Single electron experiments at S30XL (DASEL) - I

Preliminary considerations

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SLAC

New experimental opportunities

Fermilab IOTA/FAST facility:

1. Single electron dipole and undulator radiation in IOTA

SLAC LCLS-II hard X-ray (HXR) beamline:

1. RAFEL / TW photon beams at LCLS-II
2. XLEAP-II: Very strong wiggler ($K \approx 50$), 4 GeV electron beam

SLAC FACET-II:

1. Strong field QED: 17 GeV + strong laser

SLAC DASEL→S3OXL project:

1. Single electron in linac with high repetition rate (from dark current)

What can we do with a single electron?

Electron in an undulator/wiggler

Classical: Continuous interaction with EM-wave

Quantum:

Furry picture (W. Furry, PRL, 81, 1, (1951))

- Photon emission is a decay of an electron-field bound state
- In an undulator "dressing" effects are small (spin flip, electron mass shift, harmonic shift, etc.), neglible when $p = p'$ or "no recoil" assumption
- Ultrarelativistic partile is a classical emitter; photons obey Poisson statistics (R. Glauber, Phys. Rev., 84, 3 (1951))
- First order quantum effects are included by $\omega \to \omega(1 - \hbar\omega/E)$ (J. Schwinger, Proc.Nat.Acad.Sci.USA, 40, 132 (1954).)
- $\rho = \hbar\omega/E_e$, recoil parameter must be non-neglible for many quantum effects

Electron in IOTA (on loan from NLCTA) undulator

External field intensity

- Not a Lorentz invariant, scales as γ^2
- In a boosted frame of electron of $\gamma = 300$ in an undulator: $I^*_{und} \approx 10^{17}$ W/cm^2 , $\hbar\omega_u = 10^{-2}$ eV.

Critical field intensity

- Critical $\lambda_C = \hbar/mc$ (Heisenberg fluctuations) $\rightarrow E_{cr} = mc^2/(e\lambda_C)$
- $I_{cr} = 4.6 \times 10^{29}$ W/cm^2, $I^*_{und} \ll I_{cr}$
- $\chi = \sqrt{I/I_{cr}}$, quantum parameter

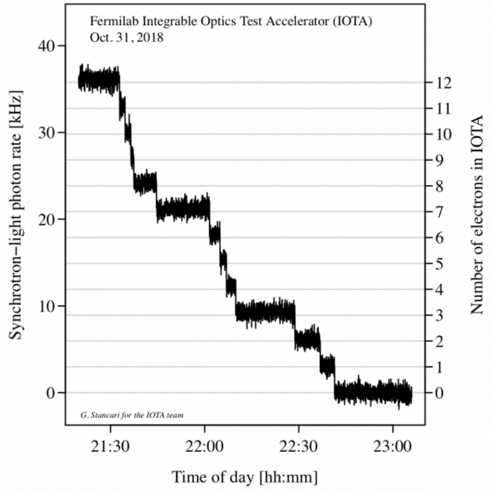
Undulator in IOTA

- $\rho = 3.5 \cdot 10^{-9}$, $\chi \approx 10^{-6}$, $K = 1$
- No measurable spin effects/harmonics shift
- What about other effects?

* - electron rest frame intensity

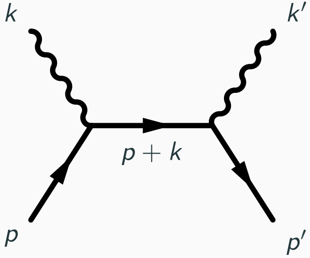
IOTA single electron experiment status update (3/2019)

IOTA is preparing to send single electron through the undulator for the first time; life-time 5 min + 50 min of tuning.

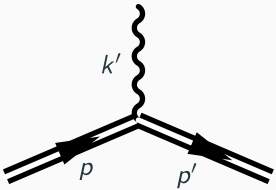


Dressed states and intensity parameter

Electron-field interaction (laser pulse, undulator):



Textbook example of Compton scattering (Peskin,Schroeder)



“Dressed” electron (Volkov, Ritus), Furry picture

Introduce intensity parameter (meaning of K parameter)

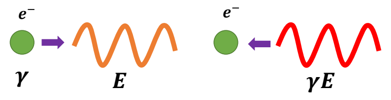
$$\xi = \frac{e\sqrt{A_\mu A^\mu}}{mc^2} \approx \frac{eE}{mc\omega}$$

Laser: $\chi < 1$, $\rho \propto 10^{-3}$, $\xi \leq 1$ **Undulator:** $\chi \ll 1$, $\rho < 10^{-6}$, $\xi \geq 1$

Photon emission in an undulator similar to non-linear Compton scattering

QED calculation by Ritus, and others

- **Laser:** (non-)pertubative, non-linear (preferable for SFQED)
- **Undulator:** perturbative, non-linear



Differential emission for a single photon*

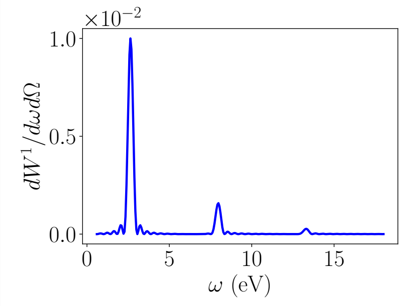
$$\frac{d^2W}{d\omega' d\Omega} = \frac{1}{2}\sum_{r,r'}\sum_{\lambda'} \frac{\alpha\omega'}{16\pi^2(k\cdot p)(k\cdot p')}|M^1(s;,r,r',\lambda')|^2$$

Limitations of theory: 1. Infinite number of field photons (no field depletion) 2. Theory is numerically divergent at $K > 2$.

*Detailed calculation of M is e.g. given in: D. Seipt, PhD dissertation, Technische Universität Dresden (2012)

Numerical evaluation for IOTA (NLCTA) undulator

$p = (m, 0, 0, 0)$, $k = \gamma\omega_u(1, 0, 0, -1)$, $\epsilon = (0, 1, 0, 0)$



Differences from the laser

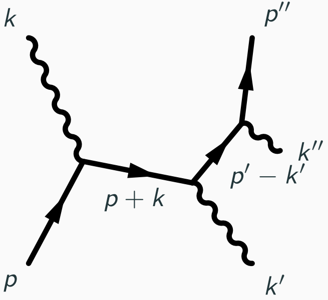
- Narrow spectrum, bandwidth determined by N_u
- "Square" $A_\mu(\phi)$ envelope $g(\phi) = \Theta(\Delta - \phi)\Theta(\Delta + \phi)$

Two-photon Compton scattering (weak field)

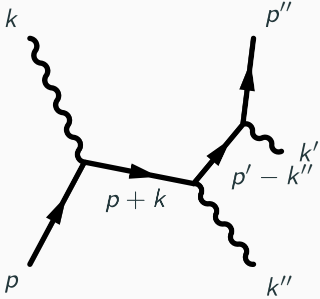
Two-photon emission is a quantum process (no classical analogue)

Two contributions: coherent (same formation region, scales as $\alpha^2\rho^2$), incoherent (different formation regions, scales as α^2).

Weak-field regime



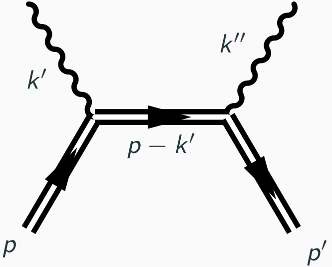
plus 4 interchangeables

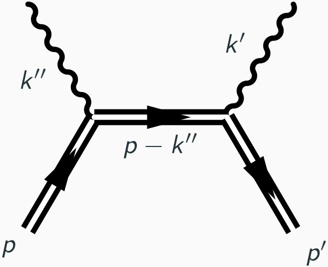


First experimental observation: I. F. Boekelheide, Ph. D. Thesis, State Univ. of Iowa, Ames, Iowa, 1952;
P. E. Cavanaugh, Phys. Rev. 87, 1131 (1952).

Two-photon Compton scattering (undulator/dipole)

Dressed Feynman diagrams





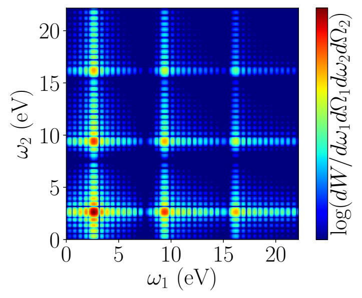
Synchrotron radiation (in dipoles):

$$w_2 \equiv \frac{25}{24}\alpha^2 \left(\frac{e_0 H}{m_0 c}\right) \frac{1}{2\pi} + O(\chi, \rho) = \frac{1}{2\tau} W_1^2 + O(\chi, \rho)$$

Calculation by Sokolov (Sokolov, A., *et al*, "Two-photon synchrotron emission", Izvestiya VUZ, Fizika, No. 9, pp. 46-52, (1976).)

Expect similar scaling in an undulator:
coherent part strongly suppressed, incoherent $\propto \alpha^2$

Two-photon undulator radiation (numerical calculation)



preliminary, work in progress; on-shell in leading order; $M^2 = 1/2(M^1 M^1)$

- Presumably no off-shell effects, pure two incoherent emissions
- Two photons have the same $\omega_1 = \omega_2$ (more probable)
- "Soft" and "hard" photon pair (less probable)
- Two "hard" photons (very rare)

Experimental plan at IOTA

Single electron

1. Count number of single- and double-photon events, if assumptions above are correct, the ratio $R_{single/double} \approx 10^2$
2. Count rates of: two "soft", one "soft" and one "hard", two "hard" photon events (expected to scale pertubatively)
3. Two-photon polarizations, expected to have no correlations, using Hong-Ou-Mandel interferometer
4. Statistics of single- and double-photon events (expect Poisson)
5. Possible information on electron wavepacket localization

In collaboration with SLAC

What are the advantages of DASEL?

Repetition rate

1. Expected much more single electron time than in IOTA ring

Two and more electrons

1. Two (small number) electron SASE; low ρ parameter regime
2. Electron wavefunction interference effects (need laser)

Advantages of 4 GeV beam (+ laser)

1. Larger (χ, ρ), especially combined with the laser
2. Entangled two-photon emitter for quantum optics experiments
3. When combined with XLEAP-II, strong angular-frequency correlations

Thank you for your attention

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