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Independent test of loop bremsstrahlung

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If the sharp e^+e^- peaks seen in the Darmstadt experiments are due to the loop bremsstrahlung (LB) mechanism, the suggestion is made that it should be possible to reproduce those peaks in a relatively simple low-Z ion experiment. "Rutherford scattering," with e^+e^- detection added, could provide an independent test of LB. Estimates of $Z_{\min}$ for both e^+e^- and $\mu^+\mu^-$ peaks are given.

One of the possible explanations for the sharp e^+e^- "resonances" seen in the Darmstadt scattering of heavy ions[1] has been called "loop bremsstrahlung"[2] (LB), and involves the behavior of a virtual, closed electron loop (CEL) in the presence of the strong electric fields produced by the heavy ions, as illustrated in Fig. 1. The experimental peaks are characterized in LB as a cooperative enhancement during the process of interference[3] between the fields built from the low-frequency radiative corrections between loop and ions, and from those radiative corrections across the loop itself. The former define the ionic field acting on the loop, while the latter provide a mechanism for the rapid transfer of energy across the loop. LB is a nonperturbative effect, necessarily involving extraction of the low-frequency or "coherent" contributions of an infinite number of "soft" radiative corrections, each graph containing all frequencies from zero up to the order of the electron mass m.

Techniques for the isolation and extraction of such "infrared" (IR) behavior were developed in connection with chiral-symmetry-breaking studies[4] in two-dimensional QED [$(\mathrm{QED})_2$] and $(\mathrm{QCD})_2$, and can easily be extended to $(\mathrm{QED})_4$. The results, while still kinematically incomplete, are able to match the experimental masses and widths in a reasonable way, while the presence of a special enhancement factor associated with such interference effects in the presence of intense fields is able to compensate the expected factor of α which must appear to multiply every CEL.[5]

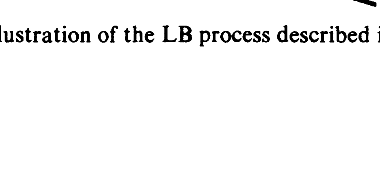

FIG. 1. Illustration of the LB process described in the text.

It has been noted[6] that the sharp e^+e^- peaks do not have the same experimental Z dependence as that of the well-understood background distributions; and the question may be posed: What is the range of ionic charge over which the peaks will be seen? The purpose of this paper is to provide a qualitative answer to that question in the context of the LB mechanism; the result is a minimum Z value that is remarkably small: $Z_{\min} \sim 2$.

In the physical picture of LB for heavy ions, one imagines[3] a pair of high-Z nuclei slowly approaching each other in their c.m. frame—they are practically at rest on the natural time scale of the virtual CEL which is to appear—with a vanishingly small total electric field in the region between these two, similarly charged, scattering particles. Suppose, for simplicity, that the two ions are at their distance b of closest approach, when suddenly there appears between them a virtual CEL, which one may think of in the vacuum-polarization sense as a small, temporary separation of positive and negative charge. There follows a rapid rearrangement of the fields between the ions, aided by the presence of soft radiative corrections "across the loop," which are able to transfer an amount of energy $\sim m$ in a time interval $\sim m^{-1}$. But after that time period $t_{\mathrm{cl}} \sim m^{-1}$, the virtual CEL disappears, the field between the ions tries to return to its previous values, and "loop bremsstrahlung" results, with the photons radiated from the loop converting to an e^+e^- pair as they leave the region. Note that the ions remain at distances $b \sim m^{-1}$ for times $\Delta t \gg t_{\mathrm{cl}}$, and that the most important field-strength rearrangements occur when both scatterers have the same charge. Note also that the mechanism outlined here for e^+e^- pair production is completely different from that suggested for and verified in the continuum e^+ production in the scattering of heavy ions.[7]

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Can this picture be modified by replacing the heavy ions by other charged particles? As long as one is willing to contemplate sufficiently small b values, there is no reason why such a LB mechanism could not be operative, at least if certain simple kinematical restrictions are enforced. Namely, the scattering particles should be in close proximity, with $b < m^{-1}$, for a time $\Delta t \gg t_{\rm cl}$. However, there should be no possibility of nuclear or hadronic interactions, which would only complicate the issue, so that b should not be too small.

A crude but qualitative argument proceeds as follows, using ions of identical charge and mass for simplicity. In the ions' c.m., with a relative separation $b = \xi/m$, their total energy is given by $H = Mv^2 + Z^2e^2/b$; here, M and m denote the ionic and electron mass, respectively, with their ratio $R = M/m$; and ξ is a constant which, to avoid hadronic complications, should lie in the range $1 > \xi > 10^{-2}$. We make three essentially physical restrictions, as follows.

If an eikonal model is to be at all relevant, the momentum transfer q of a scattered ion should be significantly less than its c.m. momentum magnitude p. For Coulomb scattering, which is the essential process to which the LB model adjoins a single CEL, the classical c.m. scattering angle Θ is given by $\tan(\Theta/2) = 2(Ze)^2Mbv^2$. The restriction $q/p \ll 1$ then means that Θ is very small, or equivalently that the potential portion of H is to be much smaller than its kinetic part, which requires

$$(v/c)^2 = f_1 Z^2 \alpha/\xi R \,, \tag{1}$$

with $\alpha = e^2/hc \sim (137)^{-1}$, and $f_1 \gg 1$. We shall subsequently choose, as a reasonable value, $f_1 \sim 10$.

Further, H must be sufficiently large to be able to produce an e^+e^- pair of total energy $\sim 3mc^2/2$, as seen in the Darmstadt experiments; this energy should be provided by the kinetic portion of H, so that $Mv^2 > 3mc^2/2$, or

$$(v/c)^2 = f_2(3m_e/2M) \,, \tag{2}$$

with $f_2 > 1$. A value for f_2 somewhat larger than unity may be expected to correspond to a more probable situation, although we shall use $f_2 \sim 1$ to define the minimum possible Z, below.

Finally, the time Δt that the two, nonrelativistic particles will spend in close proximity, with separation on the order of b, is given by $\Delta t \sim b/v$; and if this should be much larger than the natural time scale h/mc^2 of the loop, one requires

$$\xi = f_3(v/c) \,, \tag{3}$$

with $f_3 \gg 1$. As for f_1, we shall assume that $f_3 \sim 10$ is a sufficiently large value; this is, probably, the weakest point in the analysis, because precise estimates of Δt can be somewhat less than b/v, which then correspond to using a somewhat larger value for f_3.

For light nuclei, it is qualitatively correct to neglect binding effects and to identify $R \sim 2ZM_p/m \sim (4\times 10^3)Z$, where m_p denotes the proton mass. Combining (1) and (3) then yields $\xi^3 = f_1 f_3^2 \alpha Z/4\times 10^3$; and if $f_1 = 10 = f_3$, then $\xi = (Z\alpha/4)^{1/3}$ and remains in the desired range. From (1), one then reaffirms that the motion is nonrelativistic, with $(v/c) = [(2\alpha Z)^{1/3}]/20$. Finally, from (2) one has $f_2 = \frac{20}{3}(2\alpha)^{2/3}Z^{5/3}$, and if the requirement $f_3 > 1$ is to be enforced, one must choose

$$Z > (\tfrac{3}{20})^{3/5}(2\alpha)^{-2/5} \sim 1.74 \,. \tag{4}$$

If no *a priori* selections are made for $f_{1,3}$, one has $\xi = (f_1 f_3^2 Z\alpha/4\times 10^3)^{1/3}$ and $Z_{\rm min} = (\frac{3}{20})^{2/5}(f_3/2\alpha f_1)^{2/5}$, so that if f_3 is doubled, the $Z_{\rm min}$ above will be raised from 2 to 3. Clearly, one can produce a variety of results with different choices of $f_{1,3}$; but reasonable estimates, as above, correspond to a reasonable value for ξ and to a surprisingly low $Z_{\rm min}$. The conclusion suggested by (4) is that it is possible to have the kinematic restrictions necessary for LB when Z is very small indeed, of the minimum value of 2.

A modified form of "Rutherford scattering" (the quotation marks refer to low- rather than to high-momentum-transfer scattering) is therefore, according to LB, a possibility: Surround the scattering area with e^+e^- counters and look for the sharp e^+e^- peaks which may accompany the scattering of nonrelativistic α particles, or of slightly more massive ions. It would be very satisfying if light-ion scattering, extended to production in this way, could illustrate fundamental QED properties involving CEL's.

It may be of interest to ask how the above arguments are modified for $\mu^+\mu^-$ production via the LB mechanism. One can estimate this possibility by imagining the CEL of Fig. 1 to be that of an electron, and only the final lepton pair to be muonic. Repeating the above analysis then yields the modification $Z_{\rm min} = (f_3/2\alpha f_1)^{2/5}(m_\mu/5m_e)^{3/5}$, while if the total energy of the μ pair is taken as on the order of $2m_\mu$, the same analysis gives $Z_{\rm min} \approx 50$.

Such an estimate, however, is not really compelling, because in order to transfer an amount of energy $\approx 2m_\mu$ "across the loop," the maximum virtual-photon energy in the original LB calculation should be $\sim m_\mu$; and this, in turn, suggests that the proper way to estimate $Z_{\rm min}$ for μ-pair production is via a closed muon loop (CML). This has the effect of rescaling m_e up to m_μ everywhere above, and generates

$$Z^{\mu}_{\rm min} = [(f_3/2\alpha f_1)^2(\tfrac{3}{2})^3\tfrac{1}{5}]^{1/5} \approx 5 \tag{5}$$

for $f_3 \approx f_1$, which is again surprisingly low. Note that the corresponding ξ value here is changed to ~ 1.2, but that $b \sim 10^{-2}/m_e$, which should still provide an hadronic-free environment.

It is also interesting to attempt an estimate of the ratio of production rates for such e^+e^- and $\mu^+\mu^-$ processes. In the first case, where one considers a CEL for muon production, there is a clear distinction between muon-pair and electron-pair production for the two-virtual-photon model (as illustrated in Fig. 1), but not for a one-virtual-photon mode, with the amplitude of the former decreased by a factor of m_e/m_μ compared to electron-pair production. In the other case, where muon-pair production takes place via a CML, the rates appear to be qualitatively the same (and both are similarly dependent on momentum transfer given to the scattering ions).

Inasmuch as the crude kinematics of the LB model may be used to predict anything, one may recall that the first two members (at 1.64 and 1.84 MeV) of the "*A* family" correspond to a two-photon virtual state; and that each pair is experimentally seen to be emitted at 180° in the ions' c.m. In contrast, LB associates the 1.76-MeV pair with a one-photon intermediate state, and treats it as the lowest-energy member of the "*B* family;" experimentally, that pair is observed to be emitted in a forward cone. Combining this information with the above estimates, one might guess that $\mu^+\mu^-$ pairs seen above $Z \approx 50$ would be "*B*-family" pairs preferentially emitted in the forward direction; but that this would change for smaller Z, where their rates should be qualitatively the same as those for electron-pair production.

Finally, it should be remarked that the sharp $\mu^+\mu^-$ peaks will, according to the original LB mechanism, be produced at very different energies depending on whether the relevant closed loop is that of an electron or muon. In the first case of a CEL, one would expect the peaks to be infinitesimally above the two-muon threshold, measured on the scale of m_μ, for the cooperative enhancements of LB would be scaled to the CEL mass, m_e. For the second case of a CML, all scales are given in terms of m_μ, so that the observed peaks would appear at about three times the muon mass.

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[6]See, for example, H. Bokemeyer, in *Tests of the Fundamental Laws in Physics* (Ref. 3).

[7]See, for example, B. Müller, in *Tests of the Fundamental Laws in Physics* (Ref. 3).