First Measurements of the Unique Influence of Spin on the Energy Loss of Ultrarelativistic Electrons in Strong Electromagnetic Fields

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Although some authors have claimed that the effect is not detectable, we show experimentally for the first time that as the quantum parameter χ grows beyond 1, an increasingly large part of the hard radiation emitted arises from the spin of the electron. Results for the energy loss of electrons in the energy range 35–243 GeV incident on a W single crystal are presented. Close to the axial direction the strong electromagnetic fields induce a radiative energy loss which is significantly enhanced compared to incidence on an amorphous target. In such continuously strong fields, the radiation process is highly nonperturbative for ultrarelativistic particles and a full quantum description is needed. The remarkable effect of spin flips and the energy loss is connected to the presence of a field comparable in magnitude to the Schwinger critical field, $\mathcal{E}_0 = m^2c^3/e\hbar$, in the rest frame of the emitting electron.

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Under small angles of incidence to a crystal, the strong electric fields of the nuclear constituents add coherently such as to obtain a macroscopic, continuous field of the order $\mathcal{E} \simeq 10^{11}$ V/cm. This is evidenced by, e.g., the channeling phenomenon [1] or the so-called "doughnut scattering" [2]. Therefore, in the rest frame of an ultrarelativistic electron with a Lorentz factor of $\gamma \simeq 10^5$, the field encountered becomes comparable to the critical (or Schwinger-) field, $\mathcal{E}_0 = m^2c^3/e\hbar = 1.32 \times 10^{16}$ V/cm, corresponding to a magnetic field $B_0 = 4.41 \times 10^9$ T. Here, m is the rest mass of the electron, c is the speed of light, e is the elementary charge, and $\hbar$ is Planck's constant divided by 2π. The incident particle moves in these immensely strong fields over distances up to that of the crystal thickness, i.e., up to several mm. Thereby the behavior of charged particles in strong fields as $\mathcal{E}_0$ can be investigated.

Strong field effects can be investigated by other means. One example is in heavy ion collisions where the field becomes comparable to the Schwinger field, but the collision is of extremely short duration. Another—technically demanding—example is in multi-GeV electron collisions with terawatt laser pulses where nonlinear Compton scattering and so-called "Breit-Wheeler" pair production are observed [3]. In nature, near-critical fields are believed to be present in the vicinity of pulsars.

However, as we point out below, in order to investigate the effect of the spin on the radiation spectrum, the electron must interact with the strong field over large distances. So crystals present unique tools for the investigation of the influence of spin on the radiation spectrum.

Already in the late 1960s, Baier and Katkov [4] calculated the photon spectrum emitted by "particles of arbitrary spin moving in an arbitrary electromagnetic field." However, the realization that the spin influences the spectrum significantly in this context lay dormant for many years and was not discussed as an observable phenomenon although radiation intensities were calculated for spin 0, $\frac{1}{2}$, and 1; see also [5]. In fact, the influence of spin was left out from many discussions of quantum effects: "quantum effects in synchrotron radiation originate in two ways: from the quantisation of the motion of the electron, and from the quantum recoil when a photon is emitted" [6,7]. Moreover, investigations of channeling radiation at MeV to few GeV energies showed that the spin did not contribute at a detectable level [8].

For multi-GeV electrons and positrons incident along crystallographic directions the invariant quantum parameter, $\chi = \gamma\mathcal{E}/\mathcal{E}_0$, is in the range 1–10. So a full quantum description starting from first principles is needed but is complicated, and so far one has been performed by Greiner's group [9].

An approximate QED calculation by use of a semiclassical method where the field is considered constant over the formation zone [10], the so-called "constant field approximation" (CFA), does not show a constant or increasing relative energy loss. On the contrary, it shows a relative energy loss proportional to $\gamma^{-1/3}$, i.e., a total energy loss proportional to $\gamma^{2/3}$. This is due to a self-suppressing effect originating from the formation length of the photon. Once the field becomes sufficiently strong, the emitting electron is deviated from the formation zone before the photon has been formed—i.e., the contribution to the radiation integral decreases with increasing energy. This suppression is similar to the Landau-Pomeranchuk-Migdal effect where multiple Coulomb scattering is responsible for the deviation outside the formation zone; see, e.g., [11].

In the mid-1980s, Bagrov *et al.* [12] discussed the possibility of observing spin flips in axial channeling, but later their results were questioned by Greiner's group [9].

Then, in the early 1990s, Lindhard [13] showed that the contribution from the spin can be derived from a Weizsäcker-Williams–type calculation and together with Sørensen [14] demonstrated explicitly that indeed theoretically the contribution from the spin dominates the hard end of the photon spectrum as soon as χ gets larger than about 1. This also means that apart from the reverse action of the photon on the electron—the recoil—an additional quantum effect of the spin of the electron influences the spectrum; see also [15]. We emphasize that the correct inclusion of the effect of spin was done by Baier and Katkov in the late 1960s [4], but the possibility of its observation was not elaborated upon.

In the following we show by very simple arguments why the spin makes its influence. The energy of a magnetic moment at rest in a magnetic field is given by

$$W_{\mathrm{mag}} = -\overline{\mu} \cdot \overline{B} \tag{1}$$

such that spin-flip transitions of electrons with $\mu = e\hbar/2mc$ have an energy $\Delta W = e\hbar B/mc$ in the rest system where the Lorentz transformation gives a magnetic field $B = \gamma\beta\mathcal{E}_{\mathrm{lab}}$. Transformation back to the laboratory yields another factor γ (as in the case of channeling radiation arising from transitions in the transverse potential) such that the result is

$$\Delta W = \gamma^2 \beta \frac{\mathcal{E}}{\mathcal{E}_0} mc^2, \tag{2}$$

which coincides with the initial energy of the electron, E_e, when $\chi = 1$. This simple consideration shows why the radiation from spin flips concentrates near the end point of the spectrum. An analogous behavior appears for synchrotron radiation where the typical fractional photon energy, $\xi_c = \hbar\omega_c/E_e \simeq 3\gamma^3\hbar eB/2pE_e = 3\gamma B/2B_0$, becomes equal to 1 for $\chi = 2/3$ and thus the recoil of the photon must be taken into account. Here, ω_c denotes the critical photon frequency for the emission of synchrotron radiation. Asymptotically, the spin contribution becomes $\xi dN/d\xi \propto [\xi^7/(1-\xi)]^{1/3} \cdot \chi^{2/3}$ for large χ such that it is *strongly* peaked at the end of the spectrum.

Furthermore, the process of radiative polarization of the electron (i.e., spin-flip transitions) takes place in a time, τ, given by [15–17]

$$\tau = \frac{8\hbar}{5\sqrt{3}\,\alpha m}\left(\frac{B_0}{B}\right)^3 \frac{1}{\gamma^2} = \frac{8\hbar}{5\sqrt{3}\,\alpha m}\frac{\gamma}{\chi^3} \tag{3}$$

such that $c\tau$ becomes 15 μm for a 150 GeV electron in a $\chi = 1$ field. It is thus—somewhat in retrospect—not surprising that a substantial fraction of the radiation events originate from spin-flip transitions as one gets to and beyond $\chi \simeq 1$.

As a result of the quantum recoil correction, the total radiated intensity for the synchrotron radiation emission for small and large values of χ are reduced with respect to the classically calculated values as [6,18]

$$\Delta E/\Delta E_{\mathrm{cl}} \simeq 1 - 55\sqrt{3}\,\chi/16 + 48\chi^2 \qquad \chi \ll 1, \tag{4}$$

$$\Delta E/\Delta E_{\mathrm{cl}} \simeq 1.2\chi^{-4/3} \qquad \chi \gg 1. \tag{5}$$

From this it is clear that the emission of synchrotronlike radiation is affected already at fairly small values of χ, e.g., $\Delta E/\Delta E_{\mathrm{cl}} \simeq 0.9$ for $\chi = 0.1$.

Investigations of the onset of QED effects in energy loss have been performed before by others [19,20] for a Ge crystal aligned on the axis and by us for a diamond crystal [21]. However, the influence of the spin was marginal for the values of χ achieved; the large energy losses dominated by channeling and thus the spin were not discussed.

The quantum recoil parameter χ is approximately given by [7]

$$\chi \simeq \frac{U_0\gamma\hbar}{m^2c^3a_s} \tag{6}$$

for a single crystal, where a_s is the screening distance and U_0 is the height of the transverse potential.

This leads to $\chi_W \simeq 3$, at an energy of 100 GeV. It is worth noting that even though the quantum corrections imply a *reduction* compared to the classical synchrotron law, the emission probabilities in the quantum regime are still *enhanced* with respect to the Bethe-Heitler value, due to the coherence. For the energies 30 and 300 GeV the energy losses are reduced by factors of 6 and 45, respectively, compared to the classical synchrotron radiation [22].

The measurements were performed in the context of the NA43 experiment in the North Area of the CERN SPS, where tertiary beams of positrons, electrons, and pions are available with different intensities in the energy range 10–300 GeV.

The 0.2 mm thick W crystal was mounted on a goniometer with 1.7 μrad step size and aligned such that the beam was incident along the $\langle 111\rangle$ axis. Alignment was performed by observing the number of photons above $\simeq 20$ GeV as a function of goniometer angle, whereby low-index planes and the axis become identifiable.

The energy of the emitted photon was determined by two methods: (i) a tagging spectrometer where the energy of the electron after the radiation event is determined by its deflection in a magnet and (ii) interception of the photon(s) in a lead glass calorimeter. Good agreement between these methods was confirmed; see also [23]. For other recent results and more details on the experimental setup, see Ref. [21].

In order to reduce the influence of channeling (flux peaking for e^-) on the spectrum, the crystal was aligned 0.3 mrad from the axis, away from any major plane. Therefore, as this angle is well below the Baier angle $\Theta_0 = U_0/mc^2$ which determines the directionality of the strong field effects, but larger than Lindhards critical angle for channeling, the electron flux is uniform in the transverse space and the CFA applies directly.

In Figs. 1(a)–1(e) are shown photon spectra for 35–243 GeV electrons incident 0.3 mrad from the axis in the W crystal. All spectra are power spectra, i.e.,

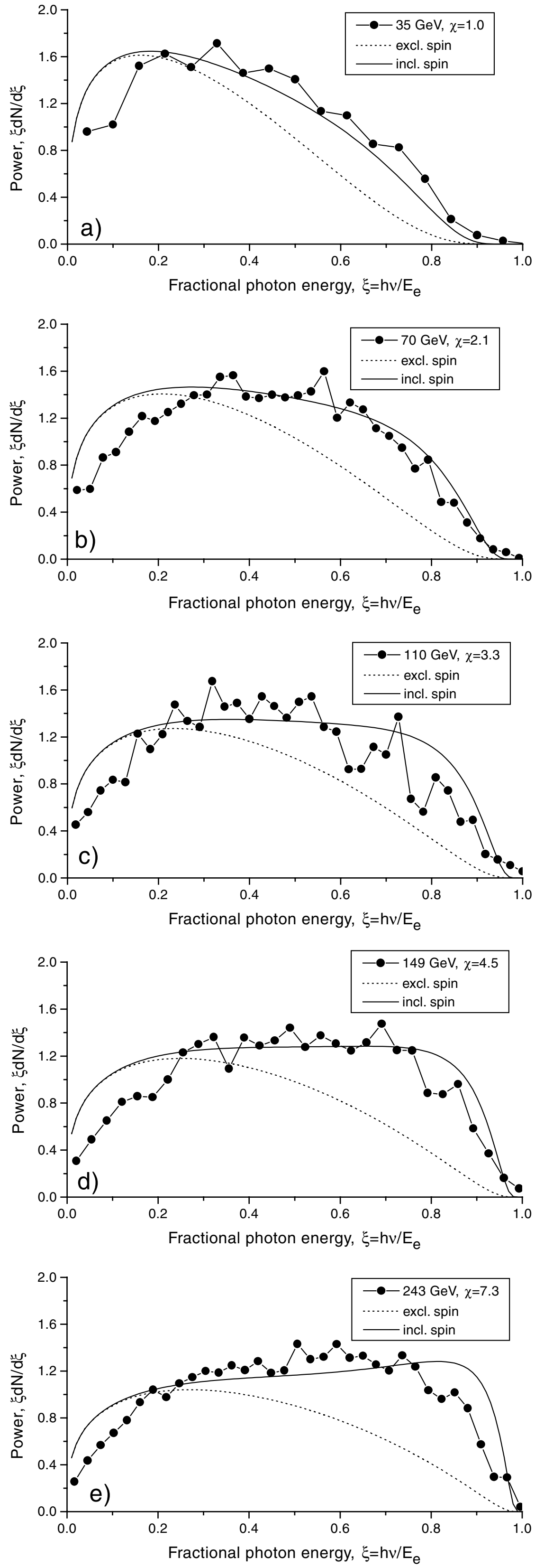

FIG. 1. Power spectrum of radiated photons, $\xi dN/d\xi$, for electrons aligned 0.3 mrad from the axis in 0.2 mm W $\langle 111 \rangle$. Filled circles denote the experimental points and the lines (full line = incl. spin; dotted line = excl. spin) the calculated values.

$\xi dN/d\xi$ vs ξ and normalized by their effective radiation length for easier comparison. The scatter of the experimental points indicates the uncertainties. The full drawn curves are calculations based on the constant field approximation and the dotted curves are again the CFA, but excluding the contribution from the spin as outlined in [14]. The calculations are rather crude—only one value of χ found from Eq. (6) is used; i.e., there is no averaging over field strengths encountered, except the one that is implicitly included in the estimate, Eq. (6). This may be one reason for the theoretical overestimate observed at high photon energies which seems to grow with increasing energy of the electron. Further, the effects of multiphotons or radiation cooling [24,25] are not included.

In spite of the simplicity of the model, in all cases the curves for the CFA including the contribution from the spin agree well with the data whereas the curves excluding the spin are far from the data points and more so the higher the energy. It is thus for the first time experimentally shown that the spin contributes significantly to the radiation spectrum for high enough energies.

The slight disagreement seen at low photon energies is most likely due to pileup of the many low-energy photons which has not been included in the model.

In Fig. 2 is shown the energy loss in the W crystal for 35 to 243 GeV electrons. Here the enhancement is seen to be approximately constant above 35 GeV, showing clearly the onset of quantum suppression. The dotted line is a least-squares fit with a power law.

The energy loss in classical synchrotronic motion is proportional to E^2, whereas the energy loss due to incoherent bremsstrahlung from a foil is proportional to E. Thus, for the classical region of radiation emission from synchrotronic motion in a crystal, an enhancement—the increase in radiation probability when comparing crystalline and amorphous materials—proportional to E is expected. Analogously, in the extreme quantum case an enhancement proportional to $E^{-1/3}$ is expected. As seen from Fig. 2, the present situation is between these two extremes, showing clearly the onset of quantum suppression.

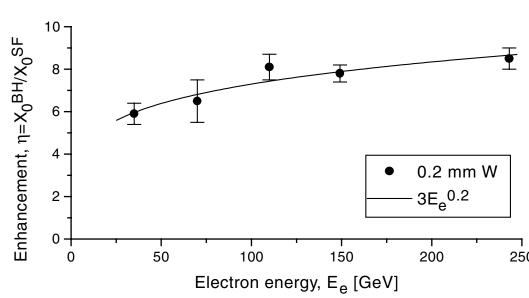

FIG. 2. The enhancement η for radiation emission from 0.2 mm W $\langle 111 \rangle$. The points with error bars are the experimental values and the line is a least-squares fit by $\eta = aE_e^b$.

Baier's group [7,20] has given a "rough estimate" of the enhancement (expected accuracy better than 10%) η, given as

$$\eta \simeq \frac{mca_s}{3Z\alpha\hbar\ln(183Z^{-1/3})} \qquad 1 < \chi < 15\,. \qquad (7)$$

In the case of tungsten, this estimate of the enhancement becomes $\eta \simeq 9$, whereas Kononets estimates from an accurate calculation based on the CFA that $\eta \simeq 7$ from about 30 GeV to a few thousand GeV [22]. Experimentally, the enhancement is defined as the ratio of effective radiation lengths, $\eta = X_0^{\mathrm{BH}}/X_0^{\mathrm{SF}}$, where X_0^{BH} is the Bethe-Heitler value for the radiation length and X_0^{SF} is the effective radiation length for the strong field case. Clearly, the rough estimates are in very good agreement with experiment, and they show that in this region the dependence on energy can be neglected to a first approximation.

In the construction of linear colliders an important phenomenon is the emission of beamstrahlung. This emission can be expressed as a function of χ (often called Υ) which for the Stanford Linear Collider is small $\simeq 10^{-3}$ but of the order of 0.2 to 0.5 for the next generation linear colliders [26]. Moreover, as there is a significant contribution from the spin, polarized electron and positron beams emit beamstrahlung that is essentially different from nonpolarized ones. It is thus vital to examine experimentally the behavior of radiation emission for χ around 1, especially the contribution from the spin.

In conclusion, we have for the first time shown experimentally the dramatic influence of the spin on the energy loss of ultrarelativistic electrons in strong fields.

Moreover, we have presented an extensive investigation showing a turnover from the classical γ^2 law for radiation emission towards the quantum expression where the energy loss becomes proportional to $\gamma^{2/3}$ because of quantum suppression in strong electromagnetic fields.

Good agreement with an analytical estimate of the enhancement as well as calculations based on the "constant field approximation" to the experimental data has been shown.

The good agreement between theory and experiment is very valuable for the understanding of elementary processes in strong electromagnetic fields and their extrapolations to new areas as, for example, radiation from neutron stars with fields near the critical $B_0 = 4.41 \times 10^9$ T. Furthermore it lends credibility to the views on many aspects of beam physics at extreme energies, as, e.g., the evaluation of beamstrahlung in ultrarelativistic electron-positron colliders.

[1] J. Lindhard, Mat. Fys. Medd. K. Dan. Vidensk. Selsk **34**, 1 (1965).
[2] A. H. Sørensen and E. Uggerhøj, Nucl. Sci. Appl. **3**, 147 (1989).
[3] C. Bamber *et al.,* Phys. Rev. D **60**, 092004 (1999).
[4] V. N. Baier and V. M. Katkov, Sov. Phys. JETP **26**, 854 (1968).
[5] W. Tsai, Phys. Rev. D **8**, 3460 (1973); W. Tsai and A. Yildiz, Phys. Rev. D **8**, 3446 (1973).
[6] V. B. Berestetskii, E. M. Lifshitz, and L. P. Pitaevskii, *Relativistic Quantum Theory* (Pergamon Press, New York, 1971).
[7] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals* (World Scientific, Singapore, 1998).
[8] *Relativistic Channeling,* edited by R. A. Carrigan, Jr. and J. A. Ellison (Plenum Press, New York, 1987).
[9] J. Augustin, A. Schäfer, and W. Greiner, Phys. Rev. A **51**, 1367 (1995).
[10] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, Sov. Phys. Usp. **32**, 972 (1989).
[11] S. Klein, Rev. Mod. Phys. **71**, 1501 (1999).
[12] V. G. Bagrov, I. M. Ternov, and B. V. Kholomai, Sov. Phys. JETP **59**, 622 (1984).
[13] J. Lindhard, Phys. Rev. A **43**, 6032 (1991).
[14] A. H. Sørensen, Nucl. Instrum. Methods Phys. Res., Sect. B **119**, 1 (1996).
[15] A. A. Sokolov and I. M. Ternov, *Radiation from Relativistic Electrons* (American Institute of Physics, New York, 1986).
[16] A. A. Sokolov and I. M. Ternov, Sov. Phys. Dokl. **8**, 1203 (1964); V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, Sov. Phys. JETP **31**, 908 (1970).
[17] J. Schwinger and W. Tsai, Phys. Rev. D **9**, 1843 (1974).
[18] J. Schwinger, Proc. Natl. Acad. Sci. U.S.A. **40**, 132 (1954).
[19] A. Belkacem *et al.,* Phys. Rev. Lett. **58**, 1196 (1987).
[20] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, Phys. Lett. **114A**, 511 (1986).
[21] K. Kirsebom *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **174**, 274 (2001).
[22] Yu. V. Kononets, Nucl. Instrum. Methods Phys. Res., Sect. B **33**, 22 (1988).
[23] R. Moore *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **119**, 149 (1996).
[24] K. Kirsebom *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **119**, 79 (1996).
[25] A. Baurichter *et al.,* Phys. Rev. Lett. **79**, 3415 (1997).
[26] K. Yokoya, in *Quantum Aspects of Beam Physics,* edited by P. Chen (World Scientific, Singapore, 1998).