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Restriction on Amount of Antimatter in the Early Universe from $\bar{p}$-^{4}He Reaction Data.

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Summary. – A limit on the possible amount of antimatter in the early universe has been deduced from $\bar{p}$-^{4}He reaction data obtained at 180 MeV.

The standard baryon-symmetrical cosmology excludes the existence of a considerable quantity of antimatter in the Universe at $t > 10^3$ s (see, for example, ref. (1,2)). On the other hand, modern astrophysics as well as the theories of grand unification

(1) G. STEIGMAN: *Ann. Rev. Astron. Astrophys.*, **14**, 339 (1976).
(2) YA. B. ZEL'DOVICH and I. D. NOVIKOV: *Structure and Evolution of the Universe* (Moscow, 1975).

predict the existence of sources of antimatter (domains of antimatter, evaporation of primordial black holes, the decays of superheavy metastable particles, etc.) after that time (for review, see ref. (3)). Most of antimatter from these sources annihilated and today we can observe only the products of this reaction. As was shown in ref. (3-5), if antiprotons annihilated on ^{4}He, this process could lead to a change in the concentration of the light elements, such as deuterium and ^{3}He.

Hence, to go back to the possible amount of antimatter in the early universe, it is essential to measure the cross-sections for the different reaction channels in the $\bar{p}$-^{4}He interaction and to compare these data with the abundance of ^{2}H, ^{3}He and ^{4}He observed to day in the Universe (3-5). As the energy of the primordial antiprotons is uncertain, the $\bar{p}$-^{4}He cross-sections should be measured at different energies down to at rest.

Recently, we have obtained the first result on the interaction of $\bar{p}$ in flight (180 MeV) on ^{4}He (6), which allows us to evaluate the amount of antimatter in the early universe on a more experimental basis than in the past (5).

The experimental apparatus, based on the use of a streamer chamber filled with helium at 1 atm and placed in a magnetic field of 0.8 T, has been described in detail in ref. (7). The sensible volume of the chamber was $(90\times 70\times 18)$ cm^3. Only the central part, 55 cm long, of the chamber has been considered for these measurements and in this fiducial volume 1097 $\bar{p}$-^{4}He reaction events at 180 MeV of kinetic energy in the laboratory have been photographed and analysed with a scanning efficiency of 99.7%. Besides the statistical errors we estimated a further sistematic error of 2% due to scanning efficiency, target transparency and beam dose counting. With this technique we measured a reaction cross-section $\sigma_r = \sigma_{tot} - \sigma_{el} = (233.3 \pm 7.1)$ mb.

(The errors quoted here and in the following are statistical only.)

Reactions involving the production of ^{3}He are readily identified in the streamer chamber, since of all the possible annihilation reactions only these involve an even number of charged-particle tracks in the final state. Using this very clear signature, we measured a cross-section for ^{3}He production $\sigma_{^3\text{He}} = (35.7 \pm 2.7)$ mb.

The amount of ^{3}He formed as a result of $\bar{p}$-^{4}He interactions in the early universe should be at a first approximation (4)

$$n_{^3\text{He}} = n_{^4\text{He}} R f^{\text{eff}}_{^3\text{He}}, \tag{1}$$

where $n_{^4\text{He}}$ represents the concentration of ^{4}He, $R = n_{\bar{p}}/n_p$ is the fraction of antiprotons in the early universe,

$$f^{\text{eff}}_{^3\text{He}} = f_{^3\text{He}} + f_{^3\text{H}}$$

represents the effective output of ^{3}He in $\bar{p}$-^{4}He annihilation. This relation takes also into account the output of tritium $f_{^3\text{H}}$, because the subsequent decay of this nuclide in the Universe contributes to the ^{3}He concentration.

The output of ^{3}He (^{3}H) is defined as follows:

$$f_{^3\text{He}(^3\text{H})} = \sigma(\bar{p}\text{-}^4\text{He} \to {}^3\text{He}\,(^3\text{H}) + \text{anything})/\sigma_{tot}\,. \tag{2}$$

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(3) V. M. Chechetkin, M. Yu. Khlopov, M. G. Sapozhnikov: *Riv. Nuovo Cimento*, **5**, 1 (1982).
(4) V. M. Chechetkin, M. Yu. Khlopov, M. G. Sapozhnikov and Ya. B. Zel'dovich: *Phys. Lett. B*, **118**, 329 (1982).
(5) I. V. Falomkin, G. B. Pontecorvo, M. G. Sapozhnikov, M. Yu. Khlopov, F. Balestra and G. Piragino: *Nuovo Cimento A*, **79**, 193 (1984).
(6) Dubna-Frascati-Padova-Pavia-Torino Collaboration: submitted to *Phys. Lett. B*.
(7) Dubna-Frascati-Padova-Pavia-Torino Collaboration: *Nucl. Instrum. Methods*, in press.

From our data one can estimate the total cross-section of $\bar{p}$-^{4}He interaction as $\sigma_{tot} = 1.5\sigma_r = (350 \pm 10)$ mb. Such a ratio holds in $\bar{p}$-^{2}H interaction ([8]) as well as in theoretical predictions for $\bar{p}$-^{3}He interaction at our energy ([9]). Therefore, we have

$$f_{^3He} = \frac{\sigma_{^3He}}{\sigma_{tot}} = 0.102 \pm 0.008 .$$

From this value it is possible also to evaluate the yield of tritium in $\bar{p}$-^{4}He annihilation, by assuming that

$$f_{^3H} = f_{^3He} r ,$$

where $r = \sigma^{ann}(\bar{p}p)/\sigma^{ann}(\bar{p}n) \simeq 1.32 \pm 0.05$ ([8]).

Thus the estimate of the effective yield of ^{3}He is the following:

$$f^{eff}_{^3He} = f_{^3He} + f_{^3H} = 0.237 \pm 0.014 . \tag{3}$$

Assuming that the amount of ^{3}He created as a result of $\bar{p}$-^{4}He annihilation could not exceed the abundance of ^{3}He observed at present, from eq. (1) we obtain the following restriction on the fraction of antimatter in the early universe:

$$R < \frac{4}{3}\frac{X_{^3He}}{X_{^4He} f^{eff}_{^3He}} , \tag{4}$$

where $X_{^3He} = (4.2 \pm 2.8)\cdot 10^{-5}$, $X_{^4He} = (0.23 \pm 0.02)$ are the observed mass abundances of ^{3}He and ^{4}He ([10]).

Utilizing eqs. (3) and (4), we finally obtain a restriction on the fraction of antimatter in the early universe:

$$R < (1.03 \pm 0.70)\cdot 10^{-3}$$

(the error includes also the uncertainties in light-element abundance).

This restriction on R exceeds by more than three orders of magnitude the earlier restriction ($R < 1$) that was based on the investigation of the permissible distortion of the Planck spectrum of the relic radiation ([3,11]). Knowledge of this ratio puts severe restrictions on the formation of primordial black holes, on the concentration of heavy metastable particles (on gravition concentration, for example) and on other parameters of sources of antimatter present in the Universe after the nucleosynthesis ([3,4]).

Although this upper limit of R refers to 180 MeV antiprotons, we are confident in this estimate, because a preliminary analysis of our data taken at 50 MeV shows an increase of at least 60% in the ^{3}He production and consequently a further decrease in R.

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([9]) L. A. Kondratyuk and M. Zh. Shmatikov: *Yad. Fiz.*, **38**, 361 (1983); *Sov. J. Nucl. Phys.*, **38** (2), 216 (1983).
([10]) S. M. Austin: *Progr. Part. Nucl. Phys.*, **7**, 1 (1981).
([11]) R. A. Sanyaev and Ya. B. Zel'dovich: *Astr. Space Sci.*, **7**, 20 (1970).

In effect, ^{3}H and ^{3}He are the only nuclides that can be produced in the $\bar{p}$-^{4}He annihilation in the absence of initial- or final-state interactions. Hence, going toward the threshold for inelastic processes (25 MeV of incident energy in the laboratory), the production of these nuclides should be more and more favoured, the contribution from other channels being due mainly to the pionic final-state interaction, which is nearly independent of the incident energy.

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