The production of anti-matter in our galactic backyard

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THE PRODUCTION OF ANTI-MATTER IN OUR GALACTIC BACKYARD

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We evaluate the production of anti-deuteron and anti-^{3}He in p-p collisions within a simple coalescence model, whose validity is checked against existing collider data. We then deduce the minimal fluxes of these species that should be present in cosmic rays due to collisions of primary protons on interstellar gas. Thanks to its increased sensitivity, the AMS experiment should detect a few of these "standard" anti-deuterons.

If we ask ourselves what would constitute the most convincing evidence for the existence of an anti-star, it is clearly the discovery of heavy anti-nuclei coming from space, e.g. in cosmic rays. Indeed, anti-star cores are presumably the only foundries where anti-nuclei can survive and pile-up into large aggregates. However, it is less clear how many anti-nuclei should we require to see before being convinced, and how heavy should they be. It is generally believed that the observation of a single anti-helium or anti-carbon would undoubtedly signal the presence of stars made of anti-matter. Such a discovery would be of paramount importance as regards the existence of a baryon symmetry in the universe and has therefore strong cosmological implications. That is why it is crucial to ascertain that cosmic rays do not already contain detectable traces of anti-nuclei which could have been directly manufactured in our galaxy. We know for instance that a fraction $\bar{\mathrm{p}}/\mathrm{p} \approx 2 \times 10^{-4}$ of anti-protons is produced by the spallation of cosmic ray protons on the interstellar gas of the galactic disk. We have computed the abundance of anti-deuterium $\bar{\mathrm{D}}$ and anti-helium $^3\bar{\mathrm{He}}$ produced through the interaction of high-energy protons with the interstellar hydrogen[1]. That calculation requires two ingredients.

First, we need to evaluate the production cross section of anti-nuclei during the interaction of a high-energy proton with a proton at rest. Let us concentrate on the case of anti-deuterons which requires the formation of both an anti-proton and an anti-neutron. The invariant cross section for the production of anti-protons is experimentally well known and is reasonably fitted by the Tan and Ng's parameterization[6]. Neglecting the breaking of isospin symmetry, the anti-neutron production cross section is equal to its anti-proton counterpart. The production of two anti-nucleons is then proportional to the square of the production of one of them, a hypothesis which is reasonably well established at high energies. However, at lower energies, factorization has to break down, if only to respect the kinematic constraints that thresholds for one and two pair production are different. We have crudely taken this into account by assuming in addition that the center of mass energy available for the production of the second anti-nucleon is reduced by twice the energy carried away by the first anti-nucleon. Once the anti-proton and the anti-neutron are formed, they merge together to give an anti-deuteron if the momentum of the corresponding two-body reduced system is less than some critical value P_{coal}. That coalescence momentum is the only free parameter of our factorization and coalescence model.

Data	Ref.	p_l(GeV)	p_t(GeV)	$\sqrt{s}$(GeV)	$E_{\bar{D}} \frac{d^3\sigma_{\bar{D}}}{dk^3}$(mb/GeV^2)
1	[5]	1.44	1.14	11.5	$9.1 \pm 1.6 \times 10^{-8}$
2	[5]	1.09	1.5	11.5	$2.2 \pm 0.8 \times 10^{-8}$
3	[3]	4.8	0.16	53	$6.8 \pm 2.7 \times 10^{-5}$
4	[3]	5.6	0.21	53	$5.6 \pm 1.9 \times 10^{-5}$
5	[3]	6.6	0.3	53	$1.4 \pm 0.6 \times 10^{-5}$
6	[4]	0	$0.2 \rightarrow 0.7$	53	$1.18 \pm 0.4 \times 10^{-3} \times e^{-(2.6\pm0.5)p_t}$

Table 1: Kinematical regimes where the measured cross-section for production of anti-deuteron has been used to constrain $P_{\rm coal}$ in figure 1:

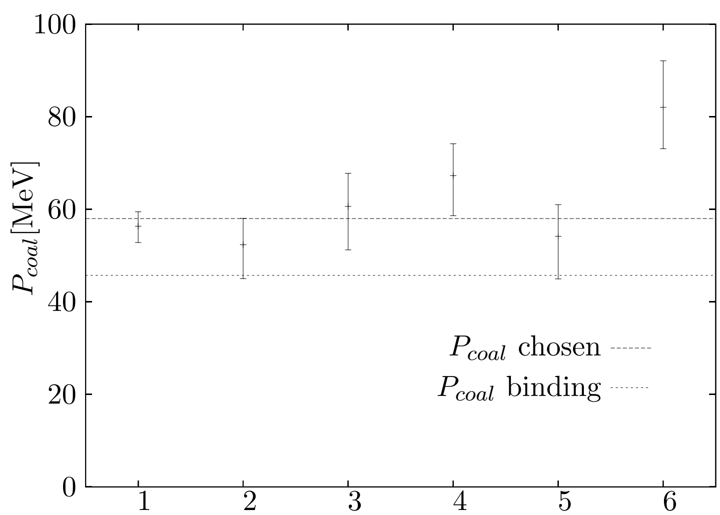

Figure 1: This figure displays various experimental constraints on the coalescence momentum $P_{\rm coal}$, the only free parameter of the model discussed in the text. Points 1 and 2 are from Serpukhov with $\sqrt{s}$= 11.5 GeV while all the other data have been collected at the ISR at $\sqrt{s}$ = 53 GeV. A coalescence momentum $P_{\rm coal}$ of order 60 MeV provides a reasonable fit of all the points but the last one. This value lies reassuringly close of the characteristic momentum derived from the binding energy of deuteron.

Experimental results [3,4,5] have been summarized in terms of P_{coal} on figure 1. Given the crudeness of our model and the wide range of kinematic regimes explored experimentally, it is quite comforting that all these data are compatible within 2 standard deviations with our predictions from our single parameter model. The first five data points are all fitted with a coalescence momentum of order 60 MeV. Because the Serpukhov data (points 1 and 2) correspond to a low center of mass energy, a kinematic regime where anti-deuteron production is astrophysically predominant, we have decided to fix the value of P_{coal} at 58 MeV. Increasing this value to 75 MeV would simply double the production of anti-deuterium.

Stars sow the interstellar medium with their own matter. That processed material mostly contains hydrogen, helium and, at a lesser level, some carbon, nitrogen and oxygen, i.e., the CNO elements. Then supernovae driven shocks sweep the interstellar gas and accelerate nuclei to generate the cosmic rays. The sources of the latter are localized in the galactic plane and correspond to supernovae remnants and pulsars. Primary cosmic rays, such as CNO, are those species already present in space before being accelerated. They subsequently diffuse in the galactic ridge during ≈ 10 million years where they undergo spallation reactions with the interstellar medium. The spallation of CNO generates a non negligible flux of lithium, beryllium and boron nuclei (LiBeB) which are orders of magnitude more abundant in cosmic rays than in stars. A single value for the column density through which the primary CNO nuclei travel and fragmentise is enough to account for the observed abundances of the secondary LiBeB species. That observation strongly supports the diffusion and spallation scheme according to which the galactic plane behaves merely as a leaky box. That simple model needs however to be slightly refined. Among the secondaries, the ^{10}Be nucleus is unstable with a half-lifetime of 1.6 million years. It plays the role of a chronometer which measures the time actually spent by cosmic rays from their production to their escape in the intergalactic medium. Its abundance with respect to its stable partner ^{9}Be has been found smaller than expected, hence a residence time in the overall galaxy of about 100 million years, ten times larger than the diffusion time in the ridge alone. This strongly suggests the existence of thick confinement layers that extend above and beneath the galactic plane. The naive leaky box has therefore to be refined into an axisymmetric two-zone diffusion model[7] which we have used in estimating the abundance of anti-deuterium and anti-tritium.

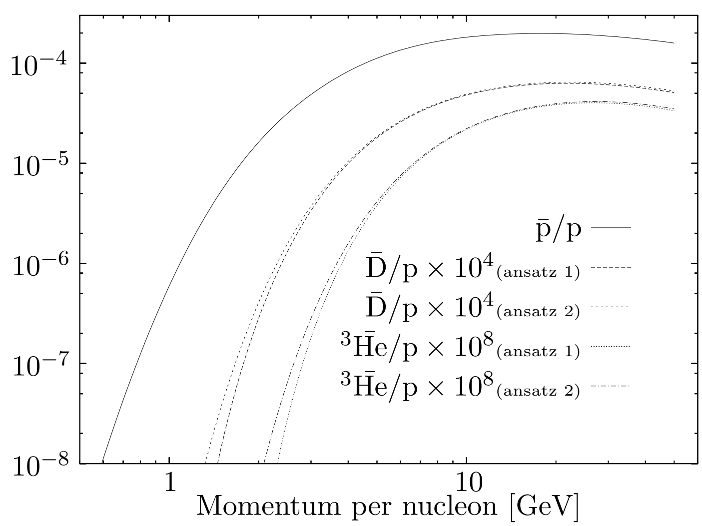

Figure 2: The fluxes of cosmic ray anti-protons and of anti-deuterium and anti-tritium nuclei, relative to the proton flux, are presented as a function of the momentum per nucleon. To fit on the same diagram, the curves have been scaled by a factor of 10^4 for $\bar{\rm D}$ and of 10^8 for $^3\bar{\rm He}$. The doubling of curves corresponds to different factorization schemes, and their closeness supports the factorization hypothesis in the relevant kinematic regime.

The flux of cosmic ray anti-protons relative to the flux of protons is plotted (solid line) in figure 2 as a function of the momentum of the particles. The curve drops sharply below a few GeV. At higher energies, it exhibits a plateau where the ratio $\bar{\rm p}/{\rm p}$ reaches a value of $\approx 2 \times 10^{-4}$, in good agreement with the previous calculation by Gaisser and Schaefer[8]. The $\bar{\rm D}/{\rm p}$ and $^3\bar{\rm He}/{\rm p}$

cases are also presented on the same plot. The energy behaviour is fairly the same as for the anti-protons. However, the magnitude of the effect is significantly suppressed. We find that the $\bar{\mathrm{D}}/\mathrm{p}$ ratio exceeds 10^{-9} above a momentum per anti-nucleon of about 4 GeV/c. It reaches a maximum of 6×10^{-9} for a momentum of ≈ 20 GeV/c. During the space station borne stage of the experiment, the AMS collaboration[2] should measure a flux of anti-nucleons with a sensitivity reaching a level of $\approx 10^{-9}$ relative to cosmic ray protons. The corresponding energy per nucleon ranges from a GeV up to 20 GeV.

We therefore conclude that AMS should detect a few cosmic ray anti-deuterons. Time is ripe to estimate the theoretical error on this prediction. A step in this direction has very recently been made[9]. This estimate is specially important in view of both the upcoming experimental measurements, and the exotic signals from the annihilation of supersymmetric dark matter[10,11,12] or the evaporation of black holes[13,14] these measurements might uncover.

The $^3\bar{\mathrm{He}}/\mathrm{p}$ abundance does not exceed $\approx 4 \times 10^{-13}$. Even allowing for a generous error of 2 in our estimates, we conclude that the anti-helium nuclei that are manufactured in our galaxy will not be detected by AMS. Alternatively, if anti-matter is processed in anti-stars, the abundance of its various components should be quite similar to the conventional stellar yields. It would follow therefore the same relative proportions as in our own interstellar material. In any case, the detection of a single anti-helium or anti-carbon by the AMS collaboration would be a smoking gun for the presence of large amounts of anti-matter in the universe and for the existence of anti-stars and of anti-galaxies.

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