Secondary particles in the Galaxy: the role of cross sections

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Paris 05.12.2022 - "Cosmic Ray in the Multi-Messenger Era"

<u>Primaries</u>: produced in the sources (SNR and Pulsars) H, He, CNO, Fe; e-, e+; possibly e+, p-, d-from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, […], (radioactive) isotopes ; e+, p-, d-

The spectrum of secondary fluxes

See talk by Paolo Zuccon

The rigidity dependence of Li, Be and B are nearly identical, but different from the primary He, C and O (and also p).

Li, Be, B fluxes measured by Pamela and AMS show an identical hardening w.r.t. energy above 200 GV. The spectral index of secondaries hardens 0.13 +- 0.03 more than for primaries

Propagation models vs data

Korsmeier & Cuoco, PRD 2021

Several propagation models are tested

Fragmentation cross section uncertainties currently prevent a better understanding of CR propagation

Propagation models vs data

Weinrich+ A&A 2020

Data on secondary/primary species are well described by propagation model with diffusione coefficient power index δ = 0.50 ± 0.03.

Convection + reaccelerating, or pure diffusion both work.

Cross sections for Galactic cosmic rays

Data driven parameterizations (Silberberg&Tsao), semi-empirical formulae (Webber+), parametric formulae/direct fit to the data (Galprop), MonteCarlo codes (Fluka, Geant, …)

Genolini, Moskalenko, Maurin, Unger PRC 2018

Differences in the XS parameterizations

Genolini, Putze, Salati, Serpico A&A 2015

Differences in one parameterization wrt a benchmark model

Even with the same, although scarce data, interpretation may be different

Fragmentation cross sections

They matter in both directions: as a loss term for progenitors, as a source term for daughters

De La Torre Luque+ JCAP 2021 Weinrich+ A&A 2021

Probably the most limiting aspect now Dedicated campaigns are needed (LHCb, NA61, Amber/Compass, …)

Improve Boron production cross sections Most relevant physics cases

Genolini, Moskalenko, Maurin, Unger PRC 2018

Antimatter

in the Galaxy

Antiproton production by inelastic scatterings

Korsmeier, FD, Di Mauro PRD 2018

$$
q_{ij}(T_{\bar{p}})=\int\limits_{T_{\rm th}}^{\infty}dT_i\,\,4\pi\,n_{{\rm ISM},j}\,\phi_i(T_i)\,\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i,T_{\bar{p}}).
$$

$$
\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T,T_{\bar{p}})=p_{\bar{p}}\int d\Omega\,\,\sigma_{\rm inv}^{(ij)}(T_i,T_{\bar{p}},\theta).
$$

Data from space are very precise

We need cross sections at <3%

Recent data at collider nel applies to a helium target and how the cross section extrapolation to high energies works. Moreover, finding an agreement between LHCb data and predictions based

 $phle \rightarrow pbar + X$ $P₁$ detection threshold above 100 $C₁$ and $C₂$ above 100 $C₃$ and $C₄$

lowering the incident proton energy below 1 TeV. In $L H CD$ (Graziani et al. M oriong 2017) $\sqrt{s} = 110 \text{ GeV}$ $T_p = 6.5$ TeV pendix C to determine the whole relevant parameter

Fraction of the pp source term covered by the kinematical parameters space

considered in previous parameterizations: isospin viola-

Fraction of the p-nucelus source term covered by the kinematical parameters space

space of *pA* cross sections to interpret AMS-02 data.

the first time how well the rescaling from the *pp* chan-

and models. The way to improve the contribution of

The antiproton source spectrum

Korsmeier, FD, Di Mauro, PRD 2018

The effect of LHCb data is to select a high energy trend of the pbar source.

A harder trend is preferred.

Effects on the total pbar production rescaling from *p* + *p* ! *p*¯ + *X* cross section. Therefore, we update the most recent parametrizations from Die Martin (Parameter (Parameter (Parameter (Parameter (Parameter (Parameter (Parameter (Parameter (Parameter
Eine Parameter (Parameter (Parameter (Parameter in Parameter (Parameter in Parameter in Parameter in Parameter exploiting the newly available NA61 data. Then we and II are compatible within uncertainties, which are ppar production *≠* dominanty is dominant to uncertainty in dominant to uncertainty in dominant to uncertainty in dominant to uncertainty in the uncertainty is dominant to uncertainty in the uncertainty in the uncertainty is dominant

nated by *p*
2018 - Xorsmeier, FD, Di Mauro, 1802,03030, PRD $i \in \{1, 2, \ldots, n\}$ is anti-induced and $i \in \{1, 3, \ldots, n\}$ in the $n \ge 0$ Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018

production increases the uncertainty by an additional

5%. Overall the secondary antiproton source spectrum

coverage of the kinematic parameter space of this data

do not allow a standalone parametrization, we apply a

determine the rescaling factor to proton-nucleus using

Result with uncertainties in the hyperon correction and isospin violation $\frac{1}{2}$ supplementary to the energydi↵erential cross sections, which are required to calcu-

The antiproton source term is affected by uncertainties of ± 10% from cross sections. \mathbf{r} the necessity of necessity of new data on antiproton proe anciprocon source cerm

> Higher uncertainties at very low energies

CALCEMS and *comodernis* AMS-02 antiprotons as the locally measured ¯*p*'s statistically consistent with the $\cos\theta$ considerations, it is bust with respect to extend in the spectrum of 100
100 ֧֧֧֧֧֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֚֬֝֝֬֝֓֝֓֝֬ 2 *R* [GV] data are defined to be to b AMS-02 antiprotons are consistent with a state and the contract of the secondary astrophysical origin Residuals [%]

*^C*model; (iii) In the most realistic case considering both

*^C*data 0.84 0.79 0.98

stat and *^C*model 1.32 0.05 0.99

We take dof= 57, i.e. the number of ¯*p* data. Total errors on

Parents

Transport

major upgrade of the ¯*p* flux prediction and analysis by:

any steady-stade propagation model of similar complex-

is calibrated), with roughly the same grammage enter-

The residuals of the eigen vectors of the total covariance ma-

M. Boudaud, Y. Genolini, L. Derome, J.Lavalle, Iah: PM Cann σ ρ . θ transportante de la composición de la
Entre el composición de la composición Total D.Maurin, P. Salati, P.D. Serpico PRD 2020

The residuals of the eigen vectors of the total covariance ma-

Secondary pbar flux is predicted c predictions in the mother contribut A dark matter contribution wo with respectively of the model confidence intervals *are consistent with a pure secondary astrophysical origin.* We stress that *this conclusion is not based on a fit to the A dark matter contribut puted from external data.* Our results should hold for F_{IGA} enLoichauk with AMS-02 Anto with residuals and 68% total confidence interval for the model for the model for the model of the model of the
The model of the model for the model of the mo (would come as a tiny effect and the cross sections (green) contributions (middle panel). Secondary pbar flux is predicted consistent with AMS-02 data A dark matter contribution would come as a tiny effect

 $\frac{1}{2}$ Parents $\frac{1}{2}$ $\overline{1}$ Total Care (i) was a constraint constraint on the latest constraints on the latest constraints on the latest constraints on the latest constant of the latest constraints on the latest constraints on the latest constraints on the late Fransport and cross section unc \mathbf{z}_i \mathbf{r} as well as the bottom panel as the bottom panel as the bottom panel are shown in the bottom panel as \mathbf{r} *i*ranspo ity, as the same "even" as the same "end" and same "even" crossed to produce boron nuclei (on which the analysis trix as well as the bottom \mathbb{R} . The bottom panel is the bottom panel in the bottom panel in the bottom panel is the bottom panel in the Transport and cross section uncertainties are comparable

For next generation experiments FFT MOXF GOMOTAFIGM OXDOTIMOMORE of the cross section which currently is experimentally determined by NA61 data in the *pp* channel (left panel) and by LHCb data in the *p*He (central panel) or He*p* (right panel) channels. We add future predictions for a possible evaluation of NA61

term of the specific channel.

data at provins at provins at provins at provins at provins at provins and to the total source to the total sour
Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018

AMS-02 accuracy is reached if pp —> pbar cross section is measured with 3% accuracy inside the regions, 30% outside. term at the uncertainty level of AMS-02 measurements [12]. We require the cross section to be known by 3% within the blue 15-02 accuracy is reached it pp -> pbar cross section is measured with figure is an update of Fig. 7b in DKD17. We exchange the kinetic variable *x*^R by *x^f* , which is suitable for the asymmetric *pA*

The new frontier of cosmic antiprotons: low energies by GAPS

Rogers et al. (GAPS Coll.) Astrop. Phys. 2023, 2206.12991

Sub-GeV antiprotons will be measured in 2023 (and 2025, 2027) by GAPS. Robust predictions are needed: cross sections, propagation, solar modulation

Positrons (e±)

e+ production channels

$$
q_{ij}(T_{e^+}) = 4\pi n_{\text{ISM},j} \int dT_i \, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+})
$$

$$
p + H
$$
\n
\n
$$
p + H
$$
\n

We include all these contributions.

Similarly for collisions with nuclei.

We repeat ALL the analysis for eunder charge conjugation

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

The e± production chain from π± production

$$
\frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+}) = \int dT_{\pi^+} \frac{d\sigma_{ij}}{dT_{\pi^+}}(T_i, T_{\pi^+}) P(T_{\pi^+}, T_{e^+})
$$

Integral over the pion production cross section convolved with the probability density function P

$$
\frac{d\sigma_{ij}}{dT_{\pi^+}}(T_i, T_{\pi^+}) = p_{\pi^+} \int d\Omega \; \sigma_{\text{inv}}^{(ij)}(T_i, T_{\pi^+}, \theta)
$$

The pion production cross section is the integral of the lorentz Invariant cross section over scattering angle (or pT)

$$
\sigma_{\rm inv}^{(ij)} = E_{\pi^+}\frac{d^3\sigma_{ij}}{dp_{\pi^+}^3}
$$

<— data

A fit is performed on the σinv data

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We use data on σinv, the multiplicity n or both.

Analytical formulae for e± production XS

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The procedure is fully data driven

$$
\sigma_{\rm inv} = \sigma_0(s) c_1 \left[F_p(s, p_T, x_R) + F_r(p_T, x_R) \right] A(s)
$$

$$
F_p(s, p_T, x_R) = (1 - x_R)^{c_2} \exp(-c_3 x_R) p_T^{c_4}
$$

× exp $\left[-c_5 \sqrt{s/s_0} \, {c_6} \left(\sqrt{p_T^2 + m_\pi^2} - m_\pi \right)^{c_7 \sqrt{s/s_0}} \, {c_6} \right]$

$$
F_r(p_T, x_R) = (1 - x_R)^{c_8}
$$

$$
\times \exp\left[-c_9 p_T - \left(\frac{|p_T - c_{10}|}{c_{11}} \right)^{c_{12}} \right]
$$

$$
\times \left[c_{13} \exp(-c_{14} p_T^{c_{15}} x_R) + \right.
$$

$$
+ c_{16} \exp\left(-\left(\frac{|x_R - c_{17}|}{c_{18}} \right)^{c_{19}} \right)
$$

$$
A(s) = \frac{1 + \left(\sqrt{s/c_{20}}\right)^{c_{21} - c_{22}}}{1 + \left(\sqrt{s_0/c_{20}}\right)^{c_{21} - c_{22}}}\left(\sqrt{\frac{s}{s_0}}\right)^{c_{22}}
$$

Fs and Fr mainly driven by NA49 data High energy behavior A(s) tested on CMS and ALICE data

Results on the σinv for π+ production

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

Data are fitted with very small uncertainties Our parameterizations result appropriate, data are very precise

Total cross section from pp—> e+ + X

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

All channels contributing >0.5% are included. Uncertainty globally contained to <10%

Effect of scattering off nuclei

We need a model for the scattering involving He. No data are there. We rely on NA49 p+C—>e++X data L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

Uncertainty is small, but very likely is not true Data on He are necessary

Final results on e+ cross section

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

He-He CNO AAfrag p-p **CNO** AAfrag p-p He-He S^{-1} q^{e^+} $T_{e^+}^{2.7}$ [GeV^{1.7} m⁻³ s⁻¹] 10^{-20} He-p Kamae He-p p-He Kamae Total p-He Total 10^{-20} $T_e^{2.7}$ [GeV^{1.7} m⁻³ 10^{-21} 10^{-21} q^e 10^{-22} 10^{-22} 0.2 0.2 Rel. unc. Rel. unc. 0.1 0.1 0.0 0.0 -0.1 -0.1 -0.2 $+$
 10^{-2} -0.2 $+$ -2 10^{-1} $10⁰$ $10¹$ $10²$ 10^{-1} $10⁰$ $10¹$ $10²$ $10³$ $10³$ T_{e^+} [GeV] T_e - [GeV]

Production cross section is now known why 7-8% uncertainty above 1 GeV. Below we extrapolate. Comparison with MonteCarlo computations is done for p-p. Similar results for e-.

Positrons Electrons

Comparison with Monte Carlo generators

Koldobskiy et al., PRD 2021, 2110.00496

Results with Aafrag

FIG. 9: Electron and positron fluxes for a power-law cosmic ray spectrum $(\propto 1/p^2 \exp(-p/p_0))$.

Different MC modelings lead to considerable differences in the Production cross section, and consequently on the source spectrum

The role of e± secondaries

M. Di Mauro, FD, S. Manconi PRD 2021

e+ secondaries contribute significantly to shape the spectrum at Earth. The flux in the GeV region is likely dominated by secondaries A PRIMARY component is surely there at high energies

The case for

Antideuterons

See M. Kachelriess' talk

Antideuterons persepctives

Serksnyte et al,PRD 2022

Low energy window keeps being a discovery field Uncertainties on Pc is ± 70%

Wishes' list

Partial, and personal

- 1. Low energy (0.1 <Tpbar<10 GeV) antiprotons from p-p
- 2. Antideuteron fusion at low energies (p beam ~ 10-102 GeV)
- $3.$ p+He-> e++X (p+He-> π ++X)
- 4. 12C+p —> LiBeB fragments with isotopes
- + many more!

Conclusions

Great efforts to better understand nuclei and antinuclei in CRS: theory models, data from space, data from colliders.

Data from space are actually hampered by lack of precise (<10%) ross section: nuclei, isotopes, antimatter, ys

Data from colliders are highly desirable. A specific receipt can be provided by the astroparticle community

Most relevant physics cases

Improve Lithium production cross sections

Genolini, Moskalenko, Maurin, Unger PRC 2018

Improve Beryllium production cross sections

Genolini, Moskalenko, Maurin, Unger PRC 2018

Data correction for feed-down

The pion production cross section can contain (or not) the pions From weak decays of strange particles.

 0.15 dn/dx_F 0.1 K_c^0 (x 0.2 0.05 0.2 0.4 Ω 0.6 0.8 X_{E}

C. Alt et al., Eur. Phys. J. C, 2005

NA49 pt integrated, MC

Almost all the data except the older ones are feed-down corrected. When not, we correct for it.

Fluka MC generator

N. Mazziotta+, AP 2017

Points are from Dermer 1986

Te is severely degraded from Projectile energy

Propagated e+ and e- w.r.t. data

Light nuclei: primaries and secondaries

Genolini, Moskalenko, Maurin, Unger PRC 2018

TABLE I. Fractions of primary/fragmentation/radioactive origin (w.r.t. total flux), and contributions of $1-2$ -/'morethan-2' step channels (w.r.t. total secondary production) at 10 GeV/n . These numbers are independent of the propagation model if sources have the same spectral index.

Results at large sqrt(s)

L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

We use σ_{inv} or multiplicity

Uncertainties between 5% and 10% - most relevant is 5% at low pt

Antimatter or γ-rays sources from DARK MATTER

Annihilation

$$
\mathcal{Q}_{\rm ann}(\vec{x},E) = \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_{e^\pm}^f}{dE}
$$

Decay

$$
\mathcal{Q}_{\mathrm{dec}}(\vec{x},E) = \quad \left(\frac{\rho(\vec{x})}{m_{DM}}\right) \sum_f \Gamma_f \frac{dN_{e^\pm}^f}{dE}
$$

- ρ DM density in the halo of the MW
- m_{DM} DM mass
- <σv> thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Annihilations take place in the whole diffusive halo

Effect of galactic propagation

Genolini+ 2103.04108

Galactic propagation has strong impact on Dark Matter induced fluxes

New AMS-02 sec/prim data allow reduction of propagation uncertainties

Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017

Antiproton data are so precise that permit to set strong upper bounds on the dark matter annihilation cross section, or to improve the fit w.r.t. to the secondaries alone adding a tine DM contribution

Heisig, Korsmeier, Winkler PRD2020 2020

