Strong-field quantum electrodynamics in magnetar magnetospheres

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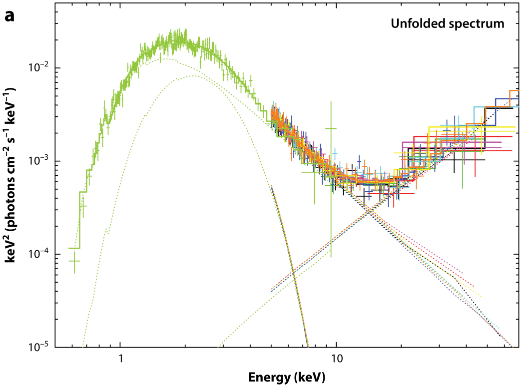
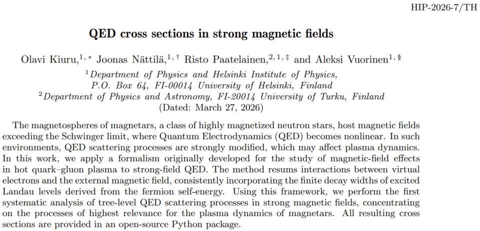
Plasma dynamics of magnetars is complicated!

- Radiation processes around magnetars are not well known.
- QED scattering cross sections are needed for magnetospheric plasma simulations.
- Quantum electrodynamics (QED) becomes nonlinear in strong magnetic fields, i.e. $B \gtrsim B_{\mathrm{Q}} \approx 4.41 \cdot 10^{13}$ G.

$\Rightarrow$ A new computational formalism is required.



Emission spectrum of a magnetar (Vogel et al., 2014).



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QED cross sections in strong magnetic fields

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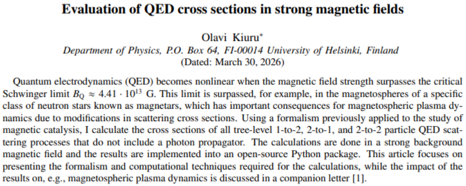
(Dated: March 27, 2026)

The magnetospheres of magnetars, a class of highly magnetized neutron stars, host magnetic fields exceeding the Schwinger limit, where Quantum Electrodynamics (QED) becomes nonlinear. In such environments, QED scattering processes are strongly modified, which may affect plasma dynamics. In this work, we apply a formalism originally developed for the study of magnetic-field effects in hot quark–gluon plasma to strong-field QED. The method resums interactions between virtual electrons and the external magnetic field, consistently incorporating the finite decay widths of excited Landau levels derived from the fermion self-energy. Using this framework, we perform the first systematic analysis of tree-level QED scattering processes in strong magnetic fields, concentrating on the processes of highest relevance for the plasma dynamics of magnetars. All resulting cross sections are provided in an open-source Python package.

arXiv:2603.25491.



Evaluation of QED cross sections in strong magnetic fields

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(Dated: March 30, 2026)

Quantum electrodynamics (QED) becomes nonlinear when the magnetic field strength surpasses the critical Schwinger limit $B_Q \approx 4.41 \cdot 10^{13}$ G. This limit is surpassed, for example, in the magnetospheres of a specific class of neutron stars known as magnetars, which has important consequences for magnetospheric plasma dynamics due to modifications in scattering cross sections. Using a formalism previously applied to the study of magnetic catalysis, I calculate the cross sections of all tree-level 1-to-2, 2-to-1, and 2-to-2 particle QED scattering processes that do not include a photon propagator. The calculations are done in a strong background magnetic field and the results are implemented into an open-source Python package. This article focuses on presenting the formalism and computational techniques required for the calculations, while the impact of the results on, e.g., magnetospheric plasma dynamics is discussed in a companion letter [1].

arXiv:2603.26545.

Magnetars: neutron stars with large B

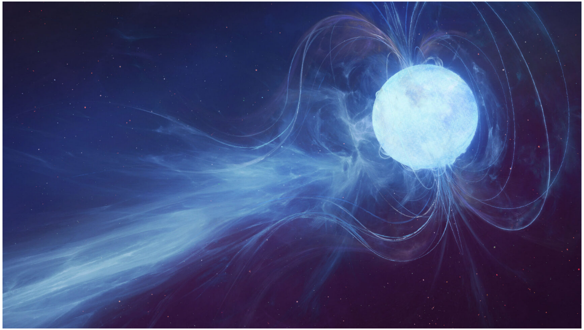
neutronstars

- The strongest long-lived magnetic fields in the universe.
- Born from a rapidly rotating progenitor.
- **Dynamo mechanism** strengthens the magnetic field.
- Sources of many extreme phenomena, e.g. magnetar outbursts and giant flares.

Magnetar properties

Magnetic field: $B \sim 30\ B_{\mathrm{Q}}$

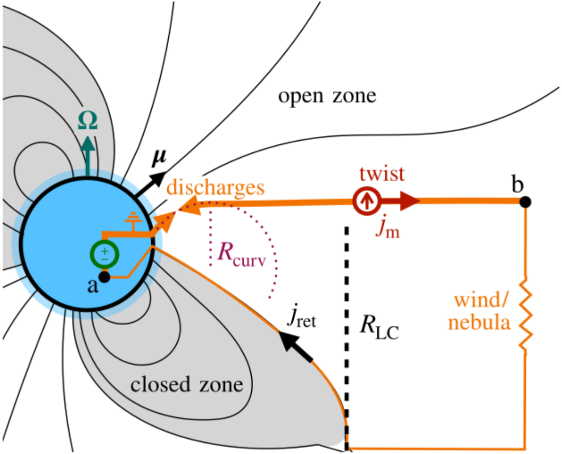
Rotational period: $T \sim 1$ s



Maciej Rebisz for Quanta Magazine.

The magnetosphere emits radiation

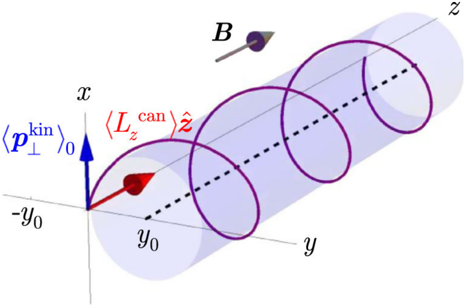
- Magnetosphere co-rotates with the star inside the light cylinder, $E_\perp = \beta_{\rm rot} B \ll B$
- At the polar caps, charged particles stream up from the surface of the star.
- Charges move along the magnetic field lines in thin sheets and emit curvature radiation ⇒ A **cascade of pair production** forms.



Magnetic field of a neutron star (Nättilä & Salmi, in prep.)

A magnetic field changes the particle dynamics

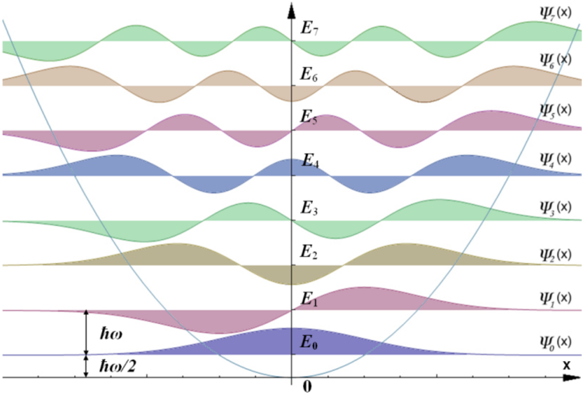
- Approximation: constant magnetic field and no electric field.
- Charged particles rotate around the magnetic field lines.
- Two polarization modes for photons: ordinary O-mode and extraordinary X-mode.



Motion of a charged particle in a magnetic field (Greenshields et al., 2015).

Quantization of energy: Landau levels

- Dirac equation ⇒ Plane wave + quantum harmonic oscillator
- Energy of the electron is quantized into **Landau levels**: $E^2 = p_z^2 + m^2\,(1 + 2bn)$, $b = B/B_{\mathrm{Q}}$.
- Lowest Landau level (LLL) dominates in a strong magnetic field. ⇒ **Dimensional reduction**.

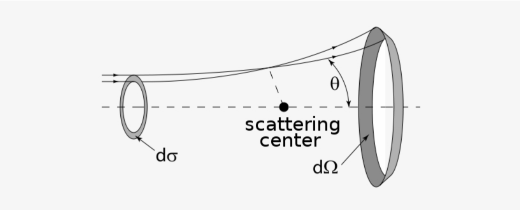


Energy levels of a quantum harmonic oscillator. By AllenMcC. at Wikipedia, CC BY-SA 3.0.

Scattering cross sections describe interaction probabilities

$$\sigma = \frac{\#\text{ of interactions per unit time per target}}{\text{incident flux}} = \int \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\mathrm{d}\Omega\,,\ \text{differential cross section: } \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}.$$

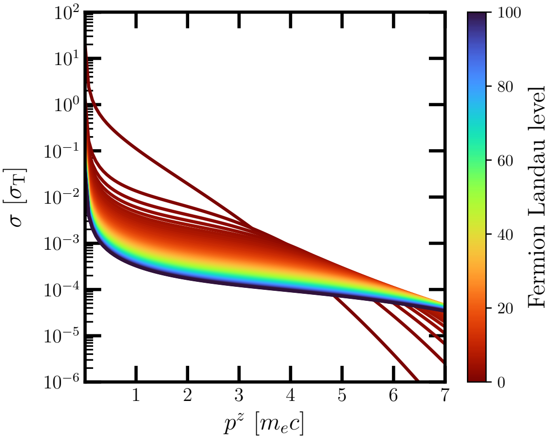
- Large cross section ⇒ more likely that a collision happens.
- Calculated with quantum field theory.
- Differential cross section gives the angular distribution of outgoing particles.



mungfali.com

The open-source SFQED Python package

- Calculates the cross sections of various QED scattering processes with full freedom over all degrees of freedom in the calculation.
- Currently implemented processes: synchrotron radiation, Compton scattering, one and two-photon pair creation, one and two-photon pair annihilation
- Available at https://github.com/hel-astro-lab/SFQED.



Cross section of one-photon pair annihilation for different Landau levels.

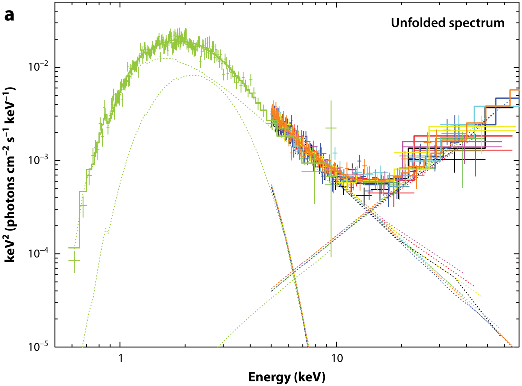
Where to go next?

- More processes to calculate!
- Some open questions remain, e.g., what happens if we add an electric field?
- Plasma simulations of magnetar magnetospheres.

Interaction	Name
$e^{\pm} \to e^{\pm} + \gamma$	Synchrotron radiation
$\gamma \to e^{+} + e^{-}$	One-photon pair creation
$e^{-} + e^{+} \to \gamma$	One-photon pair annihilation
$e^{\pm} + \gamma \to e^{\pm}$	Synchrotron self-absorption
$e^{-} + e^{+} \to \gamma + \gamma$	Two-photon pair annihilation
$\gamma + \gamma \to e^{-} + e^{+}$	Two-photon pair creation
$e^{\pm} + \gamma \to e^{\pm} + \gamma$	Compton scattering
$e^{\pm} + e^{\pm} \to e^{\pm} + e^{\pm}$	Møller scattering
$e^{\pm} + e^{\mp} \to e^{\pm} + e^{\mp}$	Bhabha scattering
$e^{\pm} \to e^{\pm} + \gamma + \gamma$	Double synchrotron radiation
$\gamma \to e^{+} + e^{-} + \gamma$	Radiative one-photon pair-creation
$\gamma \to \gamma + \gamma$	Photon splitting
$e^{\pm} + \gamma \to e^{\pm} + \gamma + \gamma$	Double Compton scattering
$e^{-} + e^{+} \to \gamma + \gamma + \gamma$	Three-quantum pair annihilation
$\gamma + \gamma \to e^{-} + e^{+} + \gamma$	Radiative pair-creation
$e^{\pm} + e^{\pm} \to e^{\pm} + e^{\pm} + \gamma$	(Møller) Bremsstrahlung
$e^{\pm} + e^{\mp} \to e^{\pm} + e^{\mp} + \gamma$	(Bhabha) Bremsstrahlung
$e^{\pm} + \gamma \to e^{\pm} + e^{+} + e^{-}$	Triplet pair production

Summary

- We do not know how magnetar emissions are produced.
- Understanding QED processes in a strong magnetic field is essential for correctly modeling plasma around neutron stars.
- Electron energies are quantized into Landau levels in a magnetic field.



Emission spectrum of a magnetar (Vogel et al., 2014).

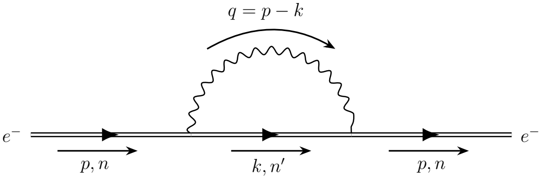
Thank you! Questions?

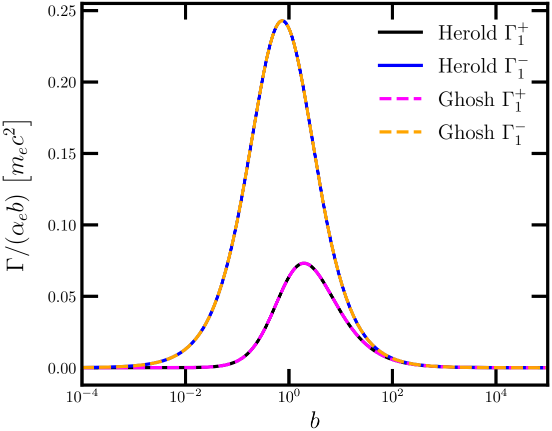
Fermion propagator definition

$$S_{\mathrm{F}}(x',x;E,p^z) \quad\equiv\quad \mathrm{i}\,\frac{\mathrm{e}^{\mathrm{i}\Phi(x',x)}\mathrm{e}^{-\frac{\xi^2}{2}}}{2\pi\lambda_B^2}\sum_{n=0}^{\infty}\frac{F_n}{E^2-(p^z)^2-m_e^2-2n|qB|}, \tag{1}$$

$$F_n = \left(\gamma^0 E-\gamma^3 p^z+m_e\right)\left(\mathcal{P}_- L_{n-1}(\xi^2)+\mathcal{P}_+ L_n(\xi^2)\right)$$
$$+\frac{\mathrm{i}}{\lambda_B^2}\vec{\gamma}_\perp\cdot(\vec{x}_\perp-\vec{x}'_\perp)L^1_{n-1}(\xi^2), \qquad \mathcal{P}_\pm\equiv\frac{1}{2}\left(1\pm\frac{q}{|q|}\mathrm{i}\gamma^1\gamma^2\right),$$
$$\xi^2\equiv\frac{(x-x')^2+(y-y')^2}{2\lambda_B^2}, \qquad \Phi(x',x)\equiv-\frac{q}{|q|}\frac{(x+x')(y-y')}{2\lambda_B^2},$$

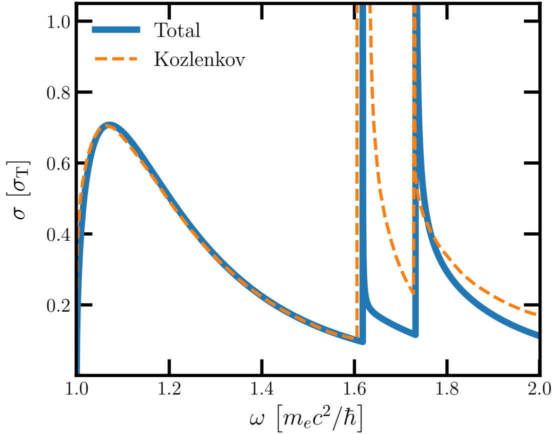
Fermion self-energy

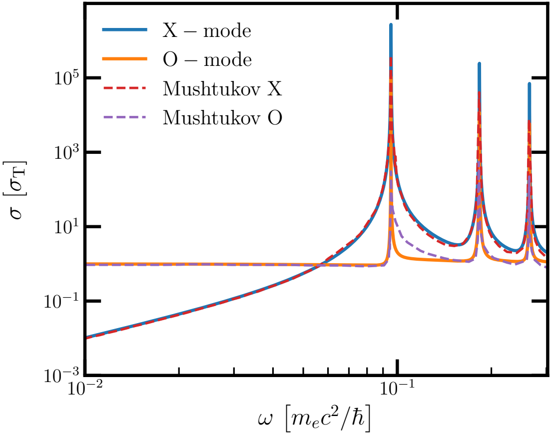




- Regulates some of the divergences in the cross sections.
- Matches with synchrotron decay rate at the poles of the propagator.

Comparisons to previous results





Non-magnetic Compton scattering

- Cross section is given by the Klein-Nishina formula.
- Approaches the Thomson cross section $\sigma_t \approx 66.5\ \mathrm{fm}^2$ at low energies.
- Falls off $\sim \ln(\omega)/\omega$ at high energies.