Meson synchrotron radiation threshold for ultra-high energy cosmic ray protons: Work in progress

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I. MOTIVATION

- Curvature and synchrotron radiation emitted by CR particles plays a important role in understanding the energy losses that it can suffer inside the acceleration mechanisms[1].
- Protons are the main component of the CR spectra up to 10^{15}eV and beyond 10^{18}eV[2]
- Following the analysis of [4–7] one can argue that the *strong coupling* of mesons with protons can generate synchrotron emission radiation composed by π's and ρ's.
- The strong channels we consider here are

$$p^+ + A_\mu \to p^+ + A_\mu + \pi^0, \tag{1}$$

$$p^+ + A_\mu \to p^+ + A_\mu + \rho^0, \tag{2}$$

II. GENERAL OUTLINE

- We set the conditions and the ranges of validity of the formalism in terms of the classical and dimensional *proper acceleration* $a = \sqrt{-a_b a^b}$ (frame independent).
- The *non recoil* condition reads

$$a < M, \tag{3}$$

  where M is the mass of the accelerated source.
- The processes will be favoured when $a \geq m$, where m is the mass of the *emitted particle.* Then

$$m_\pi \leq a \ll m_p, \tag{4}$$

$$m_\rho \leq a \ll m_p, \tag{5}$$

  for the scalar case (1) and for the vector meson emission (2), respectively.
- The proper acceleration of a proton of mass m in circular motion in a magnetic field B is given by

$$a \approx \gamma \frac{eB}{m}$$
$$\sim 100 \left(\frac{\gamma}{10^7}\right)\left(\frac{B}{10^{13}\,\text{Gauss}}\right) \text{MeV} \tag{6}$$

- Then, protons with $E \geq 10^{16}$ eV ($\gamma \geq 10^7$) has proper acceleration higher than 100 MeV.

- As m_π, $m_\rho \sim \mathcal{O}(100\text{MeV})$ this is the threshold of meson emission from the protons in circular motion.

III. EMITTED POWERS

A. The Formalism

- We have adopted a formalism where a classical source

$$j^a(x) = q \frac{\delta^3[\mathbf{x} - \mathbf{x}(\tau)]}{\sqrt{-g}u^0(\tau)} u^a(\tau) \,, \tag{7}$$

follow a prescribed trajectory $x^a(\tau)$ in the spacetime. The sources are coupled to the quantized meson fields,

$$\hat{\Phi}(x) = \int d^3\mathbf{k} \left[\hat{a}_{\mathbf{k}} \phi^{(+\omega)}_{\mathbf{k}}(x) + \hat{c}^\dagger_{\mathbf{k}} \phi^{(-\omega)}_{-\mathbf{k}}(x)\right] \,. \tag{8}$$

being $\Phi(x)$ de scalar and

$$\hat{A}^\lambda_b(x) = \int d^3\mathbf{k} \left[\hat{d}_{\mathbf{k}} u^{\lambda(\omega)}_{\mathbf{k}b}(x) + \hat{d}^{\dagger\lambda}_{\mathbf{k}} u^{\lambda(-\omega)}_{-\mathbf{k}b}(x)\right] \,, \tag{9}$$

the massive vector field. The actions that couple the fields and the source are

$$\hat{S}^{(s)}_I = \int d^4x \, j(x) \left[\hat{\Phi}(x) + \hat{\Phi}^\dagger(x)\right] \tag{10}$$

and

$$\hat{S}^{(v)}_I = \int d^4x \, j^a(x) \left[\hat{A}_a(x) + \hat{A}_a{}^\dagger(x)\right] \tag{11}$$

- The power associated to the emission are obtained from

$$W^{p^+ \to p^+}_{s,\,v} = \int d^3\tilde{\mathbf{k}} \, \tilde{\omega} \, \frac{dR^{p^+ \to p^+}_s}{d^3\tilde{\mathbf{k}}} \,, \tag{12}$$

where,

$$\frac{dR_s^{p^+\to p^+}}{d^3\tilde{\mathbf{k}}} = \frac{1}{T}|\mathcal{A}_k|^2 \tag{13}$$

and $T = \int ds$ is the *total coordinate time.* The invariant amplitude is given by

$$\mathcal{A}_{\mathbf{k}} = \langle p^+| \otimes \langle \pi^0|\hat{S}_I^{(s)}|0\rangle \otimes |p^+\rangle. \tag{14}$$

B. Results

- In a magnetic field, a charged particle follow a circular trajectory which is, in terms of the inertial coordinates $(t, \mathbf{x})$ in a rest reference frame,

$$x^a(\tau) = (t, R\cos(\Omega t), R\sin(\Omega t), 0). \tag{15}$$

- In the ultra-relativistic limit, $\gamma \gg 1$ and $a/m_\pi \gg 1$, that the associated power given by (12) is,

$$W_s^{p^+\to p^+} \approx \frac{G_{\text{eff}}^{(s)2} a^2}{12\pi}. \tag{16}$$

$$W_{(v)}^{p^+\to p^+} \approx \frac{2G_{\text{eff}}^{(v)2} a^2}{3\pi}, \tag{17}$$

where $2G_{\text{eff}} \equiv g' = \sqrt{14}$

IV. DISCUSSION

- The power emitted in the ordinary synchrotron radiation is

$$W_{\text{L}} = \frac{2\alpha^2 a^2}{3} \tag{18}$$

- Then the massive vector emission and the electromagnetic one differs only by the coupling constants,

$$\frac{g'^2}{\alpha^2} \sim 10^3 \tag{19}$$

- One should expect then, that the ρ emission could dominate over the ordinary synchrotron radiation.

- Some remarks are in order:

  Curvature radiation is still the main mechanism of energy losses of CR protons in high magnetic fields;

  Proton decay can be favoured in the high acceleration regime. The general case should be

$$N^+ + A_\mu \to N^{+(0)} + A_\mu + \pi^{0(+)}(\rho^{0(+)}). \tag{20}$$

  In the decay case the formalism developed in [8, 9] must be employed.

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