Pico-charged intermediate particles rescue dark matter interpretation of 511 keV line

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Situation today

- From CMS and ATLAS: Higgs discovery but nothing more
- Some news from LHCB
- Neutrino physics: Overall picture is consistent with $3 \times 3$ oscillation paradigm
- Dark matter
XENON collaboration, 1705.06655

Competitive result from PANDAXII, 1708.06917
Why simplest dark paradigm should be true?
SM as clue

- SM sector is sophisticated and non-trivial with a very rich phenomenology
Indirect dark matter searches

- Searching for stable product from dark matter annihilation or decay such as
  - photons
  - positrons
  - antiproton
  - antihydrogen
  - neutrinos
  - .....

Indirect dark matter searches

IceCube Lab

50 meters

1,450 meters

2,450 meters

2,820 meters

IceCube Array
86 strings, 60 sensors each

AMS-02

Alpha Magnetic Spectrometer

Europe • Asia

North America
Hints for DM from indirect search

- Signals that went away with further data: 130 GeV line observed by Fermi-LAT

- Signals that stay robust but go “out of fashion”: PAMELA Signal, INTEGRAL 511 keV line
PAMELA and AMS02 positron excess
511 keV

- It has been observed for more than 40 years
- Leventhal et al., 1978
- $e^-e^+$ annihilation
INTEGRAL

INTErnational Gamma-Ray Astrophysics Laboratory

Launched in 2002

SPI at INTEGRAL of ESA

Angular resolution: 2°

Energy resolution: 2 keV
Spectrum

- Total
- Narrow line
- Broad line
- OrthoPs
- Power law

• SPI 2004 public data

$58\sigma$ C.L.

Va’vra, 1304.0833
Morphology of the line

Distribution of the line as observed by INTEGRAL/SPI: ESA/Bouchet et al.
Flux

Siegert et al., arXiv:1512.00325

\[(0.96 \pm 0.07) \times 10^{-3} \text{ph cm}^{-2} \text{sec}^{-1}\]
Some alternative scenarios

- Radioactive decay: $^{56}\text{Ni}$  $^{44}\text{Ti}$  $^{13}\text{N}$  $^{26}\text{Al}$
- Accreting binary sources
- Pulsars
- Supermassive blackhole
Dark matter explanation


- Dark matter mass \( \sim \) few MeV

\[
\sigma(X + X \rightarrow e^- e^+) \sim 10^{-4} pb
\]
Delayed recombination

- Reionization → rescattering CMB photons

- Broadening last scattering surface

- Suppression of temperature and polarization correlation on small scales (large multipoles)

- Late time Thompson scattering → enhanced polarization correlation at large scales
Bounds from CMB

Wilkinson, Vincent, Boehm and McCabe, PRD 94 (2016)
Can p-wave annihilation rescue the DM explanation?

\[ \sigma(X + X \rightarrow e^- e^+) = (10^{-4} \text{ pb})v^2 \]

- At galaxy: \(10^{-3} \gg \) velocity at recombination

At freeze-out time:

\[ \sigma(X + X \rightarrow e^- e^+) = 10 - 100 \text{ pb} \]

suppressed relic density
Our scenario

- YF and M Rajaee, arXiv:1708.01137

\[ X \rightarrow C\bar{C} \quad C\bar{C} \rightarrow e^- e^+ \]

- The velocity of \( C \) will be above escape velocity.
Galactic magnetic field

Sun et. al 2008
The magnetic fields of our galaxy, the Milky Way

The main magnetic field structure lies in the plane of the disc and follows the spiral arms.

- The red arrows are in the opposite direction to the black ones – i.e. the magnetic field is reversed.
- There is also a toroidal and a poloidal magnetic field (not shown)
Larmour radius

\[ r_L = 5 \text{ pc} \times \left( \frac{3 \times 10^{-11}}{\xi} \right) \left( \frac{m_X}{5 \text{ MeV}} \right) \left( \frac{10 \text{ } \mu\text{Gauss}}{B} \right) \]

\[ (8 \text{ kpc}) \times \sin(2^\circ) = 280 \text{ pc} \]
We need a mechanism for energy loss.

The same mechanism that gives charge to C particles also provides a mechanism for cooling.

\[ U(1)_X \times SU(2) \times U(1)_Y \rightarrow U(1)_{em}, \]

• Stueckelberg mechanism

\[
- \frac{X_{\mu \nu} X^{\mu \nu}}{4} - \frac{\delta}{2} X_{\mu \nu} B^{\mu \nu} - (\partial_\mu \sigma + M_1 X_\mu + M_2 B_\mu)^2
\]

\[ \epsilon = \frac{M_2}{M_1} \ll 1 \quad \text{and} \quad \delta \ll 1 \]

Dark photon, \( \gamma' \), mainly composed of \( X_\mu \)
A particularly interesting limit


\[ \delta = \epsilon \rightarrow \text{Decoupling of the sectors} \]

\[ q = \frac{g}{\epsilon} \rightarrow \text{Standard SU(2) coupling} \]

Electric charge of C particles
A particularly interesting limit


$$\delta = \epsilon \quad \text{Decoupling of the sectors}$$

$$q = \frac{g}{\epsilon} \quad \text{Standard SU}(2) \text{ coupling}$$

Electric charge of C particles

For $\delta \neq \epsilon$ still $q \propto \max[\epsilon, \delta]$
A particularly interesting limit


\[ \delta = \epsilon \rightarrow \text{Decoupling of the sectors} \]

\[ q = \frac{g}{e}\epsilon \]

Dark photon mass arbitrary given by \( M_1 \)

No tree level coupling between \( \gamma' \) and SM fermions
Decay of Dark photon

- kinetically available decays modes for keV dark photons $\gamma \gamma$, $\gamma \gamma \gamma$, $\nu \bar{\nu}$
- Landau-Yang theorem $\gamma' \rightarrow \gamma\gamma$

$$\Gamma_{\gamma'} \sim m_{\gamma'} \frac{g_X^2 q^6}{4\pi (16\pi^2)^2}$$

$$\tau = 7 \times 10^{45} \text{ years} \gg 10 \text{ Gyr}$$

$$\sim m_{\gamma'} \left( \frac{m_{\gamma'}}{m_{Z'}} \right)^2 \frac{g_X^2 q^4}{4\pi (16\pi^2)^2}$$
C and γ' production in early Universe

\[ e^+ e^- \rightarrow C \bar{C} \]

\[ \frac{\dot{n}_C H^{-1}}{n_\gamma} = 5 \times 10^{-5} \left( \frac{q}{10^{-11}} \right)^2 \]

\[ \dot{n}_C + 3H n_C = -\langle \sigma(C \bar{C} \rightarrow \gamma' \gamma')v \rangle n_C^2 \]

\[ n_C = \frac{T^3}{M_{Pl}^* \langle \sigma(C \bar{C} \rightarrow \gamma' \gamma')v \rangle m_C} \text{ at } T \ll m_C. \]

\[ \frac{n_{\gamma'}}{n_\gamma} = 10^{-4} \left( \frac{q}{10^{-11}} \right)^2 \]

\[ n_{\gamma'}/n_\gamma < 0.1 \text{ which implies } q < 3 \times 10^{-10} \]
Range

\[ 10^{-11} < q < 3 \times 10^{-10} \]

\[ 10 \text{ eV} < m_{\gamma'} < 10 \text{ keV} \]

BBN: \[ \frac{n_{\gamma'}}{n_{\gamma}} < 0.1 \]

Non-relativistic at recombination

Subdominant dark matter component
Dark photon concentration in galaxy

\[ n_{\gamma'}|_{GC} = \frac{\rho_{DM}|_{GC}}{\langle \rho_{DM} \rangle} \langle n_{\gamma'} \rangle. \]

\[ \rho_{DM}|_{GC} \sim 3 \text{ GeV cm}^{-3} \quad \Rightarrow \quad n_{\gamma'} \sim 10^5 (q/10^{-11})^2 \text{ cm}^{-3} \]

\[ \Delta E_C = m_{\gamma'} \left( \frac{E_C}{m_C} \right)^2 v^2 \quad \Rightarrow \quad \sigma_s \sim 3 g_X^4 / (4\pi m_C^2) \]

\[ \tau_E = \int_{m_C(1+\nu_f^2/2)}^{m_C/2} \frac{dE_C}{\Delta E_C} \frac{1}{\sigma_s \nu_m \gamma_{\nu}}|_{GC} \approx 100 \text{ Myr} \left( \frac{m_C}{5 \text{ MeV}} \right)^3 \left( \frac{10 \text{ keV}}{m_{\gamma'}} \right) \left( \frac{0.03}{v_f} \right) \left( \frac{0.15}{g_X} \right)^4 \left( \frac{10^5 \text{ cm}^{-3}}{n_{\gamma'}} \right) \]

\[ \tau_E \text{ is given by } (n_{\gamma'} m_{\gamma'})^{-1} \]

\[ v_f = 0.3 \left( \frac{0.15}{g_X} \right)^4 \left( \frac{10^4 \text{ cm}^{-3}}{n_{\gamma'}} \right) \left( \frac{m_C}{5 \text{ MeV}} \right)^3 \left( \frac{m_{\gamma'}}{10 \text{ keV}} \right) \]
Bounds on $\frac{n_C}{n_X}$ fraction

$$n_C = \frac{\rho_X}{m_X} f \quad \text{where} \quad f = \Gamma_X t^0$$

- Dominant DM component cannot be relativistic [Audren, JCAP 1412 (2014)]
  $$f < 1 \%$$

- Not all $\gamma'$ are ejected:
  $$f < 10^{-2} \left( \frac{q}{10^{-11}} \right)^2 \left( \frac{m_{\gamma'}}{10 \text{ keV}} \right) \left( \frac{m_X}{10 \text{ MeV}} \right)$$

- $C$ should be accumulated
  $$n_C \langle \sigma(CC \rightarrow \gamma'\gamma')v \rangle t_0 \ll 1$$

  $$f < 6 \times 10^{-4} \left( \frac{m_X}{10 \text{ MeV}} \right) \left( \frac{0.15}{g_X} \right)^4 \left( \frac{m_C}{5 \text{ MeV}} \right)^2$$
What if $\delta \neq \epsilon$

Before recombination

$$\tau = 1000 \text{ yr} \left( \frac{3 \times 10^{-10}}{q'} \right)^2 \left( \frac{\text{keV}}{m_{\gamma'}} \right)$$

$q' \sim g_x \max[\delta, \epsilon] \sim 10^{-11} - 3 \times 10^{-10}$

$$\lambda_C \phi' \left| C \right|^2 (\phi')^2$$

$C \bar{C} \rightarrow \phi' \phi'$
Bounds

- **SLAC bounds on millicharged particles;** Prinz et al., PRL 81 (1998) 1175
  1 MeV-100 MeV

  \[ q < 4.1 \times 10^{-5} e - 5.8 \times 10^{-4} e \]

- **Supernova bound (energy loss)** Davidson, Hannestad and Raffelt, JHEP 05 (2000) 03

  \[ q < 10^{-9} \]
A few words on dark matter

$m_X \sim O(10 \text{ MeV})$

$$\langle \sigma (X + X \rightarrow \nu + \nu, \bar{\nu} + \nu) |_{tot} = 1 \text{ pb}$$

Bohm et al., PRD 77 (2008) 043516;
Farzan, PRD 80 (2009) 073009

The bounds from CMB on $N_{eff}$ then implies $m_X > 5 \text{ MeV}$

Wilkinson et al., PRD 94 (2016) 103525
Bounds on electric charge of C versus DM mass

- Supernova shock-waves
- Pico-charged particles trapped in galactic center
- CMB
Positronium decay

\[ e^- e^+ \rightarrow \gamma \gamma \]

- Decay at rest: 511 keV line
- Decay in flight: harder and continuous spectrum
Beacom and Yuksel, PRL 97 (2006) 071102

\[ E_{\text{inj}} < 3 \text{ MeV} \]

Assuming zero ionization

Size, Casse and Schanne, PRD 74 (2006) 063514

\[ E_{\text{inj}} < 7.5 \text{ MeV} \]

51% ionization
A fun bound from Voyager

Launched on 5th of September, 1977
A fun bound from Voyager

Containing a piece of Azarbaijani music
Voyager out of heliopause

\[ E_{\text{inj}} < 10 \text{ MeV} \]

Boudaud Lavalle and Salati, PRL 119 (2017) 021103

Voyager entered interstellar medium in summer 2012
Direct detection

$C$ relativistic

$\langle \Delta E \rangle \sim 0.035 \text{ keV} \frac{1}{1 - v^2} \left( \frac{v}{1/3} \right)^2 \left( \frac{m_C}{3 \text{ MeV}} \right)^2 \left( \frac{28 \text{ GeV}}{M_N} \right) \left( \frac{M_N}{M_N + \gamma m_C} \right)^2$

$v \sim 1/3$

Present

- LUX experiment
  - $E_{th} = 3 \text{ keV}$
- DAMA
  - $E_{th} = 2 \text{ keV}$
- CRESST II
  - $E_{th} = 0.3 \text{ keV}$

Future

- SuperCDMS
  - $E_{th} = 0.056 \text{ keV}$
- CRESST III
  - $E_{th} = 0.02 - 0.06 \text{ keV}$
- Edelweiss III
  - $E_{th} < 0.1 \text{ keV}$
Dependence on recoil energy

\[
\frac{dN_{\text{events}}}{dE_r} = \frac{1}{M_N} \frac{\rho_X}{m_X} (2f_v) \frac{d\sigma}{dE_r}
\]

\[
\frac{d\sigma}{dE_r} = |F|^2 \frac{Z^2}{4\pi M_N^2} \times \frac{e^2 q^2 m_C^2}{E_r^2} \times \frac{1}{E_r^{\text{max}}}
\]

Distinctive behavior

Different recoil energy dependence from DM signal
Even dipole or anapole DM
Tests of the scenario

- Direct dark matter search
- Positron search by Voyager
- Studying the correlation of 511 keV line with magnetic field in various dwarf galaxies (e.g. Reticulum II) and milky way
Summary

- Scenario for saving DM interpretation of 511 keV signal from CMB bounds.
- Dark matter decays to a pair of pico-charged particles that stay in galaxy and eventually annihilate to create electron positron.
- Testable by low energy DM search experiments Edelweiss II, superCDMS and CRESST III with distinctive dependence on the recoil energy.
- Search for a positron signal in outer space by Voyager
- Correlation between galactic magnetic field and 511 keV signal in our galaxy and in dwarf galaxies
- General scenario applicable for the indirect DM signal other than the 511 keV line
Direct annihilation of C pairs to electron positron pair

\[ C\bar{C} \rightarrow \phi\phi \quad \frac{\bar{e}e\bar{C}C}{\Lambda} \]

\[ \sigma(C\bar{C} \rightarrow \phi\phi) \sim 100\,pb \]

\[ \Lambda \sim 100\,GeV \]
In two steps

\[ C\bar{C} \rightarrow \phi\phi \quad \phi \rightarrow e^- e^+ \]

\[ g_\phi \phi e^- e^+ \]

\[ 0.3 \times 10^{-15} < g_\phi < 10^{-11} \]

decay length smaller than 100 pc

Supernova
Model building

\[ a_{\phi \phi} |H|^2 \]

\[ g_{\phi} = \sqrt{2} \frac{a_{\phi} v}{m_h^2} Y_e \]