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Hadronic Electrons?

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Abstract

A new form of high energy electron–hadron coupling is examined with reference to the experimental data. The electron is taken to have a neutral vector gluon cloud with a radius $\sim 10^{-18}$ m. This is shown to be consistent with measurements on $e^+e^- \rightarrow e^+e^-$ and $g_e - 2$. At low energies, only photons couple to the gluons, but at higher energies 'evaporation' then 'boiling' of ω and ϕ occurs, allowing strong interactions. The model yields accurate predictions for the form of the rise in $R = \sigma(e^+e^- \rightarrow h)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. Arguments are given for the order of magnitude of m_e and for the lack of a permanent meson cloud in leptons. Strong interaction selection rules forbid a contribution to $\pi^0 \rightarrow e^+e^-$, and interference with the one-photon channel produces minimal scaling violation in eN processes at present energies. The constant value of $\sigma(e^+e^-)/\sigma(\bar{p}p)$ is correctly predicted and evidence from high energy pp interactions is also cited. The ψ particles are interpreted as e^+e^- resonances in the evaporation region, and their properties are generated correctly. Predictions are given for the behaviour of $\sigma(e^{\pm}e^-)$ at high energies.

Introduction

The recent discoveries of scaling violation and narrow resonances in deep inelastic e^+e^- annihilation (see review of data by Gilman 1975) have raised the possibility that electrons may undergo non-electromagnetic interactions with hadrons (Bigi and Bjorken 1974; Chanda 1974; Greenberg and Yodh 1974; Pati and Salam 1974*a*, 1974*b*; Richter 1974; Soni 1974*a*, 1974*b*; Wolfram 1975). In the low energy limit $q^2 \rightarrow 0$, it is well known that electrons obey quantum electrodynamics (QED) to considerable accuracy, and hence in this region the strength of any anomalous electron–hadron coupling must be negligible. At higher energies ($q^2 \gtrsim 15\ \mathrm{GeV}^2$), however, the predictions of QED fail, and scaling is violated. In electron–nucleus interactions, there is also scaling in the low energy region ($q^2 \lesssim 0{\cdot}09\ \mathrm{GeV}^2$), but this ceases as the electrons probe the nucleon form factors and induce free pion production (Chanowitz and Drell 1973). In the hadronic electron model presented here, scaling is broken by a similar process.

Structure of the Electron

By analogy with hadrons, the core of the electron is taken as a collection of 'bitons' bound by a superstrong interaction mediated by neutral massive vector gluons with photon quantum numbers. These will not be restricted to the core, but will tend to form a cloud around it, From a comparison of the expected gradients of strong and weak Regge trajectories, we expect a characteristic weak interaction structure size of order $\sqrt{G_F} \sim 10^{-18}$ m (Greenberg and Yodh 1974).

The radius of the electron will be governed primarily by the range of the gluon interaction, so that we will have 10^{-18} m $\approx M_G^{-1}$, that is, $M_G \approx 300$ GeV.

The most sensitive tests of possible electron structure made to date are measurements on $e^+e^- \to e^+e^-$ and g_e-2 reactions. Data for e^+e^- elastic scattering set a lower limit of about 20 GeV (Beron *et al.* 1974; Richter 1974) on the cutoff parameter Λ in the electron form factor

$$F(q^2) = 1 \pm q^2/(q^2 \pm \Lambda^2), \tag{1}$$

corresponding to an upper bound of about 10^{-17} m for the electron radius. The contribution of internal structure to $g-2$ is roughly proportional to r^2, so that we expect

$$g_e-2 \sim 10^{-6}\,|g_N-2| < \alpha^3 \tag{2}$$

if the electron core has similar interactions to those of the nucleon. Hence an extended electron with a radius $\sim 10^{-18}$ m is consistent with the data.

At low energies, photons couple to the electron via its gluon cloud (Fig. 1*a*), and e appears pointlike because of the high gluon mass and the large superstrong interaction coupling constant. Similarly, photons couple to the nucleon via its vector meson cloud, but here the departure of the form factors from unity is quicker, because of the low ρ mass and the comparative weakness of the strong interaction.

Fig. 1. Photon–lepton coupling (*a*) and hadron–lepton coupling (*b*) via intermediate gluons.

Since gluons interact superstrongly, they should not be immune to the strong interaction (hadrons undergo weak interactions), so that they couple to hadronic states with photon quantum numbers (Fig. 1*b*). As any gluon–hadron vertex will be strong, it must obey strong interaction selection rules, and thus we should assign more quantum numbers to the gluon. We take $I = 0$, $G = -$ and $C = -$, although $I = 1$ and $G = +$ would also have been a possible choice. Hence gluons couple to the one-particle states $\omega(783)$, $\phi(1019)$ and $\omega(1675)$, and interactions such as $G\pi$, $G2\pi$, $\pi 2G$ and $G\rho$ are forbidden.

Contribution of Hadronic Electrons to *R*

Within the electron, gluons may spontaneously transform into virtual ω, but unless the gluon cloud has been excited most of the particles produced will not be sufficiently energetic to escape from the deep gluon potential well. However, above some critical excitation energy, nearly all the ω produced will have enough energy to escape from the gluon cloud and to mediate direct electron–hadron forces. This situation is similar to that in a drop of liquid, in which intermolecular forces keep most of the molecules inside the drop until a critical temperature (energy) is reached, when boiling occurs and the majority of the molecules escape from the drop. Even below the boiling point, some molecules evaporate from the surface of the liquid, and similarly a few ω will escape the gluon cloud even below the critical excitation energy.

The emission of virtual hadrons from the gluon cloud will cause electrons to undergo some type of strong interaction. However, the strength of this coupling will not be comparable with hadron–hadron ones, but perhaps more with electromagnetic ones, which also involve the interaction of particles with gluons. We note that our model is not equivalent to vector meson dominance, since the latter involves the photon propagator, which falls off with q^{-2}, whereas our force will decrease with q^2 only as the strong interaction does.

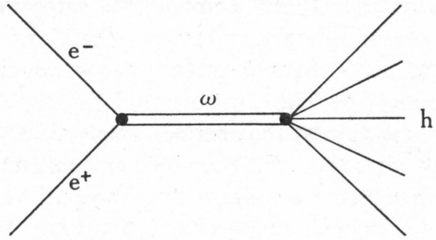

Fig. 2. Direct electron–hadron coupling contribution to the process $e^+e^- \to h$.

At the point when hadrons begin to 'boil' from the electron's gluon cloud, $\sigma(e^+e^- \to h)$ should begin to increase (Fig. 2), as observed near 3·9 GeV, and it will form a peak corresponding to the ω resonance, although the enhancement will be broadened by the gluon width, which is expected to be ~200 MeV, as it will decay strongly. At about 250 MeV above the ω 'boiling point' will come (assuming universal gluon–hadron coupling and a linear mass relationship) the ϕ 'boiling point', accompanied by another peak. These two peaks will interfere, producing a cross section in agreement with experimental data (assuming that the peaks are in phase). The $\omega(1675)$ will cause a further broad enhancement ($\Gamma \sim \Gamma_\omega + \Gamma_G \sim$ 350 MeV) around 5 GeV, as is perhaps observed. Any other bumps in the e^+e^- cross section are interpreted as resonances with ω quantum numbers and $m \gtrsim 2$ GeV. None of these have yet been identified in lower energy $\pi\pi$ interactions.* Since the $\phi(1020)$ couples predominantly to $K\bar{K}$ (80%), we might expect a rise in K production at the ϕ boiling point. This effect has probably been observed around 4 GeV. The rise in $R = \sigma(e^+e^- \to h)/\sigma(e^+e^- \to \mu^+\mu^-)$ is also accompanied by an increase in neutral particle production; decay modes such as $\omega \to \pi^0\gamma$ could contribute to this effect.

Instead of choosing $I_G = 0$, we could have taken $I_G = 1$, and in this case $\rho(770)$ and $\rho'(1600)$ would have been the dominant hadrons involved. Their masses would still roughly fit the data, but the probable increase in K production could not be explained. Furthermore, there should be quasistrong charge-exchange reactions such as $e^-p \to \nu_e n$ due to the coupling $G^\pm \rho^\pm$, and these are probably not observed.

Structure of the Interaction

In our model, the $e\gamma$ and $e\omega$ couplings are exactly equivalent, except that the latter has a cutoff energy. Thus we can apply the same arguments as those which lead to s-channel photon production in electromagnetic e^+e^- annihilation to the case of our direct electron–hadron coupling (DEHC). We begin by considering the

* $N\bar{N}(2375)$ is a candidate, and this would produce a further bump around 5·5 GeV, which is not inconsistent with the data.

Coulomb scattering of a state S from an electron. This occurs via the familiar Feynman diagram containing the t-channel exchange of a virtual photon. Similarly, the scattering of S from an electron in the DEHC model proposed here involves the t-channel exchange of a virtual hadron (ω or ϕ). The eeh vertex is simply a high-energy real electron emitting a virtual hadron, by hadron–gluon coupling and evaporation or boiling. This is a strong vertex and hence it will lead to a typical strong interaction energy dependence. Now, it is well known that we may rotate the Feynman diagram for Coulomb scattering through 90° and replace the outgoing e^- by an incoming e^+ to obtain the one-photon e^+e^- annihilation graph. Here the photon is in the s channel. Transforming the DEHC graph in the same manner, we arrive at a graph depicting a point strong interaction between the electron and positron, resulting in the production of an s-channel vector meson which then undergoes strong decay to other hadrons (see Fig. 2 above). Final-state interactions, which will have a very high cross section at the energies involved, will serve to increase the mean hadron multiplicity detected. This analysis is similar to that usually presented for $p\bar{p}$ interactions, in which we assume that the $p\bar{p}h$ vertex is pointlike and its inner structure is not determined.

By stating that the $e\bar{e}\gamma$ and $e\bar{e}h$ vertices are pointlike, we have evaded the problem of how lepton number is conserved. We consider the ultimate annihilation of the electron and positron in an e^+e^- collision as a superstrong process which can occur only when the particle cores are brought within the superstrong interaction radius by another interaction. The electron core is defined to be lepton-numbered, and the superstrong interaction is the only interaction which conserves 'number'. Since the core–gluon coupling is superstrong, the gluons in electrons must also be lepton-numbered. Thus, in e^+e^- collisions, the final superstrong core annihilation may occur, producing a vacuum state. However, in eN interactions, for example, no final core interaction may take place, since the superstrong interaction conserves 'number' and the gluons in nucleons are hadron-numbered.

If $I_G = 0$, then no charge will reside in the electron's gluon cloud (unlike the situation for the nucleon meson cloud) and hence all the charge must be concentrated in the central core. This distribution of charge would further diminish the contribution of the electron's internal structure both to $g_e - 2$ and to the electric form. factor. If $I_G = 1$, then the gluon cloud could contribute to the electron charge.

We might expect hadrons and leptons to have similar gluonic core structures, and this idea is upheld by experiment. In 300 GeV pp interactions, where the nucleon meson cloud is unimportant and the core is probed, there is a slight rise in the total cross section. This may be caused by gluons beginning to evaporate from the central region (this mass scale is also suggested by lepton size considerations). Furthermore, the relation derived from generalized vector dominance (GVD) connecting $\sigma(p\bar{p})$ to $\sigma(e\bar{e})$ at high energies (Minami and Terada 1974; Minami 1975) may owe its surprising accuracy to hadron boiling from the proton gluon core, since at $q^2 \sim 10\ \mathrm{GeV}^2$ the core is probably the most significant part of the nucleon (as indicated by eN scaling at this energy).

In the model described above, we can perform a naive calculation of the electron self mass. Since we predict that the electron has a radius $\sim 10^{-18}$ m, the range of the gluon interaction must be $\sim 10^{-3}$ times that of the strong interaction, so that we have $g(\text{superstrong}) \sim 10^3 g(\text{strong})$. The electron has an effective superstrong interaction area $\sim 10^{-6}$ times the effective strong interaction area of the nucleon, and hence we predict $10^{-6}.10^{3}m_{\rm N} \sim m_{\rm e}$, that is, $m_{\rm e} \sim 0{\cdot}9$ MeV, in excellent agreement with experiment. An interesting possibility is that the weak interaction arises simply because of gluon evaporation from lepton and hadron cores (this would favour $I_{\rm G} = 1$).

The existence of a meson cloud in hadrons but not in leptons may be accounted for in terms of the difference in gluon content between the two classes of particle. In leptons there is only one type of gluon, while in hadrons there are three, perhaps corresponding to the three colours of quarks. The interaction potential due to a single type of gluon would be attractive for $r \lesssim 10^{-18}$ m, and would then become repulsive just outside this radius (this could be the repulsion felt by two close fermions) and soon fall to zero. The three types of hadronic gluons will have slightly different masses, so that the ranges of their interactions will differ. In leptons the repulsive part of the one-gluon potential will disperse any meson cloud, but in hadrons the three gluon potentials will interfere, creating regions of slight attraction in which mesons will collect. These can undergo strong interactions with other hadrons (they will boil at a very low temperature) and hence a meson cloud will be held around the nucleon.

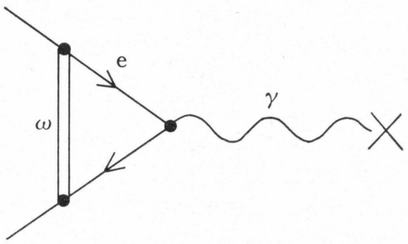

Fig. 3. DEHC contribution to the anomalous magnetic moment of the electron.

Naive hadronic electron models predict that the pseudoscalar meson decay $\pi^0 \to e^+e^-$ should receive contributions from DEHC, and experimentally it is found that $B \lesssim 10^{-5}$ (Davies *et al.* 1974). However, in the model proposed here, *G*-parity or isospin conservation forbid all DEHC diagrams contributing to the process.

$g_{\rm e}-2$ reactions should receive DEHC contributions via the third-order triangle graph (see Fig. 3), given by

$$a'_{\mu} = (4\pi^2\alpha)^{-1}\int_{4m^2}^{\infty} \sigma\, K_{\mu}^{(2)}(t)\,{\rm d}t \tag{3}$$

where $K_{\mu}^{(2)}(t)$ is the second-order vertex function in QED, which behaves as t^{-1} for large t. Thus the integral (3) is logarithmically divergent, so that the high energy domain will be comparatively unimportant.

Results for $e^+e^- \to e^+e^-$ agree with QED to within $\sim 4\%$ up to about 5 GeV. This is to be expected, since the hadronic core radius in hadrons is $\sim 10^3$ that in electrons, so that electron production via DEHC in high energy e^+e^- interactions will be suppressed by a factor $\gtrsim 10^{-3}$ relative to hadron production.

Further Evidence for Hadronic Electrons

A number of further electron experiments at high energies also favour the hadronic electron model. The slope of $E_{\pi}\,{\rm d}\sigma/{\rm d}^3p$ (E_{π} is the detected pion energy in the final state) near 90° ($q^2 \sim 0$) is similar in the cases of e^+e^- and $p\bar{p}$ high energy collisions, and a cross section roughly constant with q^2 occurs in both (Cronin *et al.*

1973; Richter 1974). Furthermore, in the naive eikonal model, we have $\sigma \sim \pi r^2$ which yields $\sigma \sim 20$ nb for $r \approx 8 \times 10^{-19}$ m ($16 < q^2 < 25$ GeV^2), in rough agreement with experiment. Assuming that hadron yield is proportional to hadronic core area (the colliding particles will be Lorentz-contracted to discs in their centre-of-mass system), our choice of radius yields

$$\sigma(\mathrm{p\bar{p}} \to \mathrm{h})/\sigma(\mathrm{e\bar{e}} \to \mathrm{h}) \approx 6 \times 10^5 \qquad (q^2 > 15\ \mathrm{GeV}^2), \tag{4}$$

in good agreement with the experimental data.

Yet more evidence for hadronic electrons comes from the observation of the process $\mathrm{pp} \to \mathrm{he^+e^-}$ at 200 GeV with a cross section $\gtrsim 5$ times that predicted by standard models (Altarelli *et al.* 1974; Jain *et al.* 1974) but consistent with DEHC. We note that the model proposed here does not contribute to hyperfine splitting in atomic spectra (Bég and Feinberg 1974) at present energies.

The ψ Particles

Even below the boiling point, some hadrons will evaporate from the electron gluon cloud, and the amount of evaporation will increase with energy. This accounts for the slight rise in R above coloured-quark model estimates even below the 3·9 GeV threshold. The quasistrong exchange of hadrons in high energy $\mathrm{e^+e^-}$ interactions may result in resonance, and this appears to happen at 3·1 and 3·7 GeV. Since the $\mathrm{e^+e^-}$ interaction is still comparatively weak, we expect $\Gamma \ll \Gamma$(strong), as observed. More specifically, by considering the deviation of R from two below boiling, we obtain g(evap.) $\sim 10^{-7} g$(strong), that is, $T \gtrsim 10^{-17}$ s. There should be slightly more evaporation at 3·7 than at 3·1 GeV, and so we predict $\Gamma_{\psi'} \gtrsim \Gamma_{\psi}$, again in agreement with experiment. The presence of ϕ particles may cause ψ and ψ' to couple to $\mathrm{K\bar{K}}$ states, and decay in these channels is observed. The 5π decay mode of ψ and the process $\psi' \to \psi 2\pi$ indicate that both ψ and ψ' have odd G-parity, as expected, since these s-channel resonances must have ω quantum numbers.

If the gluonic cores of electrons and protons are similar, then we might expect $\mathrm{p\bar{p}}$ core resonance around 3·1 and 3·7 GeV, and this is observed (CERN Theory Boson Workshop 1974). Experimentally, the $\mathrm{p\bar{p}}$ resonances are wider than the $\mathrm{e^+e^-}$ ones, but they have roughly the same production cross sections. The similarity in the resonating cores could produce the near equality in production cross section, and the additional hadronic material present in the $\mathrm{p\bar{p}}$ case would result in a larger decay width.

It is also reasonable to suppose that the $\mathrm{e^+e^-}$ system will undergo resonance at some energies above the ω boiling point. Using a quadratic Regge trajectory, and extrapolating from the known poles, we predict the next ones at 4·2, 4·7, 5·1, 5·5 GeV and so on. Although the first of these peaks is certainly observed, the rest are not, and hence we must probably conclude that a simple extrapolation of the Regge trajectory into the boiling region would not be correct.

Effects in eN Interactions

A nonvector DEHC would lead to a cross section dependent on beam polarization:

$$\sigma^{\mathrm{s,p}}_{\mathrm{pol}} = (1 \pm P^2)\sigma^{\mathrm{s,p}}_{\mathrm{unpol}}, \tag{5}$$

thus causing a time dependence in σ, since the transverse beam polarization in storage rings increases with time (Ellis 1974; Goldman and Vinciarelli 1974). Although the possible variation of σ with time cannot be tested at present energies, it seems likely that the cross section is time-independent, and hence the DEHC must be a vector interaction. Both in the ω–ϕ and ρ coupling forms, states with photon quantum numbers will be produced, so that there will be interference with the one-photon channel. This will lead to a cross section of the form (Soni 1974*a*, 1974*b*)

$$\sigma_{\text{tot}}(e^+e^- \to h)|_{q^2 \geqslant 15} = \frac{4\pi\alpha^2}{3q^2}\left(A + B\frac{fq^2\sqrt{2}}{4\pi} + C\frac{f^2q^4}{8\pi^2}\right), \tag{6}$$

where the first term is the QED one-photon prediction, the third term is the DEHC contribution, and the second term arises from interference between the two interactions. The quantities B and C will not be quite independent of q^2 since the DEHC will be significantly influenced by propagator effects. When hadrons begin to boil from electrons, both the DEHC and interference terms become large and positive, assisting in the sharp rise corresponding to boiling, but at higher energies the DEHC term will dominate.

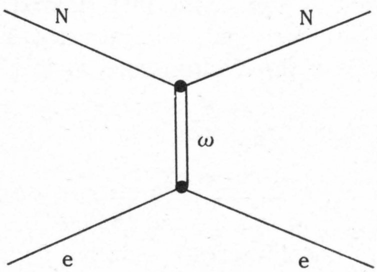

Fig. 4. DEHC contribution to eN elastic scattering.

However, for high energy eN interactions (Fig. 4), q^2 changes sign and hence the interference term in equation (6) also changes sign (Bigi and Bjorken 1974). Thus, in the energy region $q^2 \sim 16\ \text{GeV}^2$, the interference and DEHC contributions will tend to cancel and hence we will not see scaling violation. eN interactions are found to scale for $q^2 \lesssim 20\ \text{GeV}^2$ (Richter 1974, Gilman 1975), indicating that $16 \lesssim q^2 \lesssim 20\ \text{GeV}^2$ represents the cancellation region. A number of other effects could also supress eN scale-breaking. Firstly, since $q^2 \gg m_\omega^2$, we expect only a slow rise in the DEHC strength with energy, due to propagator effects. Secondly, Chanowitz and Drell (1973) predict a fall from the scaling bound as the electron probes the gluonic structure of the nucleon, and this could cancel any rise due to the DEHC at these energies. However, at higher energies, we do expect to see scale-breaking effects as the DEHC term begins to dominate the cross section. We note that, since the DEHC proposed here involves strong interaction couplings, charge independence is expected, so that $\sigma(e^-N) = \sigma(e^+N)$, in agreement with experiment (Richter 1974).

High Energy Behaviour of (e^+e^-)

In the more naive DEHC models, $\sigma_{\text{DEHC}}(e^+e^-) = \sigma_{\text{DEHC}}(e^-e^-)$ for all energies. However, no such equality is expected in our model, although the Pomeranchuk theorem in strong interactions suggests that at very high energies we should see this behaviour. The pp and $p\bar{p}$ interaction cross sections only begin to approach closely at around 200 GeV^2, so that we would certainly not expect $\sigma(ee)/\sigma(e\bar{e})$ to approach unity until at least this energy is reached. The cross section for e^-e^- elastic scattering is dominated by ω-exchange in the t channel, but $\sigma(e^+e^-)$ contains contributions both from this (via third and higher order triangle graphs) and from spacelike ω. Despite interference-term cancellation effects arising from t-channel propagator exchange, we should expect direct hadron production in high energy e^-e^- scattering with a rate rather larger than that predicted by the one-photon approximation. We note that both this process and scale-breaking in eN interactions would be absent if only zero lepton number states coupled directly to hadrons. Nevertheless, a careful study of the high energy behaviour of e^-e^- should be made, and this has recently become possible with the storage rings at DESY.

We now consider the predictions of our model for the behaviour of $\sigma(e^+e^- \to h)$ at asymptotic energies. There are good reasons to expect a broad spectrum of vector mesons and, as each of these states boils from the electron, there will be a bump in the cross section. By the dominance of nearest singularities, the contribution of DEHC to the cross section at high energies ($q^2 \gg 20$ GeV^2) will simply be proportional to the density of vector meson states, and thus we expect an asymptotically constant cross section. This prediction is similar to that derived from GVD (Sakurai 1973; Gounaris *et al.* 1974). We note that, at very high energies ($\sim$300 GeV), gluons will begin to boil from the electron core, as in hadrons. We predict

$$\sigma_{\mathrm{asymp}}(p\bar{p}) \approx 6\times 10^5\, \sigma_{\mathrm{asymp}}(e\bar{e}), \tag{7}$$

so that at $q^2 = 100$ GeV^2 we have $\sigma(e^+e^-) \approx 25$ nb. The one-photon contribution to $\sigma(e^+e^- \to \mu^+\mu^-)$ will effectively be zero for this q^2, and the DEHC contribution will be $\sim 10^{-3}\,\sigma(e^+e^- \to h)$. Hence our model implies a large but finite asymptotic value for R. At about 200 GeV, the electron form factor deduced from e^+e^- elastic scattering should begin to deviate from unity, as it 'sees' the gluon cloud.

Many of the gauge unified field theories (e.g. Pati and Salam 1974*a*, 1974*b*) predict that the asymmetric behaviour of hadrons and leptons with respect to the strong interaction should cease at asymptotically high energies, and the hadronic electron hypothesis presented here explains how this could happen. It is interesting to speculate that the gluons in particle cores could represent the gauge bosons corresponding to lepton number and baryon number.

Conclusions

We have seen that electrons with massive neutral vector gluon clouds of radius $\sim 10^{-18}$ m, which couple to hadrons at high energies, would explain many of the phenomena that cannot be accounted for by standard models, and that their properties in the proposed model are thoroughly consistent with the experimental data. We predict that R should continue to rise, and that eN interactions should soon violate scaling, although this effect may not be very marked. Extended electron structure should appear in the next generation of $g_e - 2$ and e^+e^- elastic scattering experiments, and e^-e^- experiments may yield anomalous results at high energies.

Acknowledgments

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