511 keV Photons from Color Superconducting Dark Matter

David H. Oaknin and Ariel R. Zhitnitsky

Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada

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We discuss the possibility that the recent detection of 511 keV γ rays from the galactic bulge, as observed by the International Gamma-Ray Astrophysics Laboratory, can be naturally explained by the supermassive very dense droplets (strangelets) of dark matter. These droplets are assumed to be made of ordinary light quarks (or antiquarks) condensed in a nonhadronic color superconducting phase. The droplets can carry electrons (or positrons) in the bulk or/and on the surface. The e^+e^- annihilation events take place due to the collisions of electrons from the visible matter with positrons from dark matter droplets which may result in the bright 511 keV γ-ray line from the bulge of the Galaxy.

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Introduction.—The recent detection by the SPI spectrometer on the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite of a bright 511 keV γ-ray line from the bulge of the Galaxy with spherically symmetric distribution [1] has stirred the research of the fundamental physics that describes the cosmological dark matter.

The flux of 511 keV photons (with a width of about 3 keV), produced by thermalized electron positron pair annihilation processes, has been measured to be $9.9^{+4.7}_{-2.1} \times 10^{-4}$ photons $\text{cm}^{-2}\,\text{s}^{-1}$ and has an angular distribution with a half maximum at 9° (6° to 18° at 2σ confidence), in good agreement with previous measurements [2].

The source of these thermalized positrons in the bulge of the Galaxy has been the subject of much debate. Some proposals suggest astrophysical processes, including neutron stars or black holes [3], pulsars [4], radioactive nuclei from supernova [5] or cosmic ray interactions with the interstellar medium [6], but it is rather uncertain which fraction of positrons produced in such processes can escape and, moreover, how they could fill the whole galactic bulge [7].

Recently it has been discussed that light dark matter particles annihilating into e^+e^- pairs in the galactic bulge may be the source of the thermalized positrons that produce the 511 keV emission line [8]; see also related works [9–11]. The shallow density distribution of dark matter in the bulge of the galaxy $\rho(r) \sim r^{-\gamma}$, with $\gamma = 0.4$ to 0.8, explains very naturally the angular distribution of detected 511 keV γ photons.

Dark matter as color superconductor.—We want to elaborate the proposal [8] in the context of a cosmological scenario when dark matter consists of very dense (a few times the nuclear density) macroscopic droplets of ordinary light quarks (or/and antiquarks [12,13]) condensed in a nonhadronic color superconducting phase, similar to Witten's strangelets [14].

In this Letter we argue that color superconducting dark matter also provides a natural and simple framework to explain the detected emission of 511 keV photons from the galactic bulge with the appropriate angular distribution and intensity. Indeed, the main required ingredients of the proposal are automatically present in our scenario: a large number of positrons is always present in antimatter dark matter droplets; see below. We argued in [13] that chunks of quarks or antiquarks in a condensed color superconducting phase may be formed during the QCD phase transition, and they may serve as dark matter (DM). This scenario is based on the idea that while the Universe is globally symmetric, the antibaryon charge can be stored in chunks of dense color superconducting (CS) antimatter. In different words, the baryon asymmetry of the Universe may not necessarily be expressed as a net baryon number if the antibaryon charge is accumulated in the form of the diquark condensate in the CS phase, rather than in the form of free antibaryons in the hadronic phase. We explained in [13] why such a scenario does not contradict the current observational data on antimatter in the Universe. This is mainly due to the very small volume occupied by dense droplets and specific features of interaction between the color superconducting phase and conventional hadronic matter. We also argued that the observed cosmological ratio between the energy densities of dark and baryonic matter, $\Omega_{\text{DM}} \sim \Omega_B$ within an order of magnitude, finds its natural explanation in this scenario: both contributions to Ω originated from the same physics at the same instant during the QCD phase transition. As is known, the relation $\Omega_B \sim \Omega_{\text{DM}}$ between the two very different contributions to Ω is extremely difficult to explain in models that invoke DM candidates not related to the ordinary quark or baryon degrees of freedom. The baryon to entropy ratio $n_B/n_\gamma \sim 10^{-10}$ would also be a natural outcome in this scenario. We refer to the original papers [12,13] for the details. Here we want to mention only the fact that the baryon charge of massive droplets does not change the nucleosynthesis calculations because in the color superconducting phase it is not available for nuclearsynthesis when the baryon charge is locked in the coherent superposition of Cooper pairs. Therefore, while the massive droplets carry a large baryon charge, they do not contribute to Ω_B, but, rather, they do contribute to the "nonbaryonic" cold dark matter Ω_{DM} of the Universe [12,13].

Before we estimate the probability of the e^+e^- annihilation which results in the 511 keV line, we give a short review on the basic properties of dense droplets in a color superconducting phase, which is referred to as QCD balls [12,13] in what follows. The color superconducting state of quark matter is a novel phase in QCD that is realized when light quarks are squeezed to a density which is a few times the nuclear density. The ground state in this phase is a single coherent state with diquark condensation, analogous to Cooper pairs of electrons in the BCS theory of ordinary superconductors. In the approximation of three light quarks $m_u, m_d, m_s \ll \mu$ and relatively large chemical potential $\mu \gg \Lambda_{\rm QCD}$, the so-called color-flavor-locking (CFL) phase is a preferred state of matter; see original papers [15] and a recent review [16] on the subject. For the physical value of m_s and $\mu \simeq 500$ MeV a number of different CS phases may result. It is not the goal of this Letter to describe a variety of possibilities when parameters (such as m_s and μ) vary. Rather, we emphasize below that the sufficient number of positrons will always accompany the QCD balls made of antimatter (QCD antiballs).

Indeed, first of all, consider the most symmetric, the CFL phase. While this phase does not support the leptons in the bulk [17], the finite volume effects lead to the accumulation of the positive charge on the surface [18], which must be neutralized by negative electron charge (for droplets made of matter). For droplets made of antimatter, the corresponding positron charge will be accumulated. In most other phases which may be realized in nature, the leptons will be present on the surface as well as in the bulk of a droplet. The electron density can be roughly estimated as $n_e \simeq \frac{\mu_e^3}{3\pi^2}$, with μ_e being the electron chemical potential (in the case of matter droplets) or positron chemical potential in the case of antimatter droplets. In this case, the electrons (positrons) in droplets can be treated as a Fermi liquid. A numerical estimation of μ_e strongly depends on the specific details of the CS phase under consideration, and varies from a few MeV to tens MeV [19–21].

However, the important property that plays an essential role for the present work (and which is shared by all CS phases) is as follows. Consider an electron that hits the DM droplet (made of antimatter). What is the fate of this nonrelativistic electron? It can form a bound state (positronium with arbitrary quantum numbers $|n, l, m\rangle$) which eventually decays to two $\sim$511 keV photons. It may also annihilate with an energetic positron into two photons in nonresonance manner with emitting two γ's with a typical energy determined by μ_e (few MeV scale). However, the probability for the later annihilation is suppressed by a small coupling constant α^2, in comparison with the former process, when the probability for the formation of positronium from two nonrelativistic particles e^+ and e^- could be the order of 1. Indeed, the probability for the positronium formation (as well as for its decay to the free e^+e^- pair) if the system gets an instantaneous jolt (with relative momentum $q = mv$) is determined by the overlap of two wave functions $\sim |\langle\psi_{\rm out}|\psi_{\rm in}\rangle|^2 \sim |\int e^{-r/a} e^{i\vec{q}\vec{r}} d^3r|^2$ where $e^{-r/a}$ represents a typical positronium wave function in state $|n, l, m\rangle$ with $a \simeq 10^{-8}$ cm. Of course, this expression assumes the validity of the instantaneous perturbation theory when parameter $qa \gg 1$, while the maximum probability is achieved when $qa \simeq 1$; see below. It is obvious that the main contribution to the positronium formation is due to the process when the incoming electron picks up a positron from the droplet with a typical velocity determined by the condition $qa \sim 1$. This corresponds to $v/c \sim \alpha$ for a typical positronium size, $a \sim \hbar^2/me^2$. Eventually, it decays to two $\sim$511 keV photons. The flux of emitted photons produced by this mechanism will naturally have a width of order $\Gamma/(511\ \text{keV}) \sim v/c \sim \alpha \sim 10^{-2}$, which is what observations apparently suggest [1]. We note that the positronium formation (with a consequent emission of 511 keV photons) is expected to occur on the surface of the droplet such that a considerable portion of 511 keV photons leave the system without reabsorption.

To conclude, the annihilation cross section for the electron falling to the DM antidroplet is given by the geometrical size of the object, $4\pi R^2$, while a typical width of outgoing flux of 511 keV photons is of order $\Gamma \sim \alpha m \sim$ few keV. These features are very universal, do not depend on specific details of the phase under consideration, and remain unaltered for all possible CS phases. With these points in mind, we estimate the e^+e^- annihilation rate and the flux of 511 keV photons and compare it with the observational available data.

First rough estimate.—We start with a first estimation of the annihilation assuming that visible matter density follows the spatial distribution of dark matter, with the fixed ratio given by the cosmological $\Omega_B/\Omega_{\rm DM}$. We also assume that the electron density from the visible matter is roughly determined by the number density of protons. The system could be in an ionized state (HII) or in a neutral atomic hydrogen state. It is quite obvious that corresponding calculations lead to a strong underestimation of the annihilation rate because the visible matter is strongly peaked in the center of the galaxy, the effect which is completely ignored in our first estimate. The positive elements of such an assumptions are the following: (a) it allows us to follow closely the original analysis in [8], such that the spatial integration over matter density can be extracted from this Letter, and the corresponding comparison with [8] can be made; (b) it gives us a lower bound for the corresponding annihilation rate as argued above. More importantly, this lower bound depends only on a typical size of the droplets, and does not depend on the specific assumptions on behavior of visible matter density in the center of the Galaxy.

The estimation of the flux of 511 keV photons coming to Earth from the bulge of the Galaxy along the angular direction Ω goes as follows. As we mentioned above, the number of electrons is roughly determined by the number density of protons, $n_{e^-} \simeq n_B$, and all electrons which hit the QCD antiball (antidroplet made of antimatter) with radius R will annihilate such that a considerable portion of the process will lead to the production of two 511 keV photons. The probability per unit time $\frac{dW}{dt}$ that this happens in the presence of a single QCD ball is given by

$$\frac{dW}{dt} = 4\pi R^2 n_{e^-} v \simeq 4\pi R^2 n_B v \simeq 4\pi R^2 \frac{0.15\rho_{\rm DM}}{1\ {\rm GeV}} v, \quad (1)$$

where $v/c \sim 10^{-3}$ and we express the baryon density in terms of dark matter density, $(1\ {\rm GeV})n_B \simeq \rho_B \simeq \Omega_B/\Omega_{\rm DM}\rho_{\rm DM} \simeq 0.15\rho_{\rm DM}$ to make our first rough estimate. In order to estimate the probability of such events per unit volume per unit time $\frac{dW}{dVdt}$ one should multiply Eq. (1) by the inverse volume occupied by a typical QCD ball with a typical baryon charge B. In our framework when the dark matter is identified with QCD balls and antiballs with a typical mass $M \simeq m_N B$, the corresponding number density of the DM particles is nothing but $n_{\rm DM} \simeq \frac{\rho_{\rm DM}}{1\ {\rm GeV}} \frac{1}{B}$. Therefore, we arrive at the following estimate:

$$\frac{dW}{dVdt} \simeq 0.15 v \frac{4\pi R^2}{B}\left(\frac{\rho_{\rm DM}}{1\ {\rm GeV}}\right)^2. \quad (2)$$

The total flux of photons resulting from annihilation is obtained by integrating Eq. (2) over the line of sight and over the whole solid angle of observation. The numerical evaluation was done in [8]. We follow their analysis and implement it in our framework. We arrive at

$$\Phi = \int ds \int_{\Delta\Omega} d\Omega \frac{dW}{dVdt} \simeq (10^{-3}\ {\rm cm}^{-2}\,{\rm s}^{-1})\bar{J}(\Delta\Omega)\Delta\Omega\left(\frac{10^{18}}{B}\right)^{1/3}, \quad (3)$$

where $\bar{J}(\Delta\Omega)\Delta\Omega \equiv \int_{\Delta\Omega} d\Omega J(\Omega)$ with

$$J(\Omega) = \left(\frac{1}{0.3\ {\rm GeV/cm}^3}\right)^2 \frac{1}{8.5\ {\rm kpc}} \int ds[\rho_{\rm DM}(s)]^2. \quad (4)$$

In expression (3) we traded R from Eq. (2) in favor of $B \simeq \frac{4\pi R^3}{3} n_{\rm CS}$ assuming that a typical baryon number density in the color superconducting phase, $n_{\rm CS}$, is 3 times the nuclear saturation density, $n_{\rm CS} \simeq 3n_0$ with $n_0 \sim (108\ {\rm MeV})^3$.

The factor $J(\Omega)$ has been evaluated in Ref. [8] for different density profiles $\xi(r) \propto r^{-\gamma}$ with $\gamma = 0.4$–0.8 providing the best fit. For these favorite γ's the value $\bar{J}(\Delta\Omega)\Delta\Omega$ has been shown to vary in the range 0.3–1.6. This value should be substituted into Eq. (3) and compared with the observations, $9.9^{+4.7}_{-2.1} \times 10^{-4}$ photons $\rm cm^{-2}\,s^{-1}$.

As we mentioned above, we consider this estimate as the lowest extreme case (within our framework). Indeed, our assumption on visible matter density distribution, $\rho_B \simeq 0.15\rho_{\rm DM}$ with $\rho_{\rm DM} \sim r^{-\gamma}$ and $\gamma = 0.6$, normalized to the local density $\rho_{\rm DM} \simeq 0.3\ {\rm GeV/cm}^3$ would lead to the total visible material (within 8.5 kpc region) of about $(4 \times 10^9)M_\odot$ instead of the observed $\sim 10^{11} M_\odot$.

Nevertheless, this simple estimate is very instructive. First of all, one can explicitly compare our expression (3) with the corresponding formula from Ref. [8] when the same factor describing the DM distribution, $\bar{J}(\Delta\Omega)\Delta\Omega$, enters the relevant formulas. Second, even the obviously underestimated expression (3) is not in contradiction with the existing bound on this kind of dense droplets; see Eq. (20) in Ref. [12] where bound $B > 10^{20}$ is quoted.

Unaccounted effects; further complications.—Here we discuss some new effects (ignored above) that certainly increase the rate. Unfortunately, the corresponding estimates are strongly model dependent (see below) and, therefore, should be taken with some caution. First, let us take into account the properties of the visible matter distribution in the galaxy in a more appropriate way than it is done above. We replace formula (2) by the following expression:

$$\frac{dW}{dVdt}(r) \simeq \frac{4\pi R^2}{B} v\left(\frac{\rho_B}{1\ {\rm GeV}}\right)\left(\frac{\rho_{\rm DM}}{1\ {\rm GeV}}\right). \quad (5)$$

The number density of electrons and the number density of dark matter particles are estimated as before, $n_{e^-} \sim n_B \simeq (\frac{\rho_B}{1\ {\rm GeV}})$, $n_{\rm DM} \simeq \frac{\rho_{DM}}{1\ {\rm GeV}} \frac{1}{B}$. We parametrize DM density as

$$\rho_{\rm DM} \simeq 0.03 \frac{M_\odot}{{\rm pc}^3} \frac{1}{(r/{\rm kpc})^{0.6}}, \quad (6)$$

normalized to the local density $\rho_{\rm DM} \simeq 0.3\ {\rm GeV/cm}^3$, which is the central value adopted by [8]. For the visible matter we adopt the following scaling behavior (close to the r^{-2} behavior of an izothermal sphere [22]):

$$\rho_B \simeq 0.7 \frac{M_\odot}{{\rm pc}^3} \frac{1}{(r/{\rm kpc})^{1.8}}, \quad (7)$$

normalized to the total visible mass of $M_{\rm tot} = \int^{8.5\ {\rm kpc}} d^3x \rho_B \simeq 10^{11} M_\odot$ within 8.5 kpc. We notice that such a peaked distribution of visible matter would, in principle, produce a narrower distribution of 511 keV photons than is currently preferred by observational values, $\frac{dW}{dVdt}(r) \sim r^{-2\gamma}$, with γ between 0.4 and 0.8 [8]. However, if we take $\gamma \simeq 0$ for the dark matter, the angular distribution that follows from Eqs. (5) and (7) would be close to the upper bound of the preferred value [8].

Combining Eqs. (5)–(7) we arrive at the following final expression for the flux:

$$\Phi = \int dr \Delta\Omega \frac{dW}{dVdt} \simeq 10^{-3}\ {\rm cm}^{-2}\,{\rm s}^{-1}\left(\frac{10^{33}}{B}\right)^{1/3}. \quad (8)$$

In obtaining the estimate (8) we cut off the integral $\int_{0.5\ {\rm pc}}^{8.5\ {\rm kpc}} dr$ at 0.5 pc at small distances where the visible matter rises very fast $\sim r^{-2.7}$ while the DM behavior at such scales is absolutely unknown. Such a cutoff obviously brings a large uncertainty into our estimate. There is also a large uncertainty due to the unknown scaling properties of the dark matter distribution at small distances. Finally, different clumps and structures (such as stars, massive compact halo objects, asteroids, etc.) of the baryonic matter can strongly enhance the estimate (8) due to the fact that a large number of positrons from the bulk (rather than from the surface) of the QCD balls can participate in annihilation. Unfortunately, we do not know how to account for this effect properly. The main goal here is to demonstrate the sensitivity of the calculations with a variation of the visible and DM distributions: the difference between two estimates, (3) and (8), is almost 5 orders of magnitude.

Conclusion.—The main goal of this Letter is to argue that the color superconducting dark matter (introduced with a quite different motivation [12,13]) provides a natural and simple framework to explain the detected emission of 511 keV photons from the galactic bulge with the appropriate angular distribution and intensity. While there are many other possibilities to explain this rate based on some specific DM features, such as annihilation or decay, the present proposal is unique in many respects and can easily be discriminated from other explanations based on DM particles. Indeed, a unique feature of our scenario is proportionality of the local flux of photons to the density of both the visible and the dark matter; see Eq. (5). In other DM based explanations the local flux does depend only on the distribution of dark matter. The corresponding matter distributions are obviously very different. In particular, an observation of the effect on the same level but in a different direction (not pointing to the center of the galaxy) would rule out our explanation.

We also point out that $\bar{q}q$ annihilation might be sufficiently large for relatively energetic protons (with kinetic energy about 1 GeV) [13]. In this case e^+e^- annihilation with a single bright 511 keV line (discussed in this Letter) is accompanied by the wide (70 MeV–1 GeV) γ spectral density due to the baryon-antibaryon annihilation. These very different spectra in different frequency regions must be related to each other due to their common origin. Corresponding calculations are beyond the scope of the present work; however, a very simplified estimate of the corresponding flux can be obtained by replacing the electron velocity v in formula (5) by a proton velocity $v_p/v \sim \sqrt{m_e/m_p} \sim 2 \times 10^{-2}$ [23]. This corresponds to the assumption of the thermal equilibrium between electrons and protons in the ionized region in the bulge of the galaxy (the HII has a vertical scale height of $\sim$90 pc [22]). Estimated in such a way, flux is definitely not in immediate contradiction with observations, where some access of γ rays, indeed, has been observed by Energetic Gamma Ray Experiment Telescope. We add that the observed access has been interpreted in [24,25] as due to the dark matter annihilation, and in [26] as due to $p\bar{p}$ annihilation. One more phenomenological consequence of the suggested scenario is that baryon-antibaryon annihilation which always accompanies the 511 keV line eventually may be responsible for a ‘‘nonobservation’’ of the cusp behavior near the Galactic Center. It might be worthwhile to investigate this possibility in more detail in the future.

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