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TEST OF QUANTUM ELECTRODYNAMICS BY BHABHA SCATTERING IN THE GeV REGION

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Electron-positron elastic scattering has been investigated experimentally using colliding beams of total energy ranging from 1.4 to 2.4 GeV. The results, based on the analysis of 3255 wide angle scattering events, agree with the predictions of quantum electrodynamics up to the highest space-like momentum-transfers involved.

Electron-positron elastic scattering

$$e^+ + e^- \rightarrow e^+ + e^- , \qquad (1)$$

a process which was first investigated theoretically by Bhabha as early as 1935 [1], has been studied experimentally with the Frascati storage ring, Adone [2], at total energies of the colliding beams ($E_+ + E_- = 2E$) ranging from 1.4 to 2.4 GeV. Measurements were taken simultaneously for large angles of scattering ($53^o < \theta < 127^o$) ** and for small angles ($3.5^o < \theta < 6.1^o$). At these energies wide angle scattering (WAS) is a process suitable to test quantum electrodynamics (QED) for the large space-like ** momentum transfers involved. Only small momentum transfers are involved, instead, in the case of small angle scattering (SAS), which is therefore unaffected by a possible breakdown of QED at large momentum transfers. The SAS process can then be used as a monitor to determine the luminosity, L, of the machine, through the relationship ***

$$\dot{n} = L\langle\sigma\rangle \qquad (2)$$

which relates the cross section, $\langle\sigma\rangle$, integrated over the angular acceptance of the apparatus used to detect the events, to the counting rate, $\dot{n}$, of the recorded events. The integration over the solid angle must of course take into account the finite extension of the region where the e^+ and e^- bunches collide. This region defines the "source", S, of the "good events".

The bunches in Adone have a gaussian distribution in all directions [3]. While their transversal dimensions are of the order of 1 mm, their longitudinal standard deviation, δ_0, is much greater. For a rf peak voltage of 70 kV it is expected to be given by $\delta_0 = 29\ E^{3/2}$ cm, if E is expressed in GeV. Since Adone has been operated thus far with head-on collisions of the bunches, the source S has also a gaussian distribution characterized by the length $\delta = \delta_0/\sqrt{2}$. From the distribution of the emission points of well identified WAS events one gets $\delta = 20 \pm 1.5$ cm at E = 1 GeV. This agrees well with the previous formula and with the results of independent measurements by the machine group [4].

The colliding beam technique has been applied

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** Since the charge of the scattered particles is not determined in our experiment, no distinction is made between forward and backward scattering. Thus the effective angular interval is 53^o-90^o. In all this interval the term of the theoretical cross-section associated with a space-like momentum transfer is dominant with respect to the other (annihilation and interference) terms.

*** Eq. (2) assumes 100% efficiency for the detecting apparatus. The maximum luminosity of Adone increases steeply with the beam energy [4] and is typically 10^{33} cm^{-2} hr^{-1} at E = 1 GeV soon after injection. Other typical conditions of operation at E = 1 GeV are as follows: vacuum 10^{-9} torr; beam currents ~50 mA/beam; luminosity lifetime ~10 hrs.

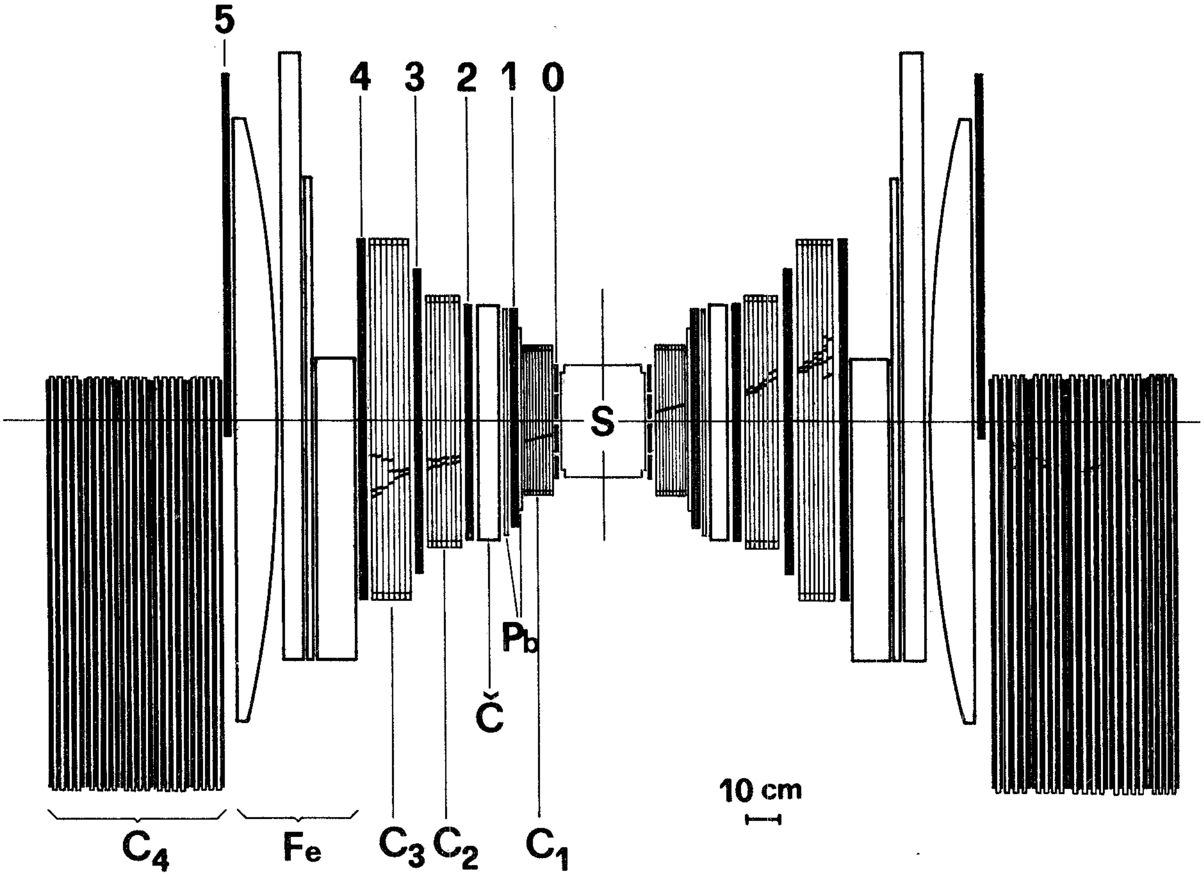

Fig. 1. View of the main apparatus along the beam direction. C_1 are thin foil spark chambers used for space reconstruction of the events produced at the source, S, where the e^+, e^- bunches collide. C_2, C_3, ... are thick plate spark chambers used to observe the development of electromagnetic showers and/or the stop of charged particles. Suitable coincidences among the scintillation counters (numbered from 0 to 5), trigger the spark chambers and advance the film on which views of the chambers are recorded together with other relevant information. The Čerenkov counter, Č, was used for information on other events than those discussed in this paper. Sparks from a real e^+e^- wide angle scattering event are shown.

previously to test QED at short distances by the investigations of both Møller scattering at Stanford [5] and Bhabha scattering at Novosibirsk [6], at Orsay with ACO [7], and more recently at Adone [8,9]. The results reported in this letter extend those tests to shorter distances, giving a further confirmation of the validity of QED. They are based on measurements carried out in the period from January to July, 1970. Preliminary results on part of these measurements have been previously reported [8]; results were given not only for process (1), but also for other reactions involving hadrons, as well as for the annihilation into muon pairs. The latter reaction involves only time-like momentum transfers and, therefore, can be regarded as a complementary test of QED with respect to process (1). Results on all of these reactions, including current measurements, will be reported elsewhere.

The WAS events are recorded with the apparatus shown schematically in fig. 1, consisting of two identical telescopes, placed on opposite sides of the vacuum chamber. Each telescope contains spark chambers ($C_1, C_2, C_3, \ldots$), absorbers (Pb and Fe) and plastic scintillators (numbered from 0 to 5) †, with electronics suitable for time-of-flight and pulse-height measurements [10]. The time-of-flight technique is applied to counter pairs 3 and 4, to distinguish cosmic ray

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† Counters labeled "0" were not present during the first weeks of these measurements. They were added later to increase the detection efficiency for other types of events not considered here.

Table 1
Experimental results.

Total energy (MeV)	Nr. of detected WAS events	Integrated luminosity (10^{33} cm^{-2})	$\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle$* ($10^{33}$ cm^{2})	$\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle/\langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle$
1400	414	5.36	83.7	0.999 ± 0.049
1500	284	4.54	66.7	0.968 ± 0.057
1600	285	6.05	54.8	0.961 ± 0.057
1650	429	8.87	56.7	1.086 ± 0.053
1700	198	5.45	44.8	0.943 ± 0.067
1750	396	10.86	44.6	1.028 ± 0.051
1800	169	5.89	34.0	0.852 ± 0.066
1850	123	2.84	42.9	1.172 ± 0.105
1900	328	9.97	35.8	1.062 ± 0.061
2000	446	18.84	28.3	0.986 ± 0.046
2200	28	1.72	18.8	0.891 ± 0.169
2400	157	10.00	18.9	1.189 ± 0.095

* The results reported in column 4 are obtained as ratios of the corrected numbers, N_{WAS}, of $e^+e^- \to e^+e^-$ events and the integrated luminosity values reported in column 3. The numbers N_{WAS} are derived from the corresponding data given in column 2, after introducing the corrections outlined in the text.

particles from events originating in S. The trigger rate, due mostly to cosmic ray muons, is thereby reduced by a factor of ~50. Concrete and lead shieldings, noth shown in fig. 1, are also utilized against machine background. A further reduction in the trigger rate, resulting in ~ 1/min, is achieved by selecting events occurring at the instant of beam collisions, using a pulse from the machine rf.

Events are identified as due to process (1) if the following conditions are fulfilled: a) two tracks are present, one in each of the thin foil chambers C_1; b) they appear to have originated in a point of a fixed fiducial region around S; c) electromagnetic showers associated with the tracks are observed in the plate chambers C_2, C_3 in at least one telescope. There are 2.5 radiation lengths before C_2 and 3.8 before C_3 (fig. 1). The probability for an electron from process (1) to develop a shower in C_2 or C_3, was determined experimentally for each telescope and found to be about 90% at E = 1 GeV. These criteria allowed the detection of WAS events with high efficiency and with no contamination from other events.

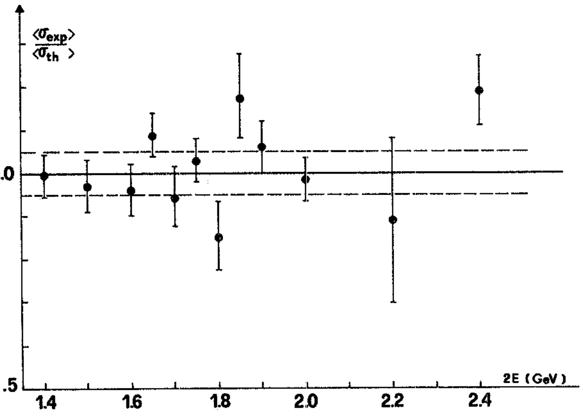

Fig. 2. Experimental cross section for $e^+e^- \to e^+e^-$ events, normalized to the values expected from QED, as a function of the total energy of the colliding beams, $2E$. Only statistical errors are attached to the experimental points. The dashed line represent limits of the estimated systematic uncertainties.

The monitoring system used to detect SAS events has been described already in detail [11]. It is characterized by a rather low and well measurable background*. The counting rate of the recorded SAS events (10^3-10^4/hr at E = 1 GeV) is large enough to determine the luminosity L, via eq. (2), with a small statistical error in a relatively short time. Uncertainties in the shape and length of the source S produce, however, an

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* The main contribution to the SAS background is caused by interactions of the single e^+ or e^- beams in regions of the ring far away from S. This contribution, which increases with the beam energy E and is typically ~8% at E = 1 GeV, is measured accurately by a time-of-flight technique [11]. We are also considering the possibility of a small background (at most a few percent at the highest attained energies) due to two photon annihilation processes [12].

estimated 6% systematic error in the computation of $\langle\sigma\rangle$ and, therefore, in L. Nevertheless these uncertainties have but a small effect in comparing the experimental values, $\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle$, to the corresponding theoretical values $\langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle$ of the integrated cross-section for WAS events. In fact, if N_{SAS} and N_{WAS} are the corrected numbers of SAS and WAS events recorded at a given beam energy in a given time interval, one can apply eq. (2) to the two types of events, to obtain the integrated luminosity $\int L\,\mathrm{d}t$ from the relationship $N_{\mathrm{SAS}} = \langle\sigma^{\mathrm{th}}_{\mathrm{SAS}}\rangle \int L\,\mathrm{d}t$ and the quantity $\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle$ from the relationship $N_{\mathrm{WAS}} = \langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle \int L\,\mathrm{d}t$. Then

$$\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle / \langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle = \rho[N_{\mathrm{WAS}}/N_{\mathrm{SAS}}] \qquad (3)$$

where $\rho = \langle\sigma^{\mathrm{th}}_{\mathrm{SAS}}\rangle / \langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle$. The ratio ρ is insensitive to uncertainties in the source length*, and in the nominal values of the beam energy, since the two types of events, due to the same process, are affected in the same direction by these uncertainties. Also the effect of the radiative corrections tends to cancel in the ratio ρ. On the other hand, radiative corrections have been evaluated and found to be small, for both WAS and SAS events, as a consequence of the loose requirements in energy and momentum determination for the selected events. Thus no radiative corrections need to be applied in comparing the experimental results to the theoretical predictions of QED.

This comparison can be made using the data of table 1. In fig. 2 the ratio $\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle/\langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle$, given by eq. (3), is plotted as a function of the total energy of the colliding beams.

The numbers of WAS events recorded at each energy need a few corrections for counter inefficiencies, spark chambers recovery time and failure in the development and/or identification of electromagnetic showers in at least one of the two telescopes. The over-all correction is of the order of 10%. No correction for background WAS events is needed, since no event was simulated in many hours of background tests made with a single beam circulating in Adone. There was, however, a simulation of SAS events, mostly due to showers produced by the circulating beams. This background was measured continuously during the runs † and it was later subtracted from the recorded SAS events.

Only statistical errors are attached to the experimental points in fig. 2. The ± 5% band around the line $\langle\sigma^{\mathrm{exp}}_{\mathrm{WAS}}\rangle/\langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle = 1$ comes from the estimated systematic error due to the corrections used to obtain the final numbers of WAS and SAS events. It is assumed that events which occur via two photon annihilation processes [12] have no appreciable effect on our results. This assumption is supported by preliminary tests to be discussed elsewhere. Our results refer to a total integrated luminosity of $\sim 10^{35}\,\mathrm{cm}^{-2}$ and a total number of 3255 WAS events, observed in about 300 hrs of effective running time.

It is customary to represent a possible breakdown of QED by a single parameter, Λ. This parameter is used to modify the probability amplitudes of the lowest order diagrams of process (1) with the introduction of a form factor of the type $F(q^2) = (1 - q^2/\Lambda^2)^{-1}$, where q is the four-momentum of the virtual photon ($q^2 = -4E^2 \sin^2 \frac{1}{2}\theta$ for a space-like momentum transfer). A best fit to the experimental points of the theoretical cross-section thus modified, yields, with 95% confidence level, $\Lambda > 6$ GeV/c, corresponding to a distance of 0.03 fm. Aside from this particular interpretation, our result proves that QED is verified within the ~10% errors involved in this experiment, up to the maximum attained squared momentum transfer of $\sim -3\ (\mathrm{GeV}/c)^2$.

We gratefully acknowledge the efficient and dedicated work of Adone group, the skillful cooperation of our technicians and the extensive help by Mr. G. Giannoli during the data analysis.

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* A 10% uncertainty in the source length δ produces a variation in the ratio $\langle\sigma^{\mathrm{th}}_{\mathrm{SAS}}\rangle/\langle\sigma^{\mathrm{th}}_{\mathrm{WAS}}\rangle$ of less than 1%.

† See footnote * on previous page.

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