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Quantum Synchrotron Radiation from Protons in Strong Magnetic Field

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Abstract

Ultra-High-Energy Cosmic Rays (UHECRs) are the most energetic particles observed in nature, but their origin remain unclear although their energies can be measured. This is because their trajectories before arriving on the earth are deflected by extremely strong magnetic fields in the universe. Recently, the AMATERAS experiment detected particles with energies of up to 2.44×10^{20} eV [1], which are generally thought to be atomic nuclei. One of the promising ways to identify these particles is the astronomical observation of the synchrotron γ-rays emitted from UHECRs in extremely strong magnetic fields ($B \gtrsim 10^{15}$ G). As a first step toward this goal, we constructed a theoretical model of proton synchrotron radiation based on relativistic quantum mechanics and performed numerical calculations.
In this presentation, we study emission processes from ultra-high-energy protons in an intense magnetic field. At extremely high energies, strong-interaction as well as electromagnetic interaction become important, and thus high-energy γ-rays and other particles are generated from the synchrotron radiation. Therefore, we consider not only photon emission, but also the production of pions and ρ-mesons. In our calculation, particle motion in strong magnetic fields is quantized into Landau levels, which can be viewed as discrete energy states of circular motion of a particle. As a result, when a proton transits from a Landau level to a lower level, the proton cannot change its energy continuously. In this regime, semi-classical descriptions are no longer adequate. We therefore perform a fully relativistic quantum calculation based on the Dirac equation, by extending our previous work [2]. The Landau quantum numbers for UHE protons in strong magnetic fields become as large as $N > 10^{15}$. These extremely huge numbers make direct calculations impractical. We overcome this problem by using a generalized scaling rule for quantum transition probabilities, which has been obtained from calculations with smaller Landau numbers. This scaling enables us to calculate synchrotron radiation with extremely large Landau quantum numbers.
Our framework also includes the effect of proton recoil during emission. We find that the proton recoil significantly modifies the emission behavior: the decay width reaches a maximum and then decreases with increasing product of the proton energy and the magnetic field strength. In contrast, classical theory without recoil effects [3] predicted the monotonic increase. The present quantum treatment therefore provides useful theoretical input for interpreting high-energy radiation from cosmic-ray sources.

References

[1] Telescope Array Collaboration, Science 382, 903 (2023).
[2] A.Tokuhisa and T.Kajino, ApJ. 525, L117 (1999).
[3] T. Maruyama et al., Phys. Rev. D in press.