A Signature of Colour-Superconducting Dark Matter?

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Abstract. I describe a novel dark matter candidate in which the dark matter is composed of macroscopically large “nuggets” of ordinary quarks and antiquarks in a colour-superconducting phase. The physical properties of these objects are described entirely by QCD and the principles of condensed matter physics. An understanding of these properties allows for predictions of their interactions with the ordinary visible matter of the galaxy and leads to several testable consequences of the model. The spectrum arising from these interactions is entirely fixed by quite general predictions about the structure of dense quark matter and allows for no tuning of parameters. In this talk I present the results of a detailed Thomas-Fermi calculation which demonstrates the plausibility that the annihilation of galactic matter incident on a dark matter nugget may be responsible for both the galactic 511 keV line and a broad MeV scale continuum present in the galactic spectrum measured by COMPTEL.

1. Introduction
The dominant fraction of the mass of the galaxy is comprised of dark matter which dominates over the visible matter by a ratio of 5:1. To this point there is no accepted theory as to the microscopic composition of dark matter though a wide range of theories have been proposed. The standard model contains no particle with the correct properties to account for the dark matter. Therefore, if dark matter does represent a fundamental particle it will necessarily require the expansion of the field content of the standard model. Here I discuss an alternative possibility in which the dark matter is not a new fundamental field but is instead a composite object carrying a baryonic charge in the range $10^{20} - 10^{30}$. In this model baryogenesis occurs through a charge separation mechanism occurring at the QCD phase transition which compresses quarks and antiquarks into dense colour-superconducting (CS) nuggets. This nugget formation mechanism is slightly more efficient for antiquarks than for quarks. As there are more antiquarks locked up in the CS nuggets there will be a corresponding excess in free quarks which then hadronize making up the visible matter of the universe while the nuggets comprise the dark matter. While governed entirely by QCD physics, the details of nugget formation are strongly dependent on the phase structure of high density QCD which is not well understood at present [1]. Rather than attempting to directly calculate the details of nugget formation I instead take a phenomenological point of view. Under the assumption that the observer dark matter density is entirely in the the form of CS quark matter several non-trivial tests of the model may be made based on emissions which must necessarily accompany these objects. Many of the results of this work are based on [2] and [3] which should be consulted for further details.
2. Nugget Properties
As mentioned above the properties of the dark matter nuggets will be determined entirely by
QCD physics. However, the complexity of the calculations involved leave several properties highly
uncertain. Fortunately, numerical studies of the properties of high density quark matter allow
us to make several statements about the interaction spectrum of these objects which are largely
independent of the precise details.

2.1. Colour-Superconductivity
At asymptotically large densities the ground state of QCD is not nuclear matter but a phase in
which the quarks condense into Cooper pairs. Matter in this phase is referred to as a colour-
superconductor and is conceptually similar to conventional superconductivity. The formation of
quark Cooper pairs favours equal numbers of up and down quarks and thus the quark matter will
carry a net electric charge, positive in the case of quarks and negative in the case of antiquarks.
Electrical neutrality is enforced by the presence of leptons (either electrons or positrons.)
While the quark matter surface is very sharp, its scale being set by strong force interactions and
thus at the fermi scale, the leptons are only electromagnetically bound and are thus distributed
over a larger region. In astrophysical contexts such a layer of leptons is referred to as an
electrosphere. While the exact value depends on the phase of quark matter realized the lepton
chemical potential near the quark surface is quite generally in the range from $\mu_0 \sim 10^{-100}$ MeV.
From the surface the lepton chemical potential will extrapolate to zero far from the nugget.

2.2. Dark Matter
The idea that dark matter, with its evidently small interaction rates, could be composed of
macroscopic, strongly interacting objects may seem counterintuitive. In this model it is not the
small interaction cross section that makes the nuggets “dark” but the very small number densities
required to explain the observed dark matter density. The scale of all observable properties will
be proportional to the number density of the nuggets which is small enough to avoid most
observational constraints even if they are near the lowest possible mass (and therefore largest
number density.) The very low number densities make the prospects for earth based detection
with all but the largest detectors unlikely.

3. Emission Mechanisms
The primary observational signatures of this dark matter model will be photons produced by
the annihilation of visible galactic matter with the components of the antiquark nuggets. As
discussed above these emission mechanisms will be strongly suppressed by the small nugget
number density. It is only in regions where both the visible and dark matter densities are large
that a detectable signature may be found. As such, the galactic centre is the most likely source
for emissions with a flux large enough to be detectable.

In the following sections I will discuss the emission spectrum resulting from the annihilation
of galactic electrons in the electrosphere of an antiquark nugget. This process has the benefit of
being governed by simple QED physics from which a clear spectrum can be extracted. However,
in order to describe the resulting annihilation spectrum it is necessary to first determine the
properties of the electrosphere.

3.1. The Electrosphere
The density of leptons near the surface of the quark nugget will be determined by balancing the
electrical attraction of the leptons to the surface with the degeneracy pressure which supports
the electrosphere. The electric potential will satisfy the Poisson equation,

$$\nabla^2 \phi(r) = -4\pi en(r).$$ (1)
Where \( n \) is the lepton number density. The charge distribution must be supported by
degeneracy pressure such that \( e\phi(r) = -\mu(r) \). The expressions [1] combined with the Fermi
distribution expression for lepton number density may be solved numerically in the Thomas
Fermi approximation to obtain a mean field density distribution for the electrosphere. The
full details of this calculation are beyond the scope of this work but are presented in [3]. The
important conclusion of this calculation is that there will exist a relatively large region of the
electrosphere (roughly equivalent to the radius of the nugget itself) in which the leptons have
densities at the atomic scale and non-relativistic velocities. Very near the quark surface the
leptons will have ultrarelativistic momenta and large densities related to the length scale \( \mu^{-1} \).

3.2. Positronium Formation
If the centre of mass momentum between the incident galactic electron and the electrosphere
positron is sufficiently small the most likely annihilation channel is through an intermediate
state positronium. This positronium atom then decays through either a pair of back to back 511
keV photons or a three photon continuum the details of which are well understood. At leading
order the wavefunction overlap between an incident \( e^+e^- \) pair with centre of mass momentum
\( q \) and a positronium atom is \((1 + \frac{q}{m\alpha})^{-4}\). So that the rate of positronium formation falls off
rapidly with growing momentum, note that the characteristic momentum scale for this fall off
is \( m\alpha \). The exact cross section for positronium formation does not have a simple analytic
expression and requires a numerically complicated summation over all positronium excitation
levels. For present purposes it will suffice to note that the typical length scale of a ground state
positronium atom is the Bohr radius obtained by solving the Schrodinger equation for an \( e^+e^- \)
bound state, \( a_{Ps} = \frac{2}{m\alpha} \). This length scale gives a reasonable estimation for the formation cross
section. Combining this expression with the density distribution of the electrosphere allows for
the calculation of the strength the 511 keV line produced by galactic electrons incident on a dark
matter nugget. However, the scale of this spectrum depends on the rate of collisions between
visible and dark matter averaged along a given line of sight. This number is sensitive to the
total baryonic charge of the nuggets and the exact distribution of galactic dark matter both of
which are highly uncertain.

3.3. Direct Annihilation
As a galactic electron approaches the quark matter surface the positrons it encounters carry an
ever larger momentum and positronium formation becomes disfavoured. Instead annihilation
occurs through the direct \( e^+e^- \rightarrow 2\gamma \) channel described by a simple QED calculation. Again
the annihilation cross-section and rate may be calculated in order to determine the resulting
spectrum. The details of this spectrum were presented in [2], for this work the only necessary
details are that the spectrum covers a large range from below the electron mass up to the
chemical potential at the level where annihilation occurs. It should be noted that once the
chemical potential becomes larger than \( \sim 20\text{MeV} \) the annihilation rate becomes large enough
that virtually no electrons are able to penetrate any deeper. Thus, even if the surface chemical
potential is much larger (even above the largest predicted values of \( \sim 100\text{MeV} \)) the annihilation
spectrum will still have a maximum energy well below this level. The only unknown parameter
appearing in the resulting spectrum is the total line of sight rate of collisions between visible
and dark matter which also appeared in the positronium spectrum. While the present data does
not allow for a prediction of the magnitude of the spectrum it does allow the prediction of the
relative strengths of the 511 keV line and the direct annihilation continuum.

4. Observations
The INTEGRAL satellite has measured the flux of 511 keV photons from the galactic centre [4].
This flux is found to be strongly correlated with the galactic bulge with possible evidence for a
significantly weaker disc component. Along the line of sight of the galactic centre the observed flux is measured to be $\frac{d\Phi}{d\Omega} \simeq 0.025$ photons cm$^{-2}$s$^{-1}$sr$^{-1}$ [4]. Known astrophysical processes seem unable to explain the observed strength. The situation with emission in the MeV range is more complicated than that of the 511 keV line. This energy range has been observed by the COMPTEL satellite but with a lower energy resolution. While some background processes in this range are easily understood others, particularly cosmic rays scattering off the interstellar medium have much larger uncertainties. When the spectrum predicted from cosmic ray and astrophysical processes is subtracted from the COMPTEL data there seems to remain an unexplained diffuse component of the spectrum associated with the galactic centre [5].

5. Results

If both the 511 keV line and the diffuse MeV continuum have as their origin the annihilation of galactic electrons within the electrosphere of an antiquark nugget then several correlations must exist between these seemingly unrelated spectral features. The two sources must be spatially correlated though current data does not allow for any strong statements on such a relation. More interestingly the total magnitude of the two emission sources must be related by the branching fraction between positronium formation and direct annihilation. This fraction may be evaluated by averaging the annihilation rates for each process over the electron’s path through the electrosphere. Numerically this gives an MeV continuum with roughly one tenth the total intensity as the positronium decay spectrum. When we use this value to set the scale of the MeV spectrum the result provides a remarkably good fit to the COMPTEL data.

6. Conclusions

If the dark matter is composed of nuggets of colour-superconducting quark matter than many of its properties can be determined based on well understood physical principles. In particular the structure of the surrounding electrosphere may be determined based on calculations in QED and condensed matter physics. Once this structure is established the emission spectrum resulting from the annihilation of galactic electrons immediately follows. Both the spectral density and the branching fraction between positronium formation and direct annihilation are entirely fixed with no tunable parameters. Only the overall scale of the emission remains undetermined due to large uncertainties in both current data and theory related to high density QCD. The assumption that the observed galactic 511 keV line is associated with positronium formation and subsequent decay allows us to fix the net annihilation rate and the net strength of MeV scale continuum. It is found that the resulting spectrum falls precisely in the 1-30MeV range where the COMPTEL data seems to require a new emission source. If the predicted MeV emission scale had been found to be any larger or spread over a wider energy range this model would have been immediately ruled out. Instead, the COMPTEL data would seem to require a new emission source with precisely the amplitude and energy distribution generated from electron annihilation in the quark nugget dark matter scenario. Higher resolution data and a better understanding of astrophysical backgrounds will allow for further testing of this model. In particular both the 511 keV line and the MeV continuum should be found to have the same spacial distribution corresponding to the product of the visible and dark matter densities.

References

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