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ON REGGE POLES IN QUANTUM ELECTRODYNAMICS

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A B S T R A C T

In this article we examine the question to what extent an explicit treatment of the photon, the electron and the muon as Regge poles (in the technical sense of not being connected with quantized fields) is still possible or already excluded by the existing experimental and theoretical evidence. We find that the slope of the photon trajectory introduced through a reggeization of quantum electrodynamics is according to the existing experiments at least one order of magnitude smaller than the slope of the vacuum trajectory in strong interactions. Due to insufficient experiments the present limits for the slopes of the electron and muon trajectories are only of the same order as the slope of the vacuum trajectory. A number of suitable experiments are proposed to lower these limits.

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In the theory of strong interactions the idea of Regge poles has been widely discussed ¹⁾. Recently this idea has got support also from the experimental side ²⁾. This is especially important, since it has not been possible so far to prove any of the postulated properties of the Regge poles from general principles in a relativistic theory.

As has been stressed recently, the next step in building a general theory of elementary particles on these ideas would be to treat the photon as a Regge pole ³⁾. In quantum electrodynamics the situation is, however, quite different from that in the field of strong interactions in so far as there is (at least for moderate energy momentum transfer) an experimentally valid theory. In this region a possible Regge pole behaviour must either be already contained in the existing theory or have such a small effect as to be hidden in the experimental error. Whereas the first possibility has been considered recently for the case of electron scattering in a Coulomb field ⁴⁾, we raise here the question to what extent a "strong" reggeization, i.e., an explicit treatment of the photon, the electron, and the muon as Regge poles (in the technical sense of not being connected with quantized fields) is still possible or already excluded by the existing experimental and theoretical evidence.

The "strong" reggeization constitutes a certain way of describing a breakdown of quantum electrodynamics which is not contained in the discussions in terms of form factors at vertices and propagators in the scope of lowest order perturbation theory ^{5),6),7)}. The most important difference between this form factor approach and reggeization is the fact that after reggeization the deviations from conventional quantum electrodynamics depend not only on the momentum transfer but also on the square of the total energy (in the centre-of-mass system) in a very special way which is essentially determined by the Regge trajectory of the exchanged "particle". Besides this all possible invariant amplitudes contribute to the matrix element for a given scattering process.

To get information about the possible Regge trajectories of the photon, the electron and the muon we have to discuss three classes of experiments where, respectively, virtual photons, virtual electrons, or virtual muons are exchanged.

According to the Regge approach the high energy behaviour of a scattering process is determined by the Regge poles in the crossed reaction. Therefore, we first define the necessary kinematics through the general scattering process $1+2 \rightarrow 3+4$ with the four momenta p_i , the square of the centre-of-mass energy $s = (p_1 + p_2)^2$, and the energy momentum transfer $t = (p_1 - p_3)^2$. This gives for the centre-of-mass scattering angle ϑ

$$z = \cos \vartheta = \frac{t - m_1^2 - m_3^2 + 2 \sqrt{p'^2 + m_1^2} \sqrt{p''^2 + m_3^2}}{2p'p''} \quad (1)$$

with the centre-of-mass momenta

$$p'^2 = \frac{1}{4s} (s - m_1^2 - m_2^2)^2 - \frac{m_1^2 m_2^2}{s} \quad (2a)$$

and

$$p''^2 = \frac{1}{4s} (s - m_3^2 - m_4^2)^2 - \frac{m_3^2 m_4^2}{s} \quad (2b)$$

Since in the existing experiments s is not so large to be completely in the asymptotic region we have to consider next the magnitude of the error introduced in replacing the general Legendre function $P_\nu(z)$ by its asymptotic power z^ν which we shall do throughout this work. For $|z| > 1$ we have ⁸⁾

$$P_\nu(z) = \frac{\Gamma(\nu+1/2)}{\sqrt{\pi} \Gamma(\nu+1)} 2^\nu z^\nu F\left(\frac{1-\nu}{2}, -\frac{\nu}{2}; \frac{1}{2} - \nu; \frac{1}{z}\right) \\ + \operatorname{tg} \nu \pi \frac{\Gamma(\nu+1)}{\sqrt{\pi} \Gamma(\nu+3/2)} 2^{-\nu-1} z^{-\nu-1} F\left(\frac{\nu+1}{2}, \frac{\nu+1}{2}; \nu + \frac{3}{2}; \frac{1}{z}\right) \quad (3)$$

where $\Gamma(x)$ represents the gamma function and $F(a,b;c;x)$ the hypergeometric function with the series expansion

$$F(a,b;c;x) = 1 + \frac{ab}{c} \frac{x}{1!} + \frac{a(a+1)b(b+1)}{c(c+1)} \frac{x^2}{2!} + \dots, \quad (4)$$

which is absolutely and uniformly convergent for $|x| < 1$ ($a, b, c \neq 0, -1, -2, \dots$) i.e., in our case for $|z| > 1$.

As we shall see, ν will be slightly smaller than one or zero in the cases to be considered $\nu = 1 - \varepsilon$ respectively $\nu = -\varepsilon$, $\varepsilon > 0$. Using (3) and (4) we find that $P_\nu(z)$ can then be estimated to be for $\nu = 1 - \varepsilon$

$$P_\nu(z) \leq z^\nu \left(1 + \frac{\varepsilon}{2} \frac{1}{z^2} e^{\frac{1}{z^2}} \right) - \frac{\varepsilon}{3} z^{-\nu-1} \left(1 + \frac{3}{5} \frac{1}{z^2} e^{\frac{1}{z^2}} \right). \quad (5)$$

For $\nu = -\varepsilon$ we have to replace $\varepsilon/3$ by ε and $3/5$ by $1/3$ in the second term. From this expression we see that even for $z = 2$ the asymptotic replacement $P_\nu(z) \rightarrow z^\nu$ is still quite good under the circumstances to be considered here.

It is not so easy to estimate the influence of the line integral

$$- \frac{1}{2} \int_{-i\infty}^{+i\infty} + i\infty$$

which arises in the usual deformation of the Sommerfeld-Watson integral representation in extracting the Regge pole terms if z is not very large. Again we can show in the same way as above that this integral is bounded by $C \cdot z^{-\frac{1}{2}}$ (where C is a constant) already at moderate values of z (e.g., $z \geq 2$). If z is not very large there might also be other Regge pole trajectories important besides those of the photon, electron or muon. However, from conventional quantum electrodynamics we know that the corresponding terms differ at moderate energies in magnitude by the fine structure constant. Therefore, we can expect also the corresponding Regge trajectories to be far apart from each other. Consequently, we feel that the asymptotic representation should give even at moderate z at least the right order of magnitude.

1. THE PHOTON

We shall begin the discussion with experiments where a virtual photon is exchanged, i.e., which can give information about a possible Regge behaviour of the photon. In this class the highest energy momentum transfer has been reached in electron-proton scattering. Unfortunately this does not test electrodynamics alone because of the electromagnetic form factors of the nucleon. The situation is, however, different if we want to test a Regge pole behaviour of the photon. In this case the exchanged photon does not have spin one in the intermediate state. Therefore, the Rosenbluth formula will no longer be valid under these circumstances, whereas the effect of the electromagnetic form factors of the nucleon is contained in this formula. Besides this, the influence of the other invariant amplitudes, which do not contribute to the Rosenbluth formula, will still be small because we are in a region where the whole deviation is at most of the size of the experimental error. Moreover, in determining the maximum possible slope of the photon Regge trajectory we have to neglect these terms completely. Consequently, if we form the ratio of the cross-section $d\sigma$ to the Rosenbluth formula $d\sigma_R$, we get

$$R \equiv \frac{d\sigma}{d\sigma_R} \approx z^{2(\alpha_\gamma(t)-1)} . \quad (6)$$

Here $\alpha_\gamma(t)$ describes the possible Regge trajectory of the photon (we assume equality between the isoscalar and the isovector photon trajectory³⁾) as a function of the energy momentum transfer t and z is up to a minus sign the cosine of the scattering angle in the crossed reaction. From (1), (2a), (2b) we get with $m_1=m_2=m$ and $m_3=m_4=M$

$$z = \frac{s-m^2-M^2+t/2}{2\sqrt{(m^2-\frac{t}{4})(M^2-\frac{t}{4})}} = \frac{2EM+t/2}{2\sqrt{(m^2-\frac{t}{4})(M^2-\frac{t}{4})}} \quad (7)$$

(m electron mass, M nucleon mass, E energy of the incoming electron in the laboratory system).

If there are small deviations from the Rosenbluth formula the most natural interpretation would be to ascribe this to the next order in the fine structure constant, i.e., to the two-photon-exchange matrix element folded with the Rosenbluth matrix element. The two-photon-exchange term behaves qualitatively in several respects similar to the Regge approach. However, in this order the effect can be determined experimentally by comparing scattering of electrons and positrons from protons. This has been performed by Pine and Yount⁹⁾ who find at about 400 MeV a difference of less than 0.5%. Also theoretical estimates suggest an effect of less than 1% up to 1 GeV¹⁰⁾. The next term in the fine structure constant, which contains also the square of the two-photon-exchange matrix element should be even less in this region.

Now the Stanford and Cornell experiments¹¹⁾ show that it is possible to reach agreement of the measured cross-sections with the Rosenbluth formula within the experimental error. The size of the experimental error determines, therefore, the maximum possible slope of the Regge trajectory of the photon. If we expand

$$\alpha_{\gamma}(t) = 1 + \alpha'_{\gamma}(0)t + \dots \quad (8)$$

because t must be small (against s), we find from (6)

$$\alpha'_{\gamma}(0) = \frac{1}{2t} \frac{\ln R}{\ln z} \quad (9)$$

This gives with the most restrictive experimental data¹¹⁾

$$\alpha'_{\gamma}(0) = \frac{1}{492m_{\pi}^2} \approx \frac{1}{10} \alpha'_P(0) \quad (10)$$

where $\alpha_p'(0) \approx 1/50m_\pi^2$ is the slope of the vacuum (or Pomeranchuk) trajectory, which is important for the strong interactions. The value of z is in this case $z \approx 3.3$ which is according to the considerations in the introduction not too small to give the right order of magnitude ^{*}). However, further accurate measurements at higher energies and moderate momentum transfer (relatively small angles), so that z becomes larger (at least between 5 and 6), are highly desirable.

In determining $\alpha_\gamma'(0)$ from R the experimental cross-section has been corrected by the radiative corrections before the comparison. This is in accordance with the above mentioned standpoint to find the maximum possible slope of the Regge trajectory of the photon in a theory with "strong" reggeization, i.e., where it constitutes an alteration of the theory. On the other hand if we consider the Regge approach as a possibility to sum the important terms of the higher orders of orthodox quantum electrodynamics the radiative corrections have to be included here and, consequently, the uncorrected cross-sections must be compared. In that case one would obtain a much larger value for $\alpha_\gamma'(0)$, since the radiative corrections are already quite sizable under these circumstances (in accordance with the estimate given by M. Lévy ⁴⁾). This α would, of course, not necessarily represent the Regge trajectory of the photon.

The cleanest experiment in testing the behaviour of virtual photons is always electron-electron scattering. Here of all possible invariant amplitudes only the $\gamma_1 \cdot \gamma_2$ term contributes appreciably in the region where the whole possible effect is of the order of the experimental error. Therefore, we have only to replace in the earlier form factor calculations ¹²⁾ of electron-electron scattering the form factor $F(t)$ by

$$F(t) \rightarrow G(t) \cdot z^{\alpha_\gamma(t)-1} \quad (11)$$

^{*}) From the measurements at the highest available energies one can deduce an even more restrictive limit $\alpha_\gamma'(0) \leq \alpha_p'(0)/15$, but z is then only $z \approx 2.5$ so that this limit should not be taken for granted.

where z is again given by (7) but with M replaced by the electron mass m . To get the maximum possible slope we have to set $G = 1$ and to compare with the Möller formula including radiative corrections. Up to now there are, however, no suitable experiments on e - e scattering available to compare with. The recent measurement of Dally ¹³⁾ is carried out at 90° in the centre-of-mass system where the Regge approximation is no more valid. To give information on the question considered here future experiments should be done at relatively small angles so that z is as large as possible, $|t|$ not too small and at different energies.

The most impressive confirmations of conventional quantum electrodynamics are the Lamb shift and the anomalous magnetic moment of the electron. Contrary to scattering processes one has to integrate in these cases over the momenta of the virtual particles which makes the comparison with experiment much more indirect. Moreover, these effects are known to depend sensitively only on the region of small energy momentum transfer of the order of the mass involved. The last remark suggests that the anomalous magnetic moment of the μ meson might be a better test. In this case the error of the best available measurement is of the order 0.42% ¹⁴⁾. Since the contribution of the second order is smaller than this figure it is only necessary to consider the lowest order contribution to the anomalous magnetic moment. For reggeization we express it as a dispersional integral

$$F_2^\mu(t) = \frac{1}{\pi} \int_{\frac{4m_\mu^2}{\mu}}^{\infty} \frac{\text{Im} F_2^\mu(t')}{t' - t} dt \quad (12)$$

as has been done in conventional quantum electrodynamics ¹⁵⁾, where we place the cut in the way indicated in the dispersion diagram (Fig. 1). Because of the unitarity condition the imaginary parts of the form factors are then given by

$$\begin{aligned}
& \left(\bar{u}(p_1) \left| \text{Im} F_1(q^2) \gamma_\mu + \text{Im} F_2(q^2) \sigma_{\mu\nu} q_\nu \right| u(p_2) \right) = \\
& = \sum \langle p'_1, p'_2 | p_1, p_2 \rangle^* \langle p'_1, p'_2 | q \rangle
\end{aligned} \tag{13}$$

where $\langle p'_1, p'_2 | q \rangle$ is the amplitude for the creation of a real $\mu^+ - \mu^-$ pair of the indicated four momenta by the field q and $\langle p'_1, p'_2 | p_1, p_2 \rangle$ the non-annihilation part of the scattering amplitude of a real $\mu^+ - \mu^-$ pair (the other symbols have the usual meaning). Because q denotes an external field the exchanged photon in the $\mu^+ - \mu^-$ scattering is the only virtual particle involved in this representation. In the final dispersion relation (12) $\text{Im} F_2$ has to be integrated over $t = q^2 = (p_1 + p_2)^2$. The centre-of-mass energy of the $\mu^+ - \mu^-$ scattering amplitude becomes, therefore, very large in comparison with the energy momentum transfer. Hence, this photon can be reggeized in the same way (11) as has been described above in the electron-electron scattering. After having inserted this, the integration included in (13) (which reduces to an angular integration) and the integration in the dispersion relation (12) have to be performed. The last integration involves higher transcendentals and has not been done quite generally. Because the effect has to be very small according to the small experimental error it is only necessary to find an expansion in $\alpha'_\gamma(0)$. This gives

$$F_2^\mu(0) \approx \frac{\alpha}{2\pi} \left[1 - \alpha'_\gamma(0) m_\mu^2 8 \ln 2 + \dots \right] \tag{14}$$

and since the experimental error is 0.42%

$$\alpha'_\gamma(0) \lesssim \frac{0.0042}{5.6 m_\mu^2} \approx \frac{1}{11} \alpha'_p(0). \tag{15}$$

This is of the same order of magnitude as the restriction (10) placed by the electron-proton scattering. We should, however, stress the more indirect character of the way in which we have obtained (15). Since we had to integrate over all

q^2 , where the Regge effect may be very large, it does not seem so natural neither to put the associated form factor equal to one, which determines the otherwise undetermined scaling factor, nor to use the expansion (8) in contrast to the scattering case, where one does not have to integrate over the unknown regions and where the effect is always small. Also one could think of other ways of introducing reggeization into this problem. This has been tried with almost exactly the same result as (15). Therefore, the size of $\alpha'_T(0)$ seems to be remarkably insensitive to this.

2. THE ELECTRON

Next we come to a discussion of experiments where a virtual electron is exchanged and which, therefore, could give information about a possible Regge trajectory of the electron. As in the more conventional tests of quantum electrodynamics the most natural thing in this case would be to consider Compton scattering and two quantum pair annihilation in flight. It has been shown elsewhere ⁷⁾ that two quantum pair annihilation is especially suitable for a first test, since the four momentum of the exchanged virtual electron is always space-like in this case, whereas in Compton scattering also time-like momenta occur so that cancellations are possible. The Compton effect can then be used later to investigate the time-like region as well. As in the earlier cases we need only to consider the invariants which contribute already in the lowest order of conventional quantum electrodynamics, since we want to determine the maximum possible slope of $\alpha_e(t)$. We then have to replace the form factors in the previously calculated cross-section by ¹⁶⁾

$$G_e(t) \rightarrow G'_e(t) \cdot z^{\alpha_e(t) - \frac{1}{2}} \quad (16)$$

with the cosine of the centre-of-mass scattering angle in the crossed channel (Compton scattering)

$$z = -1 - \frac{2st}{(t-m^2)^2} \quad (17)$$

as deduced from (1), (2a), (2b) with $m_1=m_2=m$, $m_3=m_4=0$. Unfortunately suitable measurements at high energies and moderate momentum transfer are not yet available to compare with. Only a high energy precision measurement of the total cross-section for two quantum pair annihilation in flight has been done ¹⁷⁾. In the calculation of the total cross-section one has to integrate over all possible momentum transfers which exceed, therefore, the region of validity of the Regge approximation. However, because the cross-section drops very fast with angle,

only momentum transfers up to $t \approx s/10$ are practically important. Since in this region the above expressions are still valid we shall calculate the total cross-section with (16), where again we can introduce $G'_e(t) = 1$ because we are interested in the maximum possible slope of $\alpha'_e(t)$. The integration of the cross-section (27) respectively (33) of reference ⁷⁾ with (16) leads to higher transcendental functions like $Ei(x)$. With

$$\alpha'_e(t) = \frac{1}{2} + \alpha'_e(m^2)(t-m^2) + \dots \quad (18)$$

we expand in powers of α'_e and finally we get for the ratio of the reggeized total cross-section to the result of conventional quantum electrodynamics in the high energy limit

$$\frac{d\sigma_R}{d\sigma_{QE}} = 1 - \alpha'_e(m^2)m^2 \frac{\frac{4s}{m^2} \ln\left(\frac{s}{2m^2}\right)}{\ln\frac{4s}{m^2} - 1} + \dots \quad (19)$$

In the experiment of Fabiani et al. ¹⁷⁾ s was about $s \approx (100 \text{ MeV})^2$ and the experimental error 5.5%. This gives

$$\alpha'_e(m^2) \lesssim \frac{1}{9\frac{m^2}{\pi}} \approx 5.5 \alpha'_e(0) \quad (20)$$

which is not very restrictive as was to be expected. Because of the centre-of-mass motion we need in these experiments even higher energies in the laboratory system or colliding beams. The pair production experiment of Richter ¹⁸⁾ which gives the most severe test of the electron propagation function in the more conventional way cannot be used here since it includes pair production at 90° where the Regge approximation is not valid. As has been mentioned earlier ⁷⁾ a modification of the virtual electron (and muon) alone violates gauge invariance. This can be restored using the generalized Ward identity. The practical difference is, however, small in the more conventional tests of quantum electrodynamics ¹⁹⁾. Therefore, it has also been neglected here.

3. THE MUON

Finally we concentrate on a discussion of experiments with the exchange of a virtual muon. Besides the very indirect evidence which can be obtained from the magnetic moment of the muon there is at present only one experiment to be discussed here, namely photoproduction of muon pairs ²⁰⁾ (cf. Fig. 2). This process is in principle similar to the pair production experiment of Richter but is carried out at small angles. On the other hand it is a sort of inelastic process where the Regge analysis cannot be applied without further consideration. As can be seen from the diagram there are two connected virtual lines, namely the line of the muon and of the photon. In general a possible Regge pole behaviour of both cannot be factorized. However, in the present case kinematics is defined in such a way that the energy momentum transfer carried over by the photon is small compared with that of the virtual muon line. Therefore, the virtuality of the photon and a possible deviation of its spin from the real value one is very small, also because of (10) and (15). Consequently, for the purpose of this estimate we can consider this photon to be a virtual particle in the conventional sense, i.e., with spin one. Since the recoil of the nucleus has been neglected we are led to consider the whole process as two-particle-collision where one of the photons has the mass given by its momentum transfer t_γ . If we form the ratio between this reggeized cross-section and that of conventional quantum electrodynamics we get

$$R = \frac{d\sigma_R}{d\sigma_{QE}} \approx z^2 (\alpha_\mu(t) - \frac{1}{2}) \quad (21)$$

where we have set the associated form factor equal to one and neglected the other invariants as earlier because we want to determine the maximum possible slope of the muon Regge trajectory $\alpha_\mu(t)$. z is again given by the cosine of the scattering angle in the crossed channel continued to the present reaction. With $m_1 = m_\mu$, $m_2 = 0$, $m_3 = m_\mu$, $m_4 = \sqrt{t_\gamma}$ we get with the numbers of Alberigi-Quaranta

et al.²⁰⁾ from (1), (2a), (2b) $z \approx 2$ and

$$\alpha'_{\mu}(m_{\mu}^2) = \frac{\frac{\ln R}{\ln z}}{2(t-m_{\mu}^2)} \leq \frac{1}{64m_{\pi}^2} \approx \alpha'_P(0) \quad (22)$$

i.e., a maximum slope of the same order as the slope of the vacuum trajectory.

However, the value of z is too small to make this result quantitatively reliable.

4. CONCLUSIONS

Altogether we have found that the slope of the photon trajectory introduced through a reggeization of quantum electrodynamics in the sense explained above is according to the existing experimental evidence at least one order of magnitude smaller than the slope of the vacuum trajectory occurring in strong interactions. Due to insufficient experiments the present limits for the slopes of the electron and muon trajectories are only of the same order as the slope of the vacuum trajectory. New measurements of the type discussed above with sufficiently large z and not too small energy momentum transfer, i.e., at high energies and at several different energies to test the energy variation, are, therefore, highly desirable. The latter class of experiments would, in principle, allow a determination of the Regge trajectories $\alpha_\gamma(t)$, $\alpha_e(t)$ and $\alpha_\mu(t)$ themselves, instead of the maximum possible slopes only. We hope to come back to this point elsewhere.

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REFERENCES

- 1) See, e.g., the report of S.D. Drell, Proceedings of the 1962 International Conference on High Energy Physics at CERN, p. 897 (1962).
- 2) See, e.g., G. Cocconi, Proceedings of the 1962 International Conference on High Energy Physics at CERN, p. 883 (1962).
- 3) R. Blankenbecler, L.F. Cook and M.L. Goldberger, Phys. Rev. Letters 8, 463 (1962).
- 4) M. Lévy, Phys. Rev. Letters 9, 235 (1962).
- 5) H. Salecker, Z. Naturforschg. 8a, 16 (1953) ; Z. Naturforschg. 10a, 349 (1955).
- 6) S.D. Drell, Ann. Phys. 4, 75 (1958).
- 7) H. Salecker, Z. Physik 160, 385 (1960).
- 8) See, e.g., W. Magnus and F. Oberhettinger. Formeln und Sätze für die speziellen Funktionen der mathematischen Physik. Springer-Verlag, Berlin 1948.
- 9) J. Pine and D. Yount, to be published.
- 10) S.D. Drell and S. Fubini, Phys. Rev. 106, 561 (1957).
D. Flamm and W. Kummer, to be published.
- 11) F.A. Bumiller, M. Croissiaux, E. Dally and R. Hofstadter, Phys. Rev. 124, 1623 (1961).
R.M. Littauer, H.F. Schopper and R.R. Wilson, Phys. Rev. Letters 7, 141 (1961).
- 12) See Ref. ⁵⁾, 1955, formula (11) where $F(t)$ has been written as

$$F(t) = \int_0^{\infty} \lambda^2 G(\lambda) d\lambda / (\lambda^2 - t).$$

- 13) E.B. Dally, Phys. Rev. 123, 1840 (1961).
- 14) G. Charpak, F.J.M. Farley, R.L. Garwin, T. Muller, J.C. Sens and A. Zichichi, Phys. Letters 1, 16 (1962).
- 15) S.D. Drell and F. Zachariasen, Phys. Rev. 111, 1727 (1958).
- 16) See Ref. ⁷⁾, formula (27) or (33).
- 17) F. Fabiani, M. Fidecaro, G. Finocchiaro, G. Giacomelli, D. Harting, N.P. Lipman and G. Torelli, Nuovo Cimento 25, 655 (1962).
- 18) B. Richter, Phys. Rev. Letters 1, 114 (1958).
- 19) S.M. Berman, unpublished. H. Salecker, unpublished.
- 20) A. Alberigi-Quaranta, M. de Pretis, G. Marini, A. Odian, G. Stoppini and L. Tan, Phys. Rev. Letters 9, 226 (1962).

Fig. 1

Dispersion diagram for the absorptive part of the
anomalous magnetic moment of the muon

Fig. 2

One of the two diagrams for the
photoproduction of muon pairs