Cosmic rays, anti-helium, and an old navy spotlight

1704.05431, 1709.06507

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Geneva U., Sep 27 2017
CR antimatter – \( \bar{p}, e^+, \bar{d}, \) and \( \bar{\text{He}} \) – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

…and key diagnostic of CR propagation
CR antimatter – $\bar{p}$, $e^+$, $\bar{d}$, and $^3\text{He}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

A host of experiments out there to detect it.
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Some confusion in the literature, as to what and how we can calculate.

=> will try to sort this out
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Could it be that AMS02 have detected astrophysical anti-He3?
The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena.
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Need to calculate this background to learn about possible exotic sources
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**Problem**: we don’t know where CRs come from, nor how long they are trapped in the Galaxy, nor how they eventually escape.
About diffusion models

\[ K \sim (E/Z)^\delta \]

NGC 891

NIR

1.4GHz

arxiv:1708.04316
408MHz (Canadian Galactic Plane Survey)
S. Schael, Moriond 2016 for AMS02

Proton Spectrum

Flux $\times R^{2.7}$ [GV$^{1.7}$ m$^2$ sr$^{-1}$ s$^{-1}$]

Rigidity [GV]

traditional understanding

unexpected
S. Schael, **Moriond 2016 for AMS02**

**Proton Spectrum**

**Helium Spectrum**

Flux \( \times R^{2.7} \) [GeV\(^{1.7}\) m\(^2\) s\(^{-1}\) sr\(^{-1}\) s\(^{-1}\)]

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For secondary antimatter we have a handle: particle physics branching fractions

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\frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)}
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...works for secondary nuclei B, sub-Fe (T-V-Sc-Cr)
Recipe for an antiproton pie:

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Recipe for an antiproton pie:

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\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}
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\[
n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
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Average column density traversed by CR nuclei during propagation

\[
X_{\text{esc}}(\mathcal{R}) = \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})}
\]

\[
X_{\text{esc}} = \frac{(B/C)}{\sum_{P=C,N,O,\ldots} (P/C) \frac{\sigma_{P\rightarrow B}}{m} - (B/C) \frac{\sigma_B}{m}}
\]

![Graph showing \(X_{\text{esc}}\) vs. \(R\) with data points and a fitted line]
Recipe for an antiproton pie:

\[ n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R}) \]

\[ \sigma_{p \rightarrow \bar{p}}(\mathcal{R}) = \frac{2 \int_{\mathcal{R}}^{\infty} dR_p J_p(\mathcal{R}_p) \left( \frac{d\sigma_{pp \rightarrow \bar{p}X}(\mathcal{R}_p, \mathcal{R})}{dR_p} \right) }{J_p(\mathcal{R})} \]
Recipe for an antiproton pie:

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AMS proton flux

New information: The proton flux cannot be described by a single power law = \( CR^\gamma \), as has been assumed for decades

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma / S} \right]^S \]

 unexpectedly, we found the spectrum can be described by a double power law with spectral index \( \gamma \) below \( R_0 \) and \( \gamma + \Delta \gamma \) above \( R_0 \). \( S \) describes the smoothness of the transition.
We use the relation $n_{\bar{p}}(R) \approx \frac{n_B(R)}{Q_B(R)} Q_{\bar{p}}(R)$ to predict the $\bar{p}$ flux [28, 32]:

$$n_{\bar{p}}(R) \approx \frac{n_B(R)}{Q_B(R)} Q_{\bar{p}}(R).$$

The RHS of Eq. (3) is derived from laboratory cross section data and from direct local measurements of CR densities, without reference to the details of propagation. In applying Eq. (1) to $\bar{p}$, a subtlety arises due to the fact that the cross sections appearing in Eq. (2) can (and for $\bar{p}$, do) depend on energy. In Eq. (2) we define these cross sections such that the source term $Q_a(R)$ is proportion to the primary species density $n_P(R)$ expressed at the same rigidity (we will clarify this statement down the road in Eq. (6)).

For relativistic nuclei (above a few GeV/nuc) produced in fragmentation reactions, e.g. $^{12}\text{C}$ fragmenting to $^{11}\text{B}$, the energy dependence of the fragmentation cross section is much less important. Therefore, before proceeding to calculate $Q_{\bar{p}}$, we consider the factor $n_B(R)/Q_B(R)$.

The quantity $X_{\text{esc}}(R) = n_B(R) Q_B(R)$, known as the CR grammage [2], is a spallation-weighted average of the column density of ISM traversed by CRs during their propagation, the average being taken over $3$.

Note: neither the over-all CR intensity, nor the target ISM density, needs to be uniform in the propagation region in order for Eq. (1) to apply. Indeed, the ISM exhibits orders of magnitude variations in density across the Galactic gas disc and rarified halo [31]. This is, of course, provided that the CR specie being compared do not exhibit species-dependent complications like decay in flight (for radionuclei like $^{10}\text{Be}$) or radiative energy losses (for $e^+ + e^-$).

4 This is, of course, provided that the CR specie being compared do not exhibit species-dependent complications like decay in flight (for radionuclei like $^{10}\text{Be}$) or radiative energy losses (for $e^+ + e^-$). In addition, rigidity only really becomes the magic quantity for propagation at relativistic energies (see e.g. [27]).

$\sigma(\text{pp} \rightarrow \text{pbar}), 20\%$

$\sigma(^{12}\text{C} \rightarrow ^{11}\text{B}), 20\%$

$\Phi, (0.2-0.8) \text{ GV}$

$10^{-3}$

$pbar/p$

$10^{-4}$

$10^1$ $10^2$ $10^3$

$R [\text{GV}]$
\[ n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R}) \]

\[ \sigma(pp\rightarrow p\bar{p}), 20\% \]
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AMS02 2016

We stress that Eq. (1) is an empirical relation, known to apply to \( \pm 10\% \) accuracy in analyses of HEAO3 data [26, 27] and – as we shall see shortly, focusing on \( \bar{p} \) – consistent with subsequent PAMELA [10] and AMS02 [16] measurements.

From the theoretical point of view, Eq. (1) is natural [2, 28–30]. It is guaranteed to apply if the relative composition of the CRs in the regions that dominate the spallation is similar to that measured locally at the solar system. In this case, the source distribution of different secondaries is similar. Because the confinement of CRs in the Galaxy is magnetic, different CR particles that share a common distribution of sources should exhibit similar propagation if sampled at the same rigidity [4]. Thus, the ratio of propagated CR densities reflects the ratio of their net production rates.

Note that the net source defined in Eq. (2) accounts for the fact that different nuclei exhibit different degree of fragmentation losses during propagation. In this way, species like sub-Fe (with fragmentation loss cross section of order 500 mb), B (\( \sigma \approx 240 \text{ mb} \)), and \( \bar{p} \) (\( \sigma \approx 40 \text{ mb} \)) can be put on equal footing.

Further discussion of the physical significance of Eq. (1) is given in Ref. [28] and App. A.

We can use Eq. (1) together with the locally measured flux of B, C, O, p, He,... to predict the \( \bar{p} \) flux [28, 32]:

\[ n_{\bar{p}}(R) \propto \frac{n_B(R)}{Q_B(R)} Q_{\bar{p}}(R) \]

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What about e+ ?
What about e+?

AMS02, Dec 2016
Secondary *upper bound* (Based on B/C)

\[ n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} \frac{Q_{e^+}(\mathcal{R})}{Q_{e^-}(\mathcal{R})} \]
Secondary upper bound (Based on B/C)

\[ n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{e^+}(\mathcal{R}) \]

PAMELA 2008

Secondary upper bound
(Based on B/C)

\[ n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{e^+}(\mathcal{R}) \]

FIG. 5: \( e^+/\bar{p} \) flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound (\( e^+/\bar{p} \) source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in \( pp \rightarrow \bar{p}, e^+ \), not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured \( J_p \), while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [59].

The measured \( e^+/\bar{p} \) flux ratio does not exceed and is always comparable – within about a factor of two – to the secondary upper bound. Moreover, the \( e^+/\bar{p} \) ratio saturates the bound over an extended range in rigidity. The most natural interpretation of this result, is that the coincidence of the measured \( e^+/\bar{p} \) ratio with the ratio of the production rates (\( pp \rightarrow e^+ \)) (\( pp \rightarrow \bar{p} \)) is not an accident. Taking into account that, as we saw in the previous section, \( \bar{p} \) are likely of secondary origin (certainly dominated by secondary production), it is natural to deduce that AMS02 is observing secondary \( e^+ \) as well.

A compatible but less robust way to represent the secondary \( e^+ \) upper bound is by computing the zero-loss secondary \( e^+ \) flux directly from the B/C grammage, as we did for \( \bar{p} \) in Fig. 2. Namely, we write

\[ n_{e^+}(\mathcal{R}) \sim n_B(\mathcal{R}) Q_{e^+}(\mathcal{R}) \]

We stress that, similarly to the \( \bar{p}/p \) situation exhibited in Fig. 3, Eq. (9) is much more sensitive to the unknown CR spectra in the spallation regions than is the \( e^+/\bar{p} \) ratio of Fig. 5. Nevertheless, to make contact with common presentations of the data in the literature and to exploit the higher energy \( e^+ \) data reported by AMS02 [60], we show in Fig. 6 the secondary upper bound on \( e^+ \) derived Eq. (9).
Secondary upper bound (Based on B/C)

\[
n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{e^+}(\mathcal{R})
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Secondary upper bound
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\[ n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{e^+}(\mathcal{R}) \]
anti He3
anti He3

1. Handful of events

2. Energy of 1 event they show is 40GeV

AMS02, Dec 2016

An anti-Helium candidate:

At this point it is not clear if AMS02 is seeing true CR events, or some rare experimental background.

Need to reject such freak background events at a level of ~ 1:100M...

We take it as motivation for theory examination of what the astro anti-He3 flux is.
anti He3

1. Handful of events

2. Energy of 1 event they show is 40GeV

AMS02 event

An anti-Helium candidate:

Momentum $= 40.3 \pm 2.9$ GeV/c
Charge $= -2$
Mass $= 2.96 \pm 0.33$ GeV/$c^2$
Velocity $= 0.9973 \pm 0.0005$ c
anti He3

1. Handful of events

“coalescence”:

\[ E_A \frac{dN_A}{d^3 p_A} = B_A R(x) \left( E_p \frac{dN_p}{d^3 p_p} \right)^A \]

We need \( B_3 \).
anti He3

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We need \( B_3 \).

Propagation is not an issue:
Can calibrate it out just like for p-bar.

===> we know what is needed to give observable flux.

Question is:

Does this make sense w.r.t. accelerator data?
Duperray et al, PRD71 083013 (2005), pA data from SPS (1980’s)

$B_3 = 1.4 \times 10^{-5}$ GeV$^4$
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If true, then anti-helium = new physics (or super lucky AMS02).
Duperray et al, PRD71 083013 (2005), \textbf{pA data} from SPS (1980’s)
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Complimentary AA, pA, and related pp data exists elsewhere.

\textbf{Let’s take a step back and try to see the bigger picture}
\[ E_A \frac{dN_A}{d^3p_A} = B_A R(x) \left( E_p \frac{dN_p}{d^3p_p} \right)^A \]

Hadrons emitted from a finite size emission region. Typical scales \( O(\text{fm}) \sim 1/(100 \text{ MeV}) \)

Natural scaling law: \( B_A \propto V^{1-A} \)

Emission region scale size is probed by two-particle correlations:

*Hanbury Brown-Twiss (HBT)* data

A Test of a New Type of Stellar Interferometer on Sirius

R. HANBURY BROWN & DR. R. Q. TWISS

1. Jodrell Bank Experimental Station, University of Manchester
2. Services Electronics Research Laboratory, Baldock
HBT in heavy ion and pp collisions
...
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Example: CERN SPS, PbPb 20, 30, 40, 80, 158A GeV
HBT in heavy ion and pp collisions

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- Collected all systems for which we find nuclear yield & HBT data.

**FIG. 12:** Coalescence factor $B_2$ (Left) and $B_3$ (Right) vs. HBT radius. For more details, see [34].

2. The same coalescence momentum was sometimes assumed to describe $pA!\bar{d}$ and $pp!\bar{d}$. Theoretical and empirical evidence suggests that both assumptions may be incorrect. To see this, we make a brief excursion into the physics of coalescence.

The role of the factor $B_A$ is to capture the probability for $A$ nucleons produced in a collision to merge into a composite nucleus. It is natural for the merger probability to scale as $B_A / V_1^A$, where $V$ is the characteristic volume of the hadronic emission region. A model of coalescence that realises the scaling of Eq. (34) was presented in Ref. [90]. A key observation in [90] is that the same hadronic emission volume is probed by Hanbury Brown-Twiss (HBT) two-particle correlation measurements [89]. Both HBT data and nuclear yield measurements are available for AA and pA systems, allowing a test of Eq. (34).

The coalescence factor in AA, pA, and pp collisions, presented w.r.t. HBT scale deduced for the same systems, is shown in Fig. 12. The data analysis entering into making the plot is summarised in App. A of [34]. The data is roughly consistent with Eq. (34) as realised in [90], albeit with large uncertainty.

Importantly, Fig. 12 challenges the simplifying assumptions, utilised in one form or another in [84–88], of using the same coalescence parameters for pp and pA collisions, or for $\bar{d}$ and $^3$He production. In particular, $^3$He coalescence may well be more efficient than previously estimated in these references.
• Collected all systems for which we find nuclear yield & HBT data

\[ B_A \propto V^{1-A} \]

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- Collected all systems for which we find nuclear yield & HBT data
- For **pp** we have no $B_3$, but we do have HBT
FIG. 12: Coalescence factor $B_2$ (Left) and $B_3$ (Right) vs. HBT radius. For more details, see [34].

2. The same coalescence momentum was sometimes assumed to describe $p_\Lambda$ and $d$. Theoretical and empirical evidence suggests that both assumptions may be incorrect. To see this, we make a brief excursion into the physics of coalescence.

The role of the factor $B_A$ is to capture the probability for $A$ nucleons produced in a collision to merge into a composite nucleus. It is natural for the merger probability to scale as $B_A^2 A_1^{1/3}$, where $V$ is the characteristic volume of the hadronic emission region. A model of coalescence that realises the scaling of Eq. (34) was presented in Ref. [90]. A key observation in [90] is that the same hadronic emission volume is probed by Hanbury Brown-Twiss (HBT) two-particle correlation measurements [89]. Both HBT data and nuclear yield measurements are available for $A$A and $pA$ systems, allowing a test of Eq. (34).

The coalescence factor in $A$A, $pA$, and $pp$ collisions, presented w.r.t. HBT scale deduced for the same systems, is shown in Fig. 12. The data analysis entering into making the plot is summarised in App. A of [34]. The data is roughly consistent with Eq. (34) as realised in [90], albeit with large uncertainty.

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AMS02, 2017?
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• For pp we have no $B_3$, but we do have HBT
• Collected all systems for which we find nuclear yield & HBT data

• For **pp — until yesterday — we had no** B$_3$... **now we do.**
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The coalescence factor in \( \text{pA} \), \( \text{pA} \), and \( \text{pp} \) collisions, presented w.r.t. HBT scale deduced for the same systems, is shown in Fig. 12. The data analysis entering into making the plot is summarised in App. A of [34]. The data is roughly consistent with Eq. (34) as realised in [90], albeit with large uncertainty.

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2. The same coalescence momentum was sometimes assumed to describe $p_A$ and $p_\bar{A}$.

Theoretical and empirical evidence suggests that both assumptions may be incorrect. To see this, we make a brief excursion into the physics of coalescence.

The role of the factor $B_A$ is to capture the probability for $A$ nucleons produced in a collision to merge into a composite nucleus. It is natural for the merger probability to scale as $B_A^2 V_A^1$, where $V_A$ is the characteristic volume of the hadronic emission region. A model of coalescence that realises the scaling of Eq. (34) was presented in Ref. [90]. A key observation in [90] is that the same hadronic emission volume is probed by Hanbury Brown-Twiss (HBT) two-particle correlation measurements [89]. Both HBT data and nuclear yield measurements are available for $AA$ and $pA$ systems, allowing a test of Eq. (34).

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The same coalescence momentum was sometimes assumed to describe $pA$ and $p\bar{d}$.

Theoretical and empirical evidence suggests that both assumptions may be incorrect. To see this, we make a brief excursion into the physics of coalescence.

The role of the factor $B_A$ is to capture the probability for $A$ nucleons produced in a collision to merge into a composite nucleus. It is natural for the merger probability to scale as $B_A/V_{\text{had}}$, where $V_{\text{had}}$ is the characteristic volume of the hadronic emission region. A model of coalescence that realises the scaling of Eq. (34) was presented in Ref. [90]. A key observation in [90] is that the same hadronic emission volume is probed by Hanbury Brown-Twiss (HBT) two-particle correlation measurements [89]. Both HBT data and nuclear yield measurements are available for $AA$ and $pA$ systems, allowing a test of Eq. (34).

The coalescence factor in $AA$, $pA$, and $pp$ collisions, presented w.r.t. HBT scale deduced for the same systems, is shown in Fig. 12. The data analysis entering into making the plot is summarised in App. A of [34]. The data is roughly consistent with Eq. (34) as realised in [90], albeit with large uncertainty.

Importantly, Fig. 12 challenges the simplifying assumptions, utilised in one form or another in [84–88], of using the same coalescence parameters for $pp$ and $pA$ collisions, or for $p\bar{d}$ and $3^He$ production. In particular, $3^He$ coalescence may well be more efficient than previously estimated in these reference.
We got the basic picture more or less right.

But we have detailed data now: significant \( pT/A \) dependence in \( B_3 \).

Most relevant for astro is \( pT/A < 0.3 \text{ GeV} \)
Implication of ALICE results for astrophysics.

He3bar: secondary production by pp collisions unlikely to explain 1 event/yr at AMS02.
Implication of ALICE results for astrophysics.

He³bar: secondary production by **pp collisions** unlikely to explain 1 event/yr at AMS02.

1 event/5yr we could live with, but 1 event/yr unlikely.

**What about p-pbar collisions?**
FIG. 3: Coalescence factor $B_2$ (Top) and $B_3$ (Bottom) vs. HBT radius. The prediction of Eqs. (11-12) is shown as solid line. Details of the data analysis are given in App. A. (Boxes denote systems for which the coalescence factor and the HBT radius are taken from different data sets.)

Results from the ALICE experiment allow us to make a preliminary test of Eq. (14). Ref. [55] reported $^{3}$He and $^{2}$H in the ALICE pp run, corresponding to luminosity $L \approx 2 \times 10^8 \text{b}$ with a pseudo-rapidity cut $|\eta| < 0.9$ and with no further $p_T$ cut.

The $p_T$-dependent efficiency for $^{3}$He detection was given in [56]. In Fig. 4 we use these parameters to calculate the expected number of $^{3}$He or $^{3}$He events and compare with data. The result supports a coalescence factor

$$B^{(3\text{He})}_{pp} \approx (5 \pm 8) \times 10^{-4} \text{GeV}^2,$$

in agreement with Eq. (14). A dedicated analysis by the ALICE collaboration is highly motivated.

CR anti-helium. Two channels produce a final state $^{3}$He: direct $\text{pp} \to ^{3}\text{He}$ and $\text{pp} \to \text{t} \to ^{3}\text{He}$. The first channel should suffer some Coulomb suppression with a Gamow factor that can be estimated by $f_{\text{coul}} \approx e^{\frac{-r}{m_p}}$. Eq. (14) suggests $p_c \approx 0.10.2 \text{GeV}$, leading to $f_{\text{coul}} \approx 0.80.9$. This is supported by experimental results on the relative yield $^{3}$He/t [55–57] that are consistent with $f_{\text{coul}} \approx 1$. (Ref. [58] reported $^{3}$He/t < 1; however, the $^{3}$He/t data from the same publication show an opposite trend, $^{3}$He/t > 1.) In what follows, for concreteness we focus on $\text{pp} \to t$ but we include a factor of 2 increased yield from the direct $\text{pp} \to ^{3}\text{He}$ channel.

Combining Eq. (14) with the $\text{pp} \to \bar{p}p$ production cross section [38, 39], we use Eq. (6) to obtain the differential cross section

$$dE \frac{dN}{d^3p_t} = \frac{pp}{E_t} dN_t d^3p_t,$$

where $pp$ is the total inelastic pp cross section [59, 60]. The effective production cross section to be used in Eq. (2) is then

$$\frac{pp}{E_t} \frac{dN}{d^3p_t} = \left.Z_1^{\text{pp}} \frac{d}{d^3p_t} \frac{n_p}{p_{n_p}} (R) \frac{d}{d^3p_t} \frac{n_p}{p_{n_p}} \right|_{158A \text{ GeV} \sqrt{s}}$$

We thank Natasha Sharma for clarifying the experimental procedure.
FIG. 3: Coalescence factor $B_2$ (Top) and $B_3$ (Bottom) vs. HBT radius. The prediction of Eqs. (11-12) is shown as solid line. Details of the data analysis are given in App. A. (Boxes denote systems for which the coalescence factor and the HBT radius are taken from different data sets.)

Results from the ALICE experiment allow us to make a preliminary test of Eq. (14). Ref. [55] reported $^3$He and $^2$H in the ALICE pp run, corresponding to luminosity $L \approx 2 \times 10^{33}$ barn with a pseudo-rapidity cut $|y| < 0.9$ and with no further $p_T$ cut. The $p_T$-dependent efficiency for $^3$He detection was given in [56]. In Fig. 4 we use these parameters to calculate the expected number of $^3$He or $^2$H events and compare with data. The result supports a coalescence factor $B_3(p_{pp}) \approx (5 \pm 2) \times 10^{-4}$ GeV$^4$, in agreement with Eq. (14). A dedicated analysis by the ALICE collaboration is highly motivated.

CR anti-helium. Two channels produce a final state $^3$He: direct $pp \rightarrow ^3$He and $pp \rightarrow ^2$H, followed by decay to $^3$He. The first channel should suffer some Coulomb suppression with a Gamow factor that can be estimated by $f_{coul} \approx e^{-\frac{\alpha}{2m_p}}$. Eq. (14) suggests $p_T \approx 0.1$ GeV, leading to $f_{coul} \approx 0.8$. This is supported by experimental results on the relative yield $^3$He/$^2$H [55–57] that are consistent with $f_{coul} \approx 1$. (Ref. [58] reported $^3$He/$^2$H < 1; however, the $^3$He/$^2$H data from the same publication show an opposite trend, $^3$He/$^2$H > 1.) In what follows, for concreteness we focus on $pp \rightarrow ^2$H but we include a factor of 2 increased yield from the direct $pp \rightarrow ^3$He channel. Combining Eq. (14) with the $pp \rightarrow ^2$H production cross section [38, 39], we use Eq. (6) to obtain the differential cross section $E_{pp} d^2 \sigma_{pp \rightarrow ^2H} dE_{^3He} = \frac{pp}{E_{pp}} \frac{dN}{dE_{^3He}}$, where $pp$ is the total inelastic pp cross section [59, 60]. The effective production cross section to be used in Eq. (2) is then $pp \rightarrow ^3$He $(R) = 2Z_1$ 

We thank Natasha Sharma for clarifying the experimental procedure.
Implication of ALICE results for astrophysics.

*dbar*: secondary production by *pp* collisions may be seen at AMS02 5yr exposure.

![Graph showing the production of deuterons, tritons, and $^3$He nuclei and their anti-nuclei in pp collisions at $\sqrt{s} = 0.9, 2.76$, and $7$ TeV.](image)
Summary
Summary

- Antiprotons consistent w/ secondary.

- Positrons consistent with secondary.

CR propagation more interesting than supposed in simplified diffusion models

- Secondary anti-He3 events in 5-year of AMS02?

If so, it is unlikely from (the naively dominant) pp collisions
Xtra
finally, what about \[ \bar{p}p \rightarrow \bar{3}\text{He} \text{ source} \]

If cross section is \(~\text{microbarn}\), would give a few He3bar events.
finally, what about \( \bar{p}p \rightarrow ^3\text{He} \) source

If cross section is \( \sim \) microbarn, would give a few He3bar events.

We found one Tevatron ref. (CME 1.8TeV)

Quotes \( \sim \) microbarn cross section… but need to verify analysis.
finally, what about \( \bar{p}p \rightarrow \text{He}^3 \) source

If cross section is \( \sim \) microbarn, would give a few He3bar events.

We found one Tevatron ref. (CME 1.8TeV)

Unfortunately, it may be off the truth, because it also seems to be saying

\[
\frac{\sigma_{\bar{p}p \rightarrow d}}{\sigma_{\bar{p}p \rightarrow t}} \sim 3
\]

Factor \( \sim \) few suppression for He3 vs deuterium feels hard to digest: we expect much stronger suppression…
What’s going on here? (Donato et al PRL102, 071301 (2009))

Antiproton-to-proton ratio

The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena
What’s going on here? (Donato et al PRL102, 071301 (2009))

Antiproton-to-proton ratio

Proton flux assumed for making the pbar/p grey line

AMS proton flux

New information: The proton flux cannot be described by a single power law \( CR^\gamma \), as has been assumed for decades.
What’s going on here? (Donato et al PRL102, 071301 (2009))

The excess of antiprotons observed cannot come from pulsars. It can be explained by Dark Matter or by new astrophysics phenomena.

B/C grammage assumed for making the pbar/p grey line.
What we get if we use those old proton flux, B/C grammage

The excess of antiprotons cannot come from ordinary collisions.

It can be explained by Dark Matter or by new astrophysics.
What’s going on here? (Donato et al PRL102, 071301 (2009))

What we get if we use those old proton flux, B/C grammage

The excess of antiprotons cannot come from collisions of ordinary com

It can be explained by Dark matter or by new astrophysics
Propagation time scales: radioactive nuclei

Secondary radioactive nuclei carry time info (like positrons)

<table>
<thead>
<tr>
<th>reaction</th>
<th>$t_{1/2}$ [Myr]</th>
<th>$\sigma$ [mb]</th>
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<td>$^{10}<em>{4}Be \rightarrow ^{10}</em>{5}B$</td>
<td>1.51 (0.06)</td>
<td>210</td>
</tr>
<tr>
<td>$^{26}<em>{13}Al \rightarrow ^{26}</em>{12}Mg$</td>
<td>0.91 (0.04)</td>
<td>411</td>
</tr>
<tr>
<td>$^{36}<em>{17}Cl \rightarrow ^{36}</em>{18}Ar$</td>
<td>0.307 (0.002)</td>
<td>516</td>
</tr>
<tr>
<td>$^{54}<em>{25}Mn \rightarrow ^{54}</em>{26}Fe$</td>
<td>0.494 (0.006)*</td>
<td>685</td>
</tr>
</tbody>
</table>
Positrons vs. radioactive nuclei

How to compare radioactive decay of a nucleus, with energy loss of e+?

We’ll get there in a few slides.
Radioactive nuclei: Charge ratio

A STUDY OF THE SURVIVING FRACTION OF THE COSMIC-RAY RADIOACTIVE DECAY ISOTOPES $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, and $^{54}\text{Mn}$ AS A FUNCTION OF ENERGY USING THE CHARGE RATIOS Be/B, Al/Mg, Cl/Ar, AND Mn/Fe MEASURED ON HEAO–3

W. R. Webber$^1$ and A. Soutoul

Received 1997 November 6; accepted 1998 May 11

(WS98)
Radioactive nuclei: Charge ratio vs. isotopic ratio

Charge ratios

\[ \text{Be/B, Al/Mg, Cl/Ar, Mn/Fe} \]

Isotopic ratios

\[ ^{10}\text{Be}/^{9}\text{Be}, ^{26}\text{Al}/^{27}\text{Al}, ^{36}\text{Cl}/^{35}\text{Cl}, ^{54}\text{Mn}/^{54}\text{Mn} \]
Radioactive nuclei: Charge ratio vs. isotopic ratio

Charge ratios

Be/B, Al/Mg, Cl/Ar, Mn/Fe

Isotopic ratios

$^{10}\text{Be}/^{9}\text{Be}, ^{26}\text{Al}/^{27}\text{Al}, ^{36}\text{Cl}/^{35}\text{Cl}, ^{54}\text{Mn}/^{54}\text{Mn}$

- High energy isotopic separation difficult. Need to resolve mass. Isotopic ratios were measured only up to ~ 2 GeV/nuc (ISOMAX)

- Charge separation easier. Charge ratios up to ~ 16 GeV/nuc (HEAO3-C2) (AMS-02: Charge ratios to ~ TeV/nuc. Isotopic ratios ~ 10 GeV/nuc)

- **Benefit**: avoid low energy complications; significant range in rigidity

- **Drawback**: systematic uncertainties (cross sections, primary contamination)
Radioactive nuclei: Charge ratio vs. isotopic ratio

Charge ratios

$\text{Be}/B, \text{Al}/\text{Mg}, \text{Cl}/\text{Ar}$

Isotopic ratios

$^{10}\text{Be}/^{9}\text{Be}, ^{26}\text{Al}/^{27}\text{Al}, ^{36}\text{Cl}/\text{Cl}$
Positrons vs. radioactive nuclei

How to compare radioactive decay of a nucleus, with energy loss of e+?
Positrons vs. radioactive nuclei

- Suppression factor due to decay $\sim$ suppression factor due to radiative loss,

  *if compared at rigidity such that cooling time = decay time*

Explain:

$$t_c = \left| \frac{\mathcal{R}}{\dot{\mathcal{R}}} \right| \propto \mathcal{R}^{-\delta_c}$$

$$n_{e^+} \sim \mathcal{R}^{-\gamma}$$
Suppression factor due to decay ~ suppression factor due to radiative loss, if compared at rigidity such that cooling time = decay time

Explain:

\[ t_c = \left| \frac{\mathcal{R}}{\dot{\mathcal{R}}} \right| \propto \mathcal{R}^{-\delta_c} \]

\[ n_{e^+} \sim \mathcal{R}^{-\gamma} \]

Consider decay term of nuclei and loss term of e+ in general transport equation.

**decay:**

\[ \partial_t n_i = -\frac{n_i}{t_i} \]

**loss:**

\[ \partial_t n_{e^+} = \partial_{\mathcal{R}} \left( \dot{\mathcal{R}} n_{e^+} \right) = -\frac{n_{e^+}}{t_c} \]

\[ \tilde{t}_c = \frac{t_c}{\gamma - \delta_c - 1} \]

\[ \gamma \sim 3 \rightarrow \tilde{t}_c \approx t_c \]
Comparing with radioactive nuclei

Time scales:
cooling vs decay
Comparing with radioactive nuclei

Time scales:
cooling vs decay
Comparing with radioactive nuclei

FIG. 5: $e^+ / \bar{p}$ flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound ($e^+ / \bar{p}$ source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in $pp \rightarrow \bar{p}, e^+$, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured $J_p$, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [55].

AMS02 results hint for a secondary origin for CR $e^+ [34]$. However, this result comes with a puzzle. If $e^+$ are secondary, then Fig. 5 suggests that the effect of radiative energy loss in suppressing the $e^+$ flux is never very important, and possibly becomes less significant as we go to higher $e^+$ energy. As we shall see, this behaviour contradicts the expectations within common models of CR propagation [12].

To appreciate the $e^+$ puzzle, we must go into somewhat more muddy waters of CR astrophysics and consider the interplay of $e^+$ energy losses with the effects of propagation.

For later convenience it proves useful to define the loss suppression factor $f_{e^+}$ via $n_{e^+} / n_{\bar{p}} = f_{e^+}(R) Q_{e^+}(R) / Q_{\bar{p}}(R)$. In Fig. 6 we show $f_{e^+}$ as derived from Fig. 5. The upper bound means that for secondary $e^+$ we expect $f_{e^+}(R) \ll 1$. The $e^+$ puzzle concerns the observation that $f_{e^+}(R)$ is much lower than that of [56] at $R = 100$ GV. This difference led [56] to conclude that $e^+$ are not aected by radiative losses at all energies; while we believe that the data implies some radiative effect at $R = 100$ GV. The basic conclusion, putting 30-50% differences aside, is similar: $e^+$ are consistent with secondaries.

Ref. [56] recently joined this understanding. We note, however, that our evaluation of the $Q_{e^+} / Q_{\bar{p}}$ ratio in Fig. 5 is lower than that of [56] by 30-50% at $R = 100$ GV. This difference led [56] to conclude that $e^+$ are not affected by radiative losses at all energies; while we believe that the data implies some radiative effect at $R = 100$ GV. The basic conclusion, putting 30-50% differences aside, is similar: $e^+$ are consistent with secondaries.

For early comprehensive analyses see e.g. [57–59].
Comparing with radioactive nuclei

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AMS02 results hint for a secondary origin for CR $e^+[36]$. However, this result comes with a puzzle. If $e^+$ are secondary, then Fig. 5 suggests that the effect of radiative energy loss in suppressing the $e^+$ flux is never very important, and possibly becomes less significant as we go to higher $e^+$ energy. As we shall see, this behaviour contradicts the expectations within common models of CR propagation.

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$$Q_{e^+}/Q_{\bar{p}} = f_{e^+}(E) = \frac{R}{Q_{e^+}} \frac{Q_{\bar{p}}}{R}.$$  (9)

In Fig. 6 we show $f_{e^+}$ as derived from Fig. 5. The upper bound means that for secondary $e^+$ we expect $f_{e^+}(R) \approx 1$. The $e^+$ puzzle concerns the observation that $f_{e^+}(R)$ is even much 11

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For later convenience it proves useful to define the loss suppression factor $f_{e^+}$ via

$$Q_{e^+}/Q_{\bar{p}} = f_{e^+} \left( \frac{R}{R_0} \right) Q_{e^+} \left( \frac{R}{R_0} \right) Q_{\bar{p}} \left( \frac{R}{R_0} \right).$$

(9)

In Fig. 6 we show $f_{e^+}$ as derived from Fig. 5. The upper bound means that for secondary $e^+$ we expect $f_{e^+} \left( \frac{R}{R_0} \right) \lesssim 1$. The $e^+$ puzzle concerns the observation that $f_{e^+} \left( \frac{R}{R_0} \right)$ is even much $e^+$

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For early comprehensive analyses see e.g. [57–59].

\[ f(\text{Be10}) \sim 0.4 \]
\[ f(e^+) \sim 0.5 \]
Radioactive nuclei: constraints on $t_{esc}$

- Cannot (yet) exclude rapidly decreasing escape time
- AMS-02 should do better!

Need to tell between these fits

Blum, JCAP 1111 (2011) 037

$$f_{s,i} = \left( \frac{t_i}{t_{esc}} \right)^{0.5}, \quad t_{esc} = 300 \text{ Myr} \times (R/10\text{GV})^{-1}$$
\[ X_{\text{esc}} = \frac{(B/C)}{\sum_{P=C,N,O,\ldots} (P/C) \frac{\sigma_{P\rightarrow B}}{m}} - (B/C) \frac{\sigma_B}{m} \]

e.g. Tomassetti, PoS ICRC2015 (2016) 553
AMS02 (2013-2016)

\[ X_{\text{esc}} = \frac{(B/C)}{\sum_{P=C,N,O,...} (P/C) \frac{\sigma_{P \to B}}{m} - (B/C) \frac{\sigma_{B}}{m}} \]

Only C, O \to B, no (A>16) \to B

Only C \to B, no O \to B etc

All primary up to Fe56
Stable secondaries with no energy loss

Comment about applicability of the analysis: **high energy (relativistic)**

Below $R \sim 10\text{GV}$, various propagation effects can change energy of particle during trajectory; spallation cross sections are energy dependent; rigidity not transferred in fragmentation;...

Example: solar modulation

**We will keep our analysis to $R > 10\text{GV}$**
About diffusion models

\[ K \sim (E/Z)^\delta \]

2L

R

To a good approximation, disc+halo homogeneous diffusion models satisfy the criterion of uniform CR composition where spallation happens.

Should satisfy

\[
\frac{n_A}{n_B} = \frac{Q_A}{Q_B}
\]
diffusion models fit $X_{esc}$

diffusion models fit $X_{\text{esc}}$

\[
X_{\text{esc}} = X_{\text{disc}} \frac{Lc}{2D} \frac{2R}{L} \sum_{k=1}^{\infty} J_0[\nu_k(r_s/R)] \frac{\tanh[\nu_k(L/R)]}{\nu_k^2 J_1(\nu_k)}
\]
FIG. 4: Comparison of the result of Eq. (3) (green) with results from the diffusion models of [39] (blue) and [46] (yellow band). AMS02 data in black. To understand the discrepancy with [46], we use the model parameters of Ref. [46], based on early HEAO3 B/C data, to compute the effective X_{esc}. We then use this X_{esc} to calculate the \bar{p}/p flux. We also adopt the primary p and He spectra and pp \rightarrow \bar{p} cross section parametrisation of [46]. The result we obtain in this way is shown in red.

The main thing that went wrong is that the model of Ref. [46] was calibrated to fit early B/C data from HEAO3, and then extrapolated from that fit to high energy beyond the region where HEAO3 data was tested. Unfortunately, above \( R \ll 100 \) GV the extrapolation of the HEAO3 B/C data falls below the more recent AMS02 measurement. In addition, [46] assumed a primary proton flux with high energy spectral index \( p = 2.84 \), softer by about \( \rho = 0.12 \) than the proton flux seen by AMS02: the implications of this soft proton spectrum can be estimated from Fig. 3.

As a result, [46] predicted a low \( \bar{p}/p \) flux. To illustrate this fact, we show in Fig. 4 by a red line the result we find if we calculate the \( \bar{p}/p \) ratio using Eq. (1), but plugging in the value of \( X \) derived for the diffusion model of [46] with \( \delta = 0.7 \) and using the same proton flux assumed there. The discrepancy with Ref. [46] is reproduced.

III. WHAT IS THE ISSUE WITH e^+?

Measurements of the positron fraction \( e^+/e = e^+/e + e^- \) by the PAMELA [8, 9] and AMS02 [15] experiments have shown that \( e^+/e \) is rising with energy from a few GeV to at least 300 GeV. This trend of rising \( e^+/e \) was claimed by many to indicate a primary source dominating the \( e^+ \) flux at these energies. Understanding the true story behind CR \( e^+ \) is...
JCAP 1111 (2011) 037 Blum
PRL 111 (2013) no.21, 211101 Blum, Katz, Waxman
1704.05431 Blum, Ng, Sato, Takimoto
PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/c PROTON–NUCLEON COLLISIONS

A. BUSSIÈRE$^3$, G. GIACOMELLI$^1$, E. LESQUOY$^2$, R. MEUNIER$^2$, L. MOSCOSO$^2$, A. MULLER$^2$, F. RIMONDI$^1$, S. ZUCCHELLI$^1$ and S. ZYLBERAJCH$^2$
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<table>
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<tr>
<th>$p_0$ (GeV/c)</th>
<th>Target</th>
<th>Lab momentum (GeV/c)</th>
<th>$d/\pi^+$ $(10^{-4})$</th>
<th>$t/\pi^+$ $(10^{-7})$</th>
<th>$^{3}\text{He}/\pi^+$ $(10^{-7})$</th>
<th>$\bar{d}/\pi^-$ $(10^{-6})$</th>
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The data have been corrected to the centre of the production targets.
PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/c PROTON–NUCLEON COLLISIONS

sparse data

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<thead>
<tr>
<th>$p_0$ (GeV/c)</th>
<th>Target</th>
<th>Lab momentum (GeV/c)</th>
<th>$d/\pi^+$ (10$^{-4}$)</th>
<th>$t/\pi^+$ (10$^{-7}$)</th>
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<td>200</td>
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The data have been corrected to the centre of the production targets.
PARTICLE PRODUCTION AND SEARCH FOR LONG-LIVED PARTICLES IN 200–240 GeV/c PROTON–NUCLEON COLLISIONS

\[ t/\text{He} \gg 1 \text{ for antimatter, } t/\text{He} \leq 1 \text{ for matter} \]

### Table 2

Rates of production of nuclei and antinuclei relative to pions of the same sign

<table>
<thead>
<tr>
<th>( p_0 ) (GeV/c)</th>
<th>Target</th>
<th>Lab momentum (GeV/c)</th>
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The data have been corrected to the centre of the production targets.
Reported only particle/pion ratios.

Interpreted cross section by scaling w/ model of pion cross section

Prone to large error, especially at < 10 GeV
About diffusion models

\[ K \sim (E/Z)^{\delta} \]

\[ \nu \approx 0.29 \times \frac{3eB}{4\pi m_e c} \left( \frac{\epsilon}{m_e c^2} \right)^2 \approx 1 \text{ GHz} \left( \frac{B}{1 \mu G} \right) \left( \frac{\epsilon}{15 \text{ GeV}} \right)^2 \]

NGC 891

\[
\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}
\]
Secondary: upper bound

\[f_{e^+}(\mathcal{R}) \leq 1\]

AMS02 data favours secondary origin for CR \(e^+\).
In Fig. 6 we show astrophysics and consider the interplay of as we go to higher with a puzzle. If respectively, as specified in the legend. Taken from [55].

Systematic cross section uncertainties in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the secondary production regions. AMS02 data favours secondary origin for CR e+. For later convenience it proves useful to define the loss suppression factor

\[
\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}
\]

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\[f_{e^+}(\mathcal{R}) \leq 1\]

AMS02 data favours secondary origin for CR e+.
anti He3

1. Handful of events

2. Energy of 1 event they show is 40GeV (13GeV/nuc)

Kinematics:
pp → (He3bar) + X requires minimum 8 baryons

This means threshold in observer frame is 12 GeV

AMS02 press release, Dec 2016

An anti-Helium candidate:

Momentum = 40.3 ± 2.9 GeV/c
Charge = -2
Mass = 2.96 ± 0.33 GeV/c^2
Velocity = 0.9973 ± 0.0005 c
Summary
Cosmic Rays

The Galaxy is filled with a gas of high-energy particles, of several types

Magnetic rigidity

\[ \mathcal{R} = \frac{p}{Z} \]

Larmor radius

\[ L = \mathcal{R}/B \approx 3 \times 10^{-4} \left( \frac{\mathcal{R}}{\mathcal{R}_{TV}} \right) \left( \frac{B}{3 \mu G} \right)^{-1} \text{ pc} \]

Energies and rates of the cosmic-ray particles

Galactic:
CR antimatter – $\bar{p}$, $e^+$, $\bar{d}$, and $^3\text{He}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

**Antiprotons**

Some confusion in the literature, as to what and how we can calculate.

=>$\text{will try to sort this out}$

AMS02, Dec 2016
CR antimatter – \( \bar{p}, e^+, \bar{d}, \) and \( \bar{3}\text{He} \) long thought a smoking gun of exotic high-energy physics like dark matter annihilation

### Positrons
Common belief in the literature: \( e^+ \) come from either pulsars, or dark matter!

=> don’t think so.

Will try to sort this out, too

---

AMS02, Dec 2016
CR antimatter – $\bar{p}, e^+, \bar{d}$, and $\bar{3He}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

**Anti-helium**
Thought so scarce that a single event would mark new physics.
But how does one actually calculate the flux?

=> will show that previous ideas may have been *off the mark*.

**AMS02** may soon detect astrophysical anti-He3
CR antimatter – $\bar{p}$, $e^+$, $\bar{d}$, and $\bar{^3He}$ long thought a smoking gun of exotic high-energy physics like dark matter annihilation

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AMS02 may have detected astrophysical anti-He3
Cosmic Rays

The Universe is filled with a gas of high-energy particles
Cosmic Rays

The Universe is filled with a gas of high-energy particles
Cosmic Rays

Two basic populations:

1. **primary** (p, He, C, O, Fe, e-,...),

2. **secondary** (B, sub-Fe, pbar, e+,...),

Hillas, astro-ph/0607109

Energies and rates of the cosmic-ray particles
Cosmic Rays

Two basic populations:

1. **primary** \((p, \text{He}, \text{C}, \text{O}, \text{Fe}, e^-, \ldots)\), consistent with stellar material, accelerated to relativistic energy

2. **secondary** \((B, \text{sub-Fe}, \text{pbar}, e^+, \ldots)\),

Hillas, astro-ph/0607109
Cosmic Rays

Two basic populations:

1. **primary** (p, He, C, O, Fe, e−,...), consistent with stellar material, accelerated to relativistic energy

2. **secondary** (B, sub-Fe, pbar, e+,...), consistent w/ spallation products of primary component
Recipe for an antiproton pie:
Recipe for an antiproton pie:

\[
\frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)} \quad \Rightarrow \quad n_p(R) \approx \frac{n_B(R)}{Q_B(R)} Q_p(R)
\]
**Recipe for an antiproton pie:**

\[ \frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_p(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_p(\mathcal{R}) \]

\[ Q_a(\mathcal{R}) = \sum_P n_P(\mathcal{R}) \frac{\sigma_{P \rightarrow a}(\mathcal{R})}{m} - n_a(\mathcal{R}) \frac{\sigma_a(\mathcal{R})}{m} \]
**Recipe for an antiproton pie:**

\[
\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \text{for } n_p(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_p(\mathcal{R})
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\frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)}
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Average column density traversed by CR nuclei during propagation
Recipe for an antiproton pie:

\[
\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}
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\]

Average column density traversed by CR nuclei during propagation

\[
X_{\text{esc}}(\mathcal{R}) = \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})}
\]

\[
X_{\text{esc}} = \frac{(B/C)}{\sum_{P=C,N,O,...} \left( \frac{P}{C} \right) \frac{\sigma_{P \rightarrow B}}{m} - \left( \frac{B}{C} \right) \frac{\sigma_B}{m}}
\]
Recipe for an antiproton pie:

\[
\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}
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\[
n_p(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
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Recipe for an antiproton pie:

\[
n_p(R) \approx \frac{n_B(R)}{Q_B(R)} Q_p(R)
\]

\[
\sigma_{p \rightarrow p}(R) = \frac{2 \int_R^\infty dR_p J_p(R_p) \left( \frac{d\sigma_{pp \rightarrow pX}(R_p,R)}{dR_p} \right) }{J_p(R)}
\]
Recipe for an antiproton pie:

\[ n_p(R) \approx \frac{n_B(R)}{Q_B(R)} Q_{\bar{p}}(R) \]


Winkler, JCAP 1702 (2017) no.02, 048

1709.04953 Blum, Sato, Takimoto
Recipe for an antiproton pie:

\[ n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R}) \]

![Diagram of AMS proton flux](image)
Recipe for an antiproton pie:

\[
n_\bar{p}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
\]
\[
\frac{n_{e^+}}{n_{p\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{p\bar{p}}(\mathcal{R})}
\]

A more robust derivation:

**Relate e+ to pbar**

Rather than directly to B/C
In Fig. 6 we show For later convenience it proves useful to define the loss suppression factor astrophysics and consider the interplay of as we go to higher loss in suppressing the with a puzzle. If locally measured in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the.

FIG. 5:

For early comprehensive analyses see e.g. [57–59].

\[ \frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})} \]

Secondary upper bound

\[ f_{e^+}(\mathcal{R}) \leq 1 \]

A more robust derivation:

Relate e+ to pbar

Rather than directly to B/C
\[ \frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})} \]

Secondary upper bound: \( f_{e^+}(\mathcal{R}) \leq 1 \)

![Graph](image_url)

- Blue: \( J_p \propto E^{-2.4} \)
- Orange: \( J_p \propto E^{-2.7} \)
- Green: \( J_p \propto E^{-3} \)
- Dotted: \( J_{p,\text{obs}} \)
- Red: \( e^+/\bar{p}; \text{AMS02 (2016)} \)
Why would dark matter or pulsars inject \textit{this} e+ flux?
Why would dark matter or pulsars inject this e+ flux?
Why would dark matter or pulsars inject \textit{this} e\(^+\) flux?

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}

Why would dark matter or pulsars inject \textit{this} \( e^+ \) flux?
Production of light nuclei and anti-nuclei in \( pp \) and Pb-Pb collisions at energies available at the CERN Large Hadron Collider

J. Adam et al. (ALICE Collaboration)
Phys. Rev. C 93, 024917 – Published 29 February 2016

Production of nuclei and antinuclei in \( pp \) and Pb–Pb collisions with ALICE at the LHC

Natasha Sharma (for the ALICE Collaboration)
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FIG. 3: Coalescence factor $B_2$ (Top) and $B_3$ (Bottom) vs. HBT radius. The prediction of Eqs. (11-12) is shown as solid line. Details of the data analysis are given in App. A. (Boxes denote systems for which the coalescence factor and the HBT radius are taken from different data sets.)

Results from the ALICE experiment allow us to make a preliminary test of Eq. (14). Ref. [55] reported $^{3}\text{He}$ and $^{3}\text{t}$ in the ALICE pp run, corresponding to luminosity $L \sim 2\times 10^7 \, \text{nb}$. With a pseudo-rapidity cut $10^{-5} \leq \eta \leq 10^{-2}$, the expected number of events as function of $B_3$ is shown by the red line. The efficient production cross section $\sigma_{pp \rightarrow 3\text{He}}$ was given in [56]. In Fig. 4 we use these parameters to calculate the expected number of $^{3}\text{He}$ or $^{3}\text{t}$ events and compare with data. The result supports a coalescence factor $B_3 \sim 10^{-1}$, in agreement with Eq. (14). A dedicated analysis by the ALICE collaboration is highly motivated.

Two channels produce a final state $^{3}\text{He}$: direct $pp \rightarrow ^{3}\text{He}$ and $pp \rightarrow \bar{p}p$ + subsequent decay $3\text{He}$. The first channel should suffer some Coulomb suppression with a Gamow factor that can be estimated by $f_{\text{coul}} \approx e^{-\frac{\pi m_p}{2 E_{\text{kin}}}}$. Eq. (14) suggests $p_{\text{coul}} \approx 0.1$, leading to $f_{\text{coul}} \approx 0.8$. This is supported by experimental results on the relative yield $^{3}\text{He}/^{3}\text{t}$ [55–57] that are consistent with $f_{\text{coul}} \approx 1$. (Ref. [58] reported $^{3}\text{He}/^{3}\text{t} < 1$; however, the $^{3}\text{He}/^{3}\text{t}$ data from the same publication show an opposite trend, $^{3}\text{He}/^{3}\text{t} > 1$.) In what follows, for concreteness we focus on $pp \rightarrow \bar{p}p$ but we include a factor of 2 increased yield from the direct $pp \rightarrow ^{3}\text{He}$ channel.

Combining Eq. (14) with the $pp \rightarrow \bar{p}p$ production cross section [38, 39], we use Eq. (6) to obtain the differential cross section $E_{pp \rightarrow \bar{p}p} dN_{pp \rightarrow \bar{p}p} / dt$, where $E_{pp \rightarrow \bar{p}p}$ is the total inelastic pp cross section [59, 60]. The effective production cross section to be used in Eq. (2) is then $E_{pp \rightarrow \bar{p}p} / (E_{pp \rightarrow \bar{p}p} + E_{pp \rightarrow ^{3}\text{He}})$. We thank Natasha Sharma for clarifying the experimental procedure.
FIG. 3: Coalescence factor $L^2$. (Top) and $3^2$ (Bottom) vs. $N_{\text{obs}}$. The cross section for $\text{He}$ events from the ALICE collaboration is highly motivated. 

Combining Eq. (14) with the yield reported for the analysis, we use Eq. (6) to obtain the differential efficiency for $\text{He}$ or He/t $= 7$ TeV run, corresponding to some Coulomb suppression with a Gamow factor that can be estimated. Eq. (14) suggests $L^2 = \frac{1}{2}$. Eq. (15) shows by the red line. The first channel should support a coalescence factor $3^2$ $< 1$; however, the opposite trend, $3^2 < 1$, is supported by experimental procedure.

Ref. [58] reported 20 anti-He3 and 20 anti-t events observed @ L~2.2/nb
Preliminary Physics Summary:
Deuteron and anti-deuteron production in pp collisions at $\sqrt{s} = 13$ TeV
and in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Preliminary
deuterons, $|y| < 0.5$
FIG. 3: Coalescence factor $B_2$ (Top) and $B_3$ (Bottom) vs. HBT radius. The prediction of Eqs. (11-12) is shown as solid line. Details of the data analysis are given in App. A. (Boxes denote systems for which the coalescence factor and the HBT radius are taken from different data sets.)

Results from the ALICE experiment allow us to make a preliminary test of Eq. (14). Ref. [55] reported $^{3}\text{He}$ and $^{3}\text{t}$ in the ALICE pp run, corresponding to luminosity $L\sim 2\times 10^2 nb$ with a pseudo-rapidity cut $|\eta|<0.9$ and with no further $p_T$ cut.

The $p_T$-dependent efficiency for $^{3}\text{He}$ detection was given in [56]. In Fig. 4 we use these parameters to calculate the expected number of $^{3}\text{He}$ or $^{3}\text{t}$ events and compare with data. The result supports a coalescence factor $B_3(\text{pp})\sim (5\pm 8)\times 10^{-4}$ GeV$^4$, in agreement with Eq. (14). A dedicated analysis by the ALICE collaboration is highly motivated.

CR anti-helium. Two channels produce a final state $^{3}\text{He}$: direct $\text{pp} \rightarrow ^{3}\text{He}$ and $\text{pp} \rightarrow ^{3}\text{He}$ subseqeuent decay $\text{t} \rightarrow ^{3}\text{He}$. The first channel should suffer some Coulomb suppression with a Gamow factor that can be estimated by $f_{\text{coul}} \sim e^{-\frac{\mu}{m_p}p_T}$. Eq. (14) suggests $p_T \sim 0.1-0.2$ GeV, leading to $f_{\text{coul}} \sim 0.8-0.9$. This is supported by experimental results on the relative yield $^{3}\text{He}/\text{t}$ [55–57] that are consistent with $f_{\text{coul}} \sim 1$. (Ref. [58] reported $^{3}\text{He}/\text{t} < 1$; however, the $^{3}\text{He}/\text{t}$ data from the same publication show an opposite trend, $^{3}\text{He}/\text{t} \sim 1$.) In what follows, for concreteness we focus on $\text{pp} \rightarrow \text{t}$ but we include a factor of 2 increased yield from the direct $\text{pp} \rightarrow ^{3}\text{He}$ channel.

Combining Eq. (14) with the $\text{pp} \rightarrow \bar{\text{p}}$ production cross section [38, 39], we use Eq. (6) to obtain the differential cross section $E_{\text{t}} \frac{dN_{\text{t}}}{d^2p_T} = \frac{pp}{E_{\text{t}}} \frac{dN_{\text{t}}}{d^2p_T}$, where $pp$ is the total inelastic pp cross section [59, 60]. The effective production cross section to be used in Eq. (2) is then $pp \rightarrow ^{3}\text{He}(R) = \frac{Z}{2} \langle \bar{p}_n p \rangle \langle \bar{p} n \rangle (R) \frac{d\sigma_{\text{pp} \rightarrow \text{t}}}{dp_T}$.

We thank Natasha Sharma for clarifying the experimental procedure.
Implication of ALICE results for astrophysics.

He3bar: secondary production by pp collisions unlikely to explain 1 event/yr at AMS02.
Implication of ALICE results for astrophysics.

He3bar: secondary production by pp collisions unlikely to explain 1 event/yr at AMS02.

1 event/5yr we could live with, but 1 event/yr seems unlikely.

What about p-pbar collisions?
Implication of ALICE results for astrophysics.

Secondary production by $pp$ collisions may be seen at AMS02 5yr exposure.