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Antihelium-3 fluxes near Earth using data-driven estimates for annihilation cross section

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Antinuclei found in cosmic rays could provide a smoking gun signal for dark matter as this signal is virtually background free. The study of $^3\overline{\mathrm{He}}$ cosmic rays requires the knowledge of their production, propagation in the galaxy and annihilation cross-section. While the former two have been already estimated with data-driven methods, there were no experimental data available for the $^3\overline{\mathrm{He}}$ inelastic cross section. We measured for the first time the inelastic cross section of $^3\overline{\mathrm{He}}$ using the ALICE detector itself as a target. To study the effect of $^3\overline{\mathrm{He}}$ annihilation in the galaxy and estimate the transparency of the galaxy, the $^3\overline{\mathrm{He}}$ source functions and annihilation cross sections were implemented in GALPROP.

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1. Introduction

The yet undetected dark matter is expected to account for the missing mass in the Universe. Weakly interacting massive particles (WIMPs) are believed to annihilate and produce particle-antiparticle pairs of the ordinary matter. Antinuclei produced in our galaxy by dark matter annihilation processes would propagate and be detected as antimatter cosmic rays in the Earth's proximity. However, antinuclei can also be produced by cosmic ray collisions with the interstellar gas. This contribution represents a background source for dark matter searches. Luckily, the cosmic ray flux from the two sources peaks at different kinetic energies and the dark matter signal is virtually background free. The measurement of antinuclei cosmic rays would hence provide a smoking gun signal for dark matter.

The modelling of the behaviour of the background and signal is mandatory to draw conclusions for antinuclei fluxes. This work focuses on the description of the behaviour of $^{3}\overline{\mathrm{He}}$ cosmic rays in our galaxy. The full-scale description of the fluxes can be implemented in a transport equation which requires the knowledge of three main components: the production cross section of antinuclei, their annihilation cross section and their propagation in the galaxy. The transport equation can be solved numerically using the publicly available GALPROP code [1].

The $^{3}\overline{\mathrm{He}}$ production cross sections and the propagation parameters can be constrained using existing experimental data, while no measurement of the inelastic cross section of the $^{3}\overline{\mathrm{He}}$ was available up to now. We provide the first ever measurement of the inelastic cross section of $^{3}\overline{\mathrm{He}}$ using the ALICE detector as a target material. We implement the $^{3}\overline{\mathrm{He}}$ cosmic ray source functions and our obtained inelastic cross sections in GALPROP to study the effect of annihilation processes in the Galaxy.

2. $^{3}\overline{\mathrm{He}}$ Inelastic Cross Section Measurement

At LHC energies, matter and antimatter are produced in almost equal amounts. The $^{3}\mathrm{He}$ and $^{3}\overline{\mathrm{He}}$ are produced rather copiously as it can be seen in Fig. 1, where the specific energy loss measured by the ALICE Time Projection Chamber (TPC) [12] as a function of the momentum for particle (on the left) and antiparticle (right) is shown. Thus the LHC offers optimal conditions to study such nuclei. To measure the inelastic cross section of antinuclei, the different interaction of matter and antimatter with the detector is exploited. As it was shown in antideuteron studies [3], the antimatter-to-matter ratio is very sensitive to the inelastic cross sections. The $^{3}\overline{\mathrm{He}}$ /$^{3}\mathrm{He}$ can be expressed as:

$$\frac{^{3}\overline{\mathrm{He}}}{^{3}\mathrm{He}} = \left(\frac{^{3}\overline{\mathrm{He}}}{^{3}\mathrm{He}}\right)_{\mathrm{prim}} \cdot \exp\left(-\alpha(\sigma_{\mathrm{inel}}^{^{3}\overline{\mathrm{He}}} - \sigma_{\mathrm{inel}}^{^{3}\mathrm{He}})\Delta x\right). \quad (1)$$

Here, $\frac{^{3}\overline{\mathrm{He}}}{^{3}\mathrm{He}}$ is the measured ratio of the number of antihelium and helium while $\left(\frac{^{3}\overline{\mathrm{He}}}{^{3}\mathrm{He}}\right)_{\mathrm{prim}}$ is the primordial ratio. The traversed path length is indicated with Δx and $\alpha = \rho N_A/M$, where N_A is the Avogadro's number, ρ and M are the density and the molar mass of the target, respectively. The inelastic cross sections of helium and antihelium with matter are denoted as $\sigma_{\mathrm{inel}}^{^{3}\overline{\mathrm{He}}}$ and $\sigma_{\mathrm{inel}}^{^{3}\mathrm{He}}$, respectively. As the inelastic cross section of $^{3}\mathrm{He}$ is rather well known, the ratio $^{3}\overline{\mathrm{He}}$ /$^{3}\mathrm{He}$ can be used to obtain the inelastic cross section of $^{3}\overline{\mathrm{He}}$.

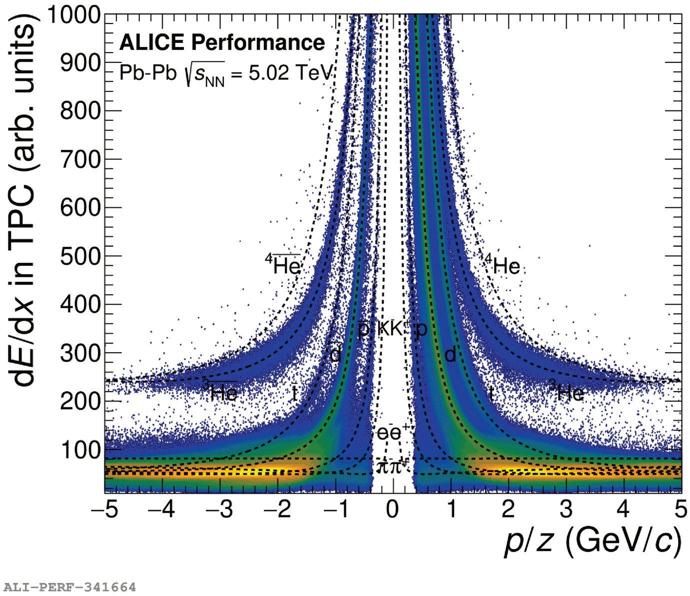

Figure 1: Specific energy loss in the ALICE TPC detector as a function of rigidity.

The $^{3}\overline{\mathrm{He}}$ inelastic cross section was measured using pp collisions at $\sqrt{s}$ = 13 TeV and Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV recorded by ALICE. Here, only pp results are presented in detail. The ALICE detector was used as a target material. Full description of the experimental setup of the ALICE detector can be found in [4, 5]. The charged (anti)particles were identified by using the specific energy loss measured by the TPC. Because of the double charge of helium and antihelium, they are very well separated from the rest of the particles in such a measurement as it can be seen in Fig. 1. To select higher quality track samples, an additional hit in the Inner Tracking System (ITS) was required. The absorption probability of $^{3}\overline{\mathrm{He}}$ in the detector increases with the amount of traversed material. Thus for particles with momenta p > 1 GeV/c, an additional hit in the Time-of-Flight (TOF) detector was required. The Transition Radiation Detector (TRD)[11] is in between the TPC and the TOF detectors and provides additional material budget. The measured ^{3}He spectra was corrected to account for secondary particles from spallation processes in the detector material. This correction is not needed for $^{3}\overline{\mathrm{He}}$ as the probability of producing secondary $^{3}\overline{\mathrm{He}}$ is extremely low. The resulting $^{3}\overline{\mathrm{He}}$ /^{3}He ratio as a function of rigidity ($p_{\rm prim}/Z$, where $p_{\rm prim}$ is the momentum at primary vertex and Z is the charge of the particle) is shown in Fig. 2. The red points represent Geant4 [13] simulation results while the blue points are measured ALICE results. The empty markers correspond to the ITS-TPC analysis while the full markers to the ITS-TPC-TOF analysis. The bars indicate the statistical uncertainties, while the boxes represent the systematic uncertainties. The $^{3}\overline{\mathrm{He}}$ /^{3}He ratio in both data and MC simulation is smaller than unity, indicating that the inelastic cross section of the $^{3}\overline{\mathrm{He}}$ is larger than that of ^{3}He. The measured $^{3}\overline{\mathrm{He}}$ /^{3}He ratio for momenta p < 1 GeV/c is much lower than in the simulation thus a larger inelastic cross section of the $^{3}\overline{\mathrm{He}}$ with respect to Geant4 is expected.

To obtain the inelastic cross section of the $^{3}\overline{\mathrm{He}}$ ($\sigma_{\rm inel}^{^{3}\overline{\rm He}}$), the Geant4 simulations were used. The $\sigma_{\rm inel}^{^{3}\overline{\rm He}}$ was varied in Geant4 bin-by-bin in momentum to reproduce the $^{3}\overline{\mathrm{He}}$ /^{3}He ratio measured by ALICE and its corresponding 1σ uncertainties. The resulting values represents the $\sigma_{\rm inel}^{^{3}\overline{\rm He}}$ measured

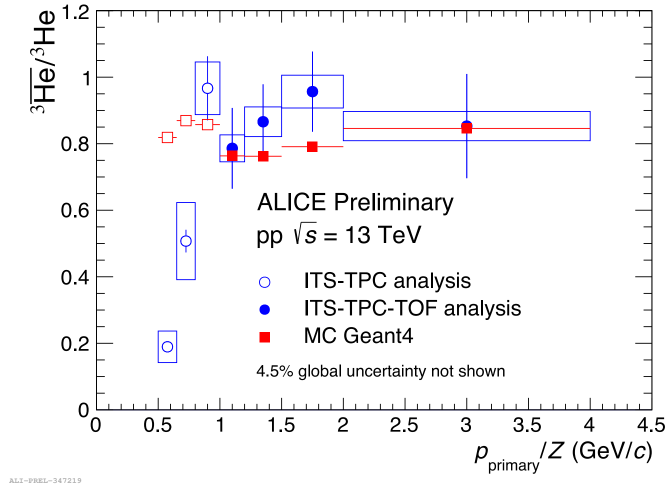

Figure 2: Raw primary $^{3}\overline{\mathrm{He}}$ /^{3}He ratio as a function of the momentum at the primary vertex divided by the charge.

by ALICE. The ALICE target material in the ITS-TPC analysis corresponds to a target with average charge number $Z = \langle 8.5 \rangle$ and mass number $A = \langle 17.4 \rangle$. In case of the ITS-TPC-TOF analysis, the corresponding values are $Z = \langle 14.8 \rangle$ and $A = \langle 31.8 \rangle$.

In case of the cosmic ray studies, the target nuclei in the interstellar medium are mainly protons and ^{4}He. The Geant4 simulation includes implementation of the inelastic cross section of $^{3}\overline{\mathrm{He}}$ on different target nuclei [7]. We used this feature to extrapolate the measured inelastic cross section to light nuclei. A correction factor was calculated for the Geant4 inelastic cross section using the measured $^{3}\overline{\mathrm{He}}$ /^{3}He ratio. Such correction factor is momentum dependent and was assumed to be the same for all target nuclei. The $^{3}\overline{\mathrm{He}}$ inelastic cross sections were estimated based on hydrogen and helium targets by applying the correction factor to the default Geant4 implementation. A 8% uncertainty on such A scaling was assigned [7]. The resulting inelastic cross sections were implemented in GALPROP to account for the $^{3}\overline{\mathrm{He}}$ annihilation in the collisions with interstellar gas in the galaxy.

3. $^{3}\overline{\mathrm{He}}$ Cosmic Rays

To study how the ALICE measurement affects the cosmic ray studies, we use GALPROP to solve the transport equation:

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{\mathrm{d}p}{\mathrm{d}t} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau}. \quad (2)$$

Here, $\psi = \psi(\mathbf{r}, p, t)$ is the time dependent cosmic ray density per unit of the total particle momentum and $q(\mathbf{r}, p)$ is the $^{3}\overline{\mathrm{He}}$ source function. The propagation parameters D_{xx}, $\mathbf{V}$ and D_{pp} are the spatial diffusion coefficient, the convection velocity and the diffusive re-acceleration coefficient, respectively. The propagation parameters are expected to be the same for all particle species and were constrained using the available cosmic ray measurements. In this work, the propagation

parameters published in [2] were used. The $-\frac{\psi}{\tau}$ term represents the particles lost via inelastic collisions with interstellar gas and is set by our $^3\overline{\text{He}}$ inelastic cross section measurement.
We implemented the $^3\overline{\text{He}}$ source functions for both dark matter annihilations and cosmic ray collisions with interstellar medium. The source function for dark matter annihilations is calculated as:

$$q(\mathbf{r}, E_{\text{kin}}) = \frac{1}{2}\frac{\rho^2_{\text{DM}}(\mathbf{r})}{m^2_\chi}\langle\sigma v\rangle\frac{\mathrm{d}N}{\mathrm{d}E_{\text{kin}}}, \tag{3}$$

where $\mathbf{r}$ is the position in the Galaxy at which the source is calculated. The $^3\overline{\text{He}}$ kinetic energy and the dark matter particle mass are indicated with E_{kin} and m_χ, respectively. The velocity averaged annihilation cross section of the dark matter is denoted as $\langle\sigma v\rangle$. We use $\langle\sigma v\rangle = 2.6 \cdot 10^{-26}$ cm^3s^{-1} [10]. The spectrum of $^3\overline{\text{He}}$ produced in dark matter annihilation is indicated as $\mathrm{d}N/\mathrm{d}E_{\text{kin}}$ and we use the spectra published in [8] for the $m_\chi = 100$ GeV dark matter particles annihilating through W^+W^- and through $b\bar{b}$ channels. The Navarro–Frenk–White [6] dark matter density profile was assumed.
The $^3\overline{\text{He}}$ source function for cosmic ray collisions with the interstellar gas is expressed as:

$$q(\mathbf{r}, p) = \sum_{\text{CR=p,He}}\sum_{\text{ISM=H,He}} n_{\text{ISM}}(\mathbf{r})\int dp'_{\text{CR}}\beta_{\text{CR}}c\frac{d\sigma\left(p, p'_{\text{CR}}\right)}{dp}n_{\text{CR}}\left(\mathbf{r}, p'_{\text{CR}}\right). \tag{4}$$

Both cosmic rays (CR) and the interstellar medium (ISM) consist mainly of protons and helium thus the pp, p–He, He–p and He–He collisions must be included. The sums over CR and ISM account for this. The density of the interstellar gas is denoted as $n_{\text{ISM}}(\mathbf{r})$, while p'_{CR}, β_{CR} and $n(\mathbf{r}, p'_{\text{CR}})$ are the momentum, the velocity and the density of the cosmic rays. p is the momentum of produced $^3\overline{\text{He}}$. $d\sigma(p, p')/dp$ is the $^3\overline{\text{He}}$ differential production cross section which was taken from [9].

As existing and planned cosmic ray detectors will operate inside the Solar System, one must account for the solar modulation. In this work, it was done by using the Force-Field approximation with a Fisk potential value of 0.4 GeV.

The $^3\overline{\text{He}}$ cosmic ray flux was first estimated by setting the $^3\overline{\text{He}}$ inelastic cross section to zero, thus no inelastic interactions of $^3\overline{\text{He}}$ nuclei with interstellar medium happen on their way to the Solar System. Then the inelastic cross section is set to values estimated using ALICE data and the $^3\overline{\text{He}}$ flux is reevaluated. The ratio of these fluxes defines the survival probability of $^3\overline{\text{He}}$ in the galaxy, or the transparency of our galaxy to the $^3\overline{\text{He}}$ nuclei. This approach allows us to calculate the transparency of the galaxy to antinuclei.

4. Conclusions

We measured the inelastic cross section of $^3\overline{\text{He}}$ using the ALICE detector as a target material. This measurement is a necessary component for indirect dark matter searches using the antinuclei cosmic rays. The described procedure to study $^3\overline{\text{He}}$ cosmic rays using GALPROP can be used to calculate the transparency of the galaxy to antinuclei. The presented $^3\overline{\text{He}}$ inelastic cross section measurement can be used as a reference in future $^3\overline{\text{He}}$ cosmic ray studies and provide experimental uncertainties from inelastic processes of $^3\overline{\text{He}}$ in the galaxy on the fluxes of $^3\overline{\text{He}}$.

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