Monopolonium Decay as a source of Ultrahigh Energy Cosmic Rays

Marina Gibilisco[a]

[a]Present Address: ECT*, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Via delle Tabarelle 286, 38050 Villazzano,Trento, Italy.

In this contribution, I will discuss the possibility to produce ultrahigh energy cosmic rays (UHECR) from the collapse of monopolonium: such a particular bound state of monopoles having an opposite magnetic charge would be formed during the early inflationary stages of the Universe; subsequently, the monopolonium would decay due to the annihilation of its constituents, so releasing its energy in the form of ultrahigh energy particles.

1. THE MONOPOLONIUM PROPERTIES.

Topological defects (TDs) recently assumed a new astrophysical relevance as possible sources of ultrahigh energy cosmic rays (UHECR). Events having an energy in the order of $1 \div 3 \times 10^{20}$ eV have been observed in many experiments [1–3] but they cannot be explained by using the standard astrophysical acceleration mechanisms. The decay of TDs originated during the phase transitions in the Early Universe really represents a powerful alternative sorce.

Among TDs, monopoles seem particularly effective [4] in producing high energy particles: I will discuss here the properties of the bound state called monopolonium and formed by monopoles having an opposite magnetic charge.

A Bohr model of the monopolonium is generally used to describe its properties [5,6]: this system classically emits electromagnetic radiation and spirals down to deeper and deeper orbits, until the final annihilation of its constituents.

The monopolonium energy is released in the form of particles (photons, gluons, quarks, Z bosons and X particles, having a mass $m_X \sim 10^{16}$ GeV). By considering the monopolonium as a dipole [5], its rate of energy loss is: [5]

$$\frac{dE}{dt} = -\frac{64}{3}\,\frac{E^4}{g_m^2 m_M^2}; \tag{1}$$

consequently, its lifetime is

$$\tau = \frac{m_M^2 r_f^3}{8\alpha_m^2} \tag{2}$$

(Note that τ depends on the third power of the formation radius r_f).

For $r_f \sim 10^{-9}$ cm, the monopolonium actually survives till the present epoch, in such a way the secondary particles coming from its collapse may presently appear as CRs. The number density evolution of X particles can be written as

$$\frac{dn_X}{dt} = \frac{dn^c_{M\overline{M}}}{dt} \cdot \frac{2m_M}{m_X}\left(\frac{t_c}{t}\right)^2, \tag{3}$$

where $m_M \sim \alpha_{GUT}^{-1} m_X \sim 45 m_X$; t_c is the collapse time of the monopolonium and the last factor takes into account the dilution due to the evolution of the Universe.

I will examine two different cases: $t_c = 4.6 \times 10^{11}$ sec, for a collapse mainly happening during the matter dominated epoch and $t_c = 4.6 \times 10^8$ sec for a collapse during the radiation dominated epoch; finally, t_0 is the present age of the Universe ($t_0 \sim 4.408 \times 10^{17}$ sec).

The collapsing monopolonium density can be expressed as a fraction $\alpha(t)$ of the formation density:

$$\frac{dn^c_{M\overline{M}}}{dt} = \alpha(t) \, < \sigma_b \, v > (t) \cdot n_M^2(t), \tag{4}$$

where $n_M(t)$ is the free monopole density and $< \sigma_b \, v >$ is the average product of the binding cross section times the thermal velocities of the monopoles:

$$< \sigma_b \, v > (t) \simeq \frac{\pi^{7/5}}{2}\,\frac{g_m^4}{m_M^2}\left(\frac{m_M}{T(t)}\right)^{9/10}. \tag{5}$$

The decay probability of the monopolonium is inversely proportional to the bound state lifetime, given by eq. (2); thus, one can reasonably take:

$$\alpha(t) \;=\; \left(\frac{t}{\tau}\right). \tag{6}$$

In such a way, $\alpha = 0$ for $t = 0$ and $\alpha = 1$ for $t = \tau$. The formation of TDs can be simulated on a cubic lattice, by identifying them with the zeros of the corresponding topological field, written in a gaussian form [7]. Then, the free monopole density geometrically calculated on-lattice is [7]

$$(n_M)_{lat} \;=\; \frac{3}{\pi^3\,\sqrt{2}\,r_0^3}. \tag{7}$$

2. THE UHECR FLUXES CALCULATION: RESULTS

For a CR particle a ($a = N$ for nucleons, $a = \gamma$ for gamma rays) one obtains the following injection spectrum [6]:

$$\Phi_a(E,t) \;=\; \frac{dn_X}{dt}\cdot\frac{2}{m_X}\,\frac{dN_a}{dx}, \tag{8}$$

where $x = 2E/m_X$, E is the injection energy and dN_a/dx is the specific fragmentation function describing the production of the particle a from quarks (see, for its detailed form, ref. [8]). Finally, the particle flux is commonly expressed as

$$E^3\;J_a(E,t) \;=\; \frac{E^3}{4\pi}\,\lambda(E)\;\Phi_a(E,t) \tag{9}$$

where $\lambda(E)$ is the absorption path length. At high energies, the energy loss rate for protons is mainly determined by the processes of pair and photomeson production and it is proportional to the energy. The resulting path, $\lambda = E/(dE/dt)$ is constant [9]: $\lambda_e = 1.504\times10^{22}$ m [10] and $\lambda_p = 1.530\times10^{16}$ m [11].

The gamma and proton fluxes obtained in such a calculation are shown in fig. 1 and 2 as a function of the energy: the gamma flux corresponding to the observations of Fly's Eye Experiment ($E_0^3 J_\gamma = 2\times10^{25}$ eV^2 m^{-2} sec^{-1} sr^{-1} at $E_0 = 3\times10^{20}$ eV [2,3]), is well reproduced for a collapse time $t_c = 4.6\times10^{11}$ sec and for a free monopole density $n_m = 1.82$ m^{-3}.

For the same density, comparable fluxes of protons are obtained only if we suppose the bulk of the monopolonia collapses happens at more recent times, namely $t_c = 4.6\times10^{14}$ sec. To conclude, the monopolonium decay might potentially be a good source for the otherwise unexplained UHECR: the most of the collapse events should happen more or less at the nucleosynthesis epoch in order to be effective in producing CR fluxes comparable with the recently observed Fly's Eye ones.

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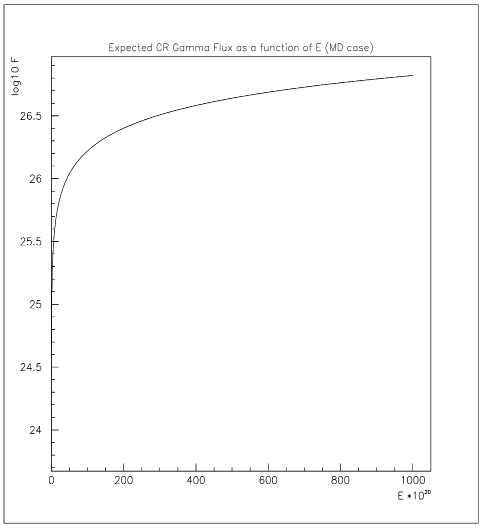

Figure 1. Expected Gamma Ray Flux as obtained from monopolonia decay; Vertical axis: $Log_{10}Flux$ (eV^2 m^{-2} sec^{-1} sr^{-1}); Horizontal axis: Energy ($\times 10^{20}$ eV); $t_c = 4.6 \times 10^{11}$ sec, $n_M = 1.82$ m^{-3}

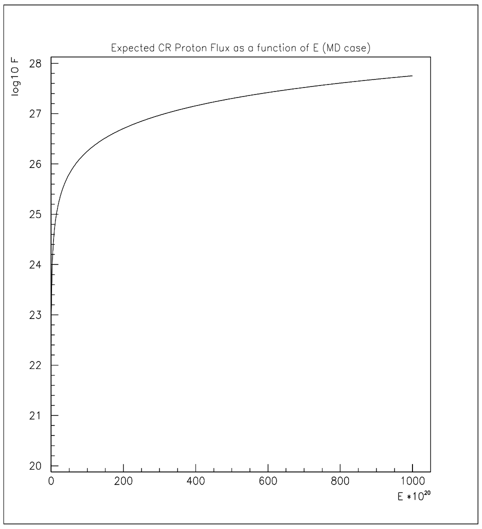

Figure 2. Expected Proton Flux as obtained from monopolonia decay; Vertical axis: $Log_{10}Flux$ (eV^2 m^{-2} sec^{-1} sr^{-1}); Horizontal axis: Energy ($\times 10^{20}$ eV); $t_c = 4.6 \times 10^{14}$ sec, $n_M = 1.82$ m^{-3}