“Cosmic Rays” from Quark Matter

Kyle Lawson
University of British Columbia

Abstract. I describes a dark matter candidate based in QCD physics in which the dark matter is composed of macroscopically large “nuggets” of quark and anti-quark matter. These objects may have a sufficiently massive low number density to avoid constraints from direct detection searches. Though not “baryonic” in the conventional sense quark matter is strongly interacting and will produce a clear signal in ground based detectors. As the prospects of detecting these objects are mainly limited by the detector cross-section large scale cosmic ray detectors are a promising search platform. To this end I describe the basic properties of the air shower induced by the passage of a quark nugget through the earth’s atmosphere. It will be shown that this shower is similar in several important ways to the shower induced by a single ultrahigh energy cosmic ray.

1. Introduction
It is now well established that our galaxy contains roughly five times more dark matter than it does visible matter. While the large scale properties of the dark matter are well described in ΛCDM cosmology there is at present no generally accepted microscopic model. In the absence of a suitable particle within the standard model the majority of dark matter candidates represent new fundamental particles, the properties of which are poorly constrained. An alternatively class of models exists in which the dark matter is a composite object composed of the known standard model quarks in a novel phase such as strange quark matter or a colour superconducting phase. In these models the dark matter forms in the early universe (most likely at the QCD phase transition) and remains “dark” due purely to its small cross-section to mass ratio. To avoid observational constraints from both cosmology and direct searches these object mass carry a baryon number of at least $10^{25}$ corresponding to a minimum mass of roughly a gram. At nuclear densities a nugget of this mass has a physical cross section of $10^{-5}$cm.

Here I will focus on a particular composite dark matter scenario [1] motivated by the seemingly unrelated problem of matter/antimatter asymmetry. While microscopic physical laws treat matter and antimatter identically it is observed that the universe contains almost exclusively matter. The mechanism responsible for generating this baryon excess is not presently known. In the scenario considered here dark matter forms out of ordinary quarks and antiquarks at the QCD phase transition. During the phase transition $CP$ violation results in a preferential formation of nuggets of antimatter and thus the visible matter (which is not compressed into nuggets) is left with a matter excess. The observed matter to dark matter ratio requires that nuggets and anti-nuggets occur in a roughly two to three ratio.

A full description of the formation dynamics requires a careful treatment of strongly coupled QCD near the phase transition which is not tractable beyond very basic arguments at this time. Constraining this models is much easier by taking an observational perspective, once formed
and cooled below the phase transition the nuggets are well described by known many-body and nuclear physics allowing quite specific predictions to be made.

The small number density of quark nuggets required to explain the observed dark matter mass density renders them invisible to the majority of ground based searches which are instead targeted towards the detection of WIMPS with masses many orders of magnitude smaller. Large scale cosmic ray detectors, such as the Pierre Auger Observatory, are among the only experiments with a sufficiently large cross-section to impose constraints on quark nuggets within the mass range on interest. From a combination of theoretical and observational considerations the nuggets are believed to carry a baryon number in the range from $10^{24}$ up to $10^{30}$ and have a density similar to that of ordinary nuclear matter.

2. Flux
Baring any significant deviations from galactic averages the dark matter has a local density of roughly $1.5 \text{ GeV/cm}^3$ and a velocity distribution centred on the virial speed of $\sim 300 \text{km/s}$. This implies that if the nuggets carry a baryonic charge $B$ the observed flux at the earth’s surface will be

$$\Phi \approx B^{-1}10^{25}\text{s}^{-1}\text{km}^{-2}$$

Here it is assumed that only antimatter nuggets will produce observable consequences in a cosmic ray detector and that the mass per baryon of quark matter is not substantially different from than in nuclear matter. In the case of a matter nugget only kinetic energy is deposited in the atmosphere. The collisions are not sufficiently energetic to produce significant air fluorescence or eject substantial numbers of charged particles from the tightly bound nugget.

3. Air Shower Properties
An antimatter nugget striking the earth’s atmosphere will release a significant amount of energy primarily through nuclear annihilations. Much of this energy thermalizes within the nugget however some fraction will be released into the atmosphere in the form of high energy photons or muons emitted by the various nuclear reactions. The resulting air shower is phenomenologically similar to that induced by a single ultra high energy cosmic ray. This is due to the simple fact that the shower is triggered by a large number of hadronic interactions that cascade down to the QCD scale. The development of the resulting air shower is determined by the microscopic interactions between the nugget and the molecules of the atmosphere. Here I will attempt to give a qualitative overview of these interactions.

When an atmospheric molecule strikes the quark nugget it must first pass through a layer of electromagnetically bound positrons present in all known forms of quark matter and referred to as the electrosphere. Here the electrons of the molecule annihilate producing gamma rays. The remaining fully ionized nuclei then penetrate into the quark matter where they annihilate. This annihilation results in jets of primarily light mesons which stream away from the annihilation site. As the collision is non-relativistic half of the energy will be directed back towards the nugget’s surface while the remainder thermalizes within the nugget’s interior. Much of the energy carried by the surface directed jets will cascade down to the positrons bound to the quark matter which are the lightest available modes. These positrons are ejected from the surface and slowed by the strong surface electric fields. They rapidly lose their kinetic energy which is emitted as a hard x-ray bremsstrahlung spectrum. Some fraction of the mesons originally produced in the annihilation will also reach the quark matter surface. Being strongly interacting they will be unable to escape from the quark matter and will scatter off the surface. This process can result in the emission of a muon through induced beta decay of the meson. Bremsstrahlung emission from these muons is less efficient than from similarly produced positrons and they will be able to escape from the nugget. In fact these are likely to be the only charged particles able to travel a large distance into the atmosphere and, as such, will dominate the air shower.
While the temperature remains low the number of muons produced will be proportional to the density of air that the nugget is traveling through. As stated above positron excitations are favoured over muon production. The number of muons produced per annihilation will depend on the exact details of the quark matter surface but is generically less than one. The muon energy spectrum is also dependent on the exact phase of quark matter of which the nugget is composed. The majority of muons will leave the nugget with energies near the plasma frequency of the quark matter, over a wide range of quark matter phases this is predicted to be at the tens of MeV level. Muon energies may be as high as a few GeV but, as they arise from low energy proton annihilations will certainly not exceed this level.

4. Shower maximum

As discussed above a significant fraction of the annihilation energy is thermalized within the nugget. The thermal evolution of the nugget is thus determined by the balance between energy deposition through annihilation and thermal radiation from the electrosphere. The thermal emission spectrum from the positrons of the electrosphere has been previously calculated for independent reasons. When applied in this context it allows for the calculation of temperature as a function of surrounding matter density.

At low temperatures electron positron annihilation happens primarily through an intermediate positronium resonance. While this process is operating annihilation proceeds rapidly and the incoming atmospheric molecules are ionized almost immediately. However, once the temperature exceeds the positonium formation threshold the resonance channel is no longer available and annihilation must occur through the much slower direct annihilation process. At low momenta elastic scattering through soft photon exchange is preferred to annihilation. As such, an incident molecule experiences a thermal pressure as it moves through the low density outer layers of the electrosphere. This pressure grows proportionally to the temperature, which is in turn established by the annihilation rate. This feedback results in an equilibrium rate at which matter can be feed onto the quark surface. The equilibrium temperature generically lies between the positronium energy scale \((m_e\alpha \sim \text{keV})\) and the electron mass \((m_e = 511\text{keV})\) where the annihilation and elastic scattering amplitudes become comparable. Numerically the rapid fall off of positronium formation with energy favours the lower end of this energy range and equilibrium is reached in the few tens of keV range. For a quark nugget moving at typical galactic velocities this occurs at a height in the atmosphere near ten kilometers. Beyond this atmospheric depth the shower will no longer increase in size.

5. Conclusion

Large area cosmic ray detectors have the ability to impose constraints on heavy composite dark matter models. In the class of these models where the dark matter has an antimatter component hadronic interactions with the atmosphere will induce an extensive air shower similar to that produced by a single high energy cosmic ray. The computation of the full properties of the air shower will require numerical simulations similar to those required for standard cosmic ray shower but are, in principle, fully tractable as they depend only on well understood nuclear interactions at energy scales that are both theoretically and experimentally accessible.

References

[1] Zhitnitsky A R 2003 JCAP 10 010 (Preprint arXiv:hep-ph/0202161)