu^-$ by multiplying it by $F^2(k^2)$, where $F(k^2) = (1 - k^2\Lambda^{-2})^{-1}$ and $k^2 = 4E^2$. We add the systematic error to twice the statistical error to obtain $|\Lambda| > 2.8$ GeV/c (95% confidence).

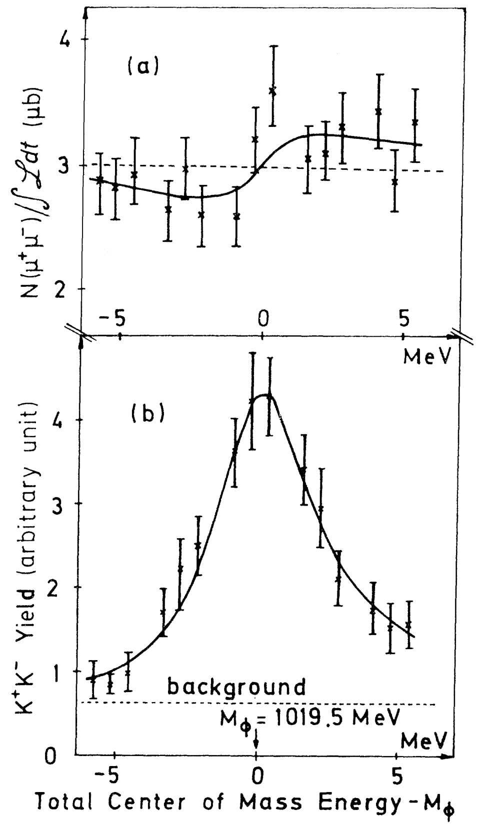

FIG. 2. (a) Best fit of the right-hand side of Eq. (3) to the normalized number of $\mu^+\mu^-$ events plotted as a function of the total c.m. energy $2E$. The dotted line shows the best fit of $\sigma(e^+e^-\to\mu^+\mu^-)$ without hadronic vacuum polarization. (b) Excitation curve for $e^+e^-\to\varphi\to K^+K^-$. This process was measured simultaneously with the $e^+e^-\to\mu^+\mu^-$ reaction in order to calibrate accurately the ring energy.

Finally, we obtain $B = [2.93 \pm 0.96$ (statistical) ± 0.32 (systematic)$]\times10^{-4}$, while the value[9,19] deduced from $\sigma_{\text{peak}}(e^+e^-\to\varphi)$ is $B = (3.01 \pm 0.12)\times10^{-4}$. The parameter B—which is almost uncorrelated to κ—characterizes the amplitude of the deviation we were looking for, and we note that a vanishing value for this parameter is rejected with a probability higher than 0.99. Therefore, this experiment[20] provides direct evidence, obtained for the first time,[21] for hadronic vacuum polarization.

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[3]Vacuum-polarization modifications due to lepton loops, and other radiative corrections, are taken into account in the usual way.

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[5]These chambers were similar to those previously built by G. Cosme *et al.*, Nucl. Instrum. Methods 99, 599 (1972).

[6]At the beginning of the experiment, the energy of the ring was only changed every 2 h. About one third of the data were taken in this way.

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[14]See, for instance, V. N. Baier, in *Physics of Intersecting Storage Rings, Proceedings of the International School of Physics "Enrico Fermi," Course 46,* edited by B. Touschek (Academic, New York, 1971), p. 1.

[15]J. Le Duff, P. C. Marin, J. L. Masnou, and M. Sommer, in Proceedings of the Third All Union Particle Accelerators Conference, Moscow, U. S. S. R., 2–4 October 1972 (unpublished).

[16]We used the results of J. C. Bizot *et al.*, Phys. Lett. 32B, 416 (1970), and a very recent measurement of Γ_φ by G. Cosme *et al.*, to be published.

[17]All systematic errors have been added (not combined).

[18]The breakdown parameter Λ may be attached either to the photon propagator or to one of the γ-lepton vertices.

[19]G. Cosme, doctoral thesis, Centre d'Orsay de l'Université de Paris-Sud, Laboratoire de l'Accélérateur Linéaire Report No. LAL-1261, 1972 (unpublished).

[20]A detailed account of this experiment will be given in F. Fulda, thesis (unpublished).

[21]Photoproduction and electroproduction of lepton pairs on nuclei also provide evidence for $\gamma\to$ vector meson $\to\gamma$ transitions, but in these processes the virtual vector meson interacts with the hadronic target (see, e.g., S. C. C. Ting, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 43.

Zeros of the Vector - Meson Production Amplitude and Their Implications

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In studying the single-pion production amplitudes in the vector-meson mass range (ρ and K^*) we observed zeros and structures in $\mathrm{Re}\rho_{10}^{11}$ and ρ_{1-1}^{11} density matrix elements. The zero of $\mathrm{Re}\rho_{10}^{11}$ is observed to be approximately independent of beam momentum, charge state, or strangeness of the vector meson and is invariant under s-t crossing at $\Delta^2\approx m_v^2-m_{ps}^2$. This gives a strong support to absorptive models. Our analysis shows inconsistencies in the recent amplitude analysis.

In order to give a quantitative description of the experimentally observed characteristics of the single-pion production amplitudes, one has to consider both t-channel exchanges and s-channel absorption effects. With a sufficiently complicated parametrization one is able to fit many reactions by emphasizing the absorptive[1] or Regge aspects[2] of the reactions. Instead we have looked for the existence of dra-