Pion Production from Proton Synchrotron Radiation under Strong Magnetic Fields in Relativistic Quantum Approach [1]

MARUYAMA, Tomoyuki (Nihon University)
KAJINO, Toshitaka (NAOJ/University of Tokyo)
CHEOUN, Myung-Ki, KWON, Yongshin, RYU, Chung-Yeol (Soongsil University)
MATHEWS, Grant J. (University of Notre Dame)

It is widely accepted that soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) correspond to magnetars [2]. In the magnetars a proton is expected to be accelerated in a strong magnetic field and to emit photons through the synchrotron radiation. The meson-nucleon couplings are about 100 times larger than the photon-nucleon coupling, and the meson production process is expected to exceed photon synchrotron emission in the high energy regime.

However, the synchrotron radiation has been studied only in the semi-classical framework [3] and it has not treated discretized Landau levels and the anomalous magnetic moment (AMM) of protons. In this work [1], then, we study the pion production from proton synchrotron radiation in the relativistic quantum approach.

We assume a uniform magnetic field along the z-direction, $\boldsymbol{B} = (0, 0, B)$, and take the electro-magnetic vector potential A^μ to be $A = (0, 0, xB, 0)$ at the position $\boldsymbol{r} \equiv (x, y, z)$. The relativistic proton wave function $\tilde{\psi}$ is obtained from the following Dirac equation:

$$\left[(i\partial\!\!\!/ - eA\!\!\!/) - m_N - \frac{e\kappa_p}{2m_N}\sigma_{\mu\nu}F^{\mu\nu}\right]\tilde{\psi}(x) = 0, \qquad (1)$$

where $F^{\mu\nu} \equiv \partial^\mu A_\nu - \partial^\nu A^\mu$, m_N is the proton mass, and κ_p is the proton AMM. By solving Eq. (1), we then obtain the energy eigenvalues as

$$e(n, p_z, s) = \sqrt{p_z^2 + \left(\sqrt{eB(2n+1-s) + m_N^2} - \frac{se\kappa_p B}{m_N}\right)^2}, \qquad (2)$$

where n is the Landau level number, $s = \pm 1$ is the spin index, and p_z is z-component of the proton momentum.

In Fig. 1 we show the initial and final spin-dependence of the proton differential pionic decay widths with (a) and without (b) the AMM with a proton kinetic energy of 1 GeV, emitted pion energy of 300 MeV and a strength of the magnetic field to be 5×10^{18} G. These widths are averaged over the initial Landau levels $0 \leq n_{max} - n_i \leq 9$.

When $\kappa_p = 0$, the contributions from the spin-flip transition, $s_i = -sf$, are about 100 times larger than those of the spin non-flip, $s_i = sf$. The spin-flip contributions become much larger than those from the spin non-flip reaction.

When the AMM is included, only the contribution from $s_i = -sf = 1$ is about 10,000 times larger than those of the other channels. When $s_i = -sf = 1$, the effects of the AMM and spin-flip are synchronized, and they increase very largely, while the two effects cancel when $s_i = -sf = 1$.

Thus, we have found that the proton AMM largely contributes to the pion production. We can clarify this effect by solving the Dirac equation in a strong magnetic field in a fully relativistic and quantum mechanical way. Furthermore, we found that the AMM effect becomes larger as the magnetic field decreases when the initial energy is fixed while the AMM effects diminish as the proton energy increases when the magnetic field is fixed. When $B \sim 10^{15}$ G, the proton is expected to be $e_p \sim 1$ TeV, and the maximum Landau level number becomes about 10^{11}, but one expects the AMM effect to remain because of the above results.

As for future studies, we must consider a method to treat huge numbers of the Landau levels for the magnetic field of $B \sim 10^{15}$ G. We should have to derive a new formulation including effects of the AMM from the exact formulation given in this paper.

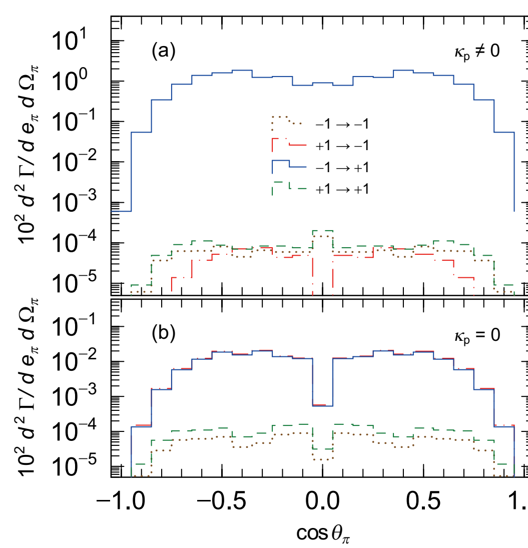

Figure 1: The differential pionic decay widths of protons with (a) and without (b) the AMM included. The widths are averaged over initial Landau numbers, $0 < n_{max} - n_i < 9$. The solid, dot-dashed, dashed, and dotted lines represents the results when $s_i = -s_f = -1$, $s_i = -s_f = 1$, $s_i = s_f = 1$, and $s_i = s_f = -1$, respectively, where $s_{i(f)}$ indicates the initial (final) spin of the proton.

References

[1] Maruyama, T., et al.: 2015, *Phys. Rev. D*, **91**, 123007.
[2] Mereghetti, S.: 2008, *Annu. Rev. Astron. Astrophys.*, **15**, 225.
[3] Tokushita, A., Kajino, T.: 1999, *ApJ.* **525**, L117.