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ON THE UPPER LIMIT OF ANTINUCLEI CONTENT IN COSMIC RAYS

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SUMMARY

The upper limit of the number of antinuclei in the content of cosmic rays is estimated on the basis of the study of nuclear emulsions exposed at 300 km, and of the investigation of all multi-charge particles at rest in the emulsion and of all interactions induced by them.

When determining the upper limit of the number of antinuclei, account was taken of the corrections of the difference in the interaction cross-sections of nuclei and antinuclei in the emulsion and for the secondary origin of a certain part of stopping multi-charged particles. A value $n\tilde{A} < 0.59\%$ is obtained for the upper limit of the multi-charge component of primary cosmic rays.

* * *

One of the interesting questions of contemporary astrophysics is that of symmetry of the Universe relative to matter and antimatter content. The investigation of primary cosmic rays may provide some information on antimatter content in our solar system.

Estimates of the upper limit of the number of antinuclei relative to standard multi-charge nuclei in cosmic rays were made in some works [1 – 3] on the investigation of the heavy component of primary rays by the photoemulsion method. Following are the assumptions made during these estimates:

a) the energy and charge spectra of primary multi-charge nuclei and antinuclei hitting the emulsion are identical;

b) the fraction of antinuclei stopped in the emulsion relative to the total number of stopped standard multi-charge nuclei must be equal to the share of antinuclei in the total flux of multi-charge cosmic rays [3].

(*) O VERKHNEM PREDELE SODERZHANIYA ANTIYADER V KOSMICHSKIKH LUCHAKH

The first assumption may be admitted with a certain approximation. Qualitative consideration shows that no great difference can be expected in the energy and charge spectra of nuclei and antinuclei at the atmosphere boundary under the condition of their identity at the outlet from the sources (provided the paths covered by nuclei and antinuclei are about identical). A certain difference is possible in the region of low energies.

As to the second point, it will be valid only in the assumption that the interaction cross-sections of nuclei and antinuclei in the emulsion are identical. However, generally speaking these cross-sections must differ on account of the annihilation process of antinuclei on nuclei of the emulsion.

In connection with this it appeared to us to be of interest to examine in detail the interaction of antinuclei ($\tilde{A}$) with nuclei (A) in the emulsion, to bring to light the singularities of annihilation stars from $\tilde{A}$ at rest and in flight and to estimate to what extent the difference in the interaction cross-sections of $\tilde{A}$ and A will be reflected in the determination of the upper limit of $\tilde{A}$ in cosmic rays.

Besides, we considered it appropriate to estimate the upper limit of $\tilde{A}$ in cosmic rays on the basis of experimental data obtained by us during the study of emulsion irradiated at 300 km altitude in the course of 72 hours aboard "Kosmos-4", account being taken of all corrections stemming from our considerations.

1. ESTIMATE OF INTERACTION PATHS OF ANTINUCLEI AND NUCLEI IN THE EMULSION

First of all the question must be clarified whether or not there is any sense in searching for the antinucleus in the emulsion among stopped multi-charge particles. Perhaps all antinuclei undergo annihilation in flight.

With this in view we estimated for our own emulsion chamber (of $10 \times 10 \times \times 10$ cm^3) the percentage of nuclei and antinuclei having hit the chamber, stoping in the emulsion upon deceleration (on condition of identical initial energy and charge distributions). To that effect deceleration and interaction must be taken into account in the case of standard multi-charge nuclei, and deceleration and interaction with annihilation (in flight) for antinuclei.

The energy distributions of incident multi-charge particles were borrowed from the experimental data of [4]. Incidently, an identical distribution was taken also for antinuclei. Calculations were conducted for the groups of nuclei L ($Z = 3 - 5$), M ($Z = 6 - 9$) and H ($Z \geqslant 10$). Correspondingly with the experimental charge distribution [5] for these groups mean values of Z were computed for these groups; these values were precisely used during computations.

Deceleration Paths. - The deceleration of antinuclei during their passage in the emulsion is conditioned by usual ionization losses and it must not differ from the deceleration of standard nuclei (for the energy region with $\beta \geqslant Z/137$).

Consequently, the deceleration paths for $\tilde{A}$ and A may be considered identical. At the end of the path, at stop, the destiny of nuclei and antinuclei is different. Antinuclei undergo annihilation.

We computed for the groups L, M and H the deceleration paths in the emulsion as a function of energy of falling particles, utilizing the standard formulas for the deceleration capability.

Interaction Paths in the Emulsion for Simple Nuclei. - The paths were determined as $\lambda_{int} = 1 / \Sigma n_i \sigma_i$, where n is the number of nuclei of the kind in the emulsion and σ_i is the cross-section on that nucleus. λ_{int} may be computed knowing the composition of the emulsion and utilizing the semiempirical formula for the cross section [6] $\sigma_i = \pi(R_j + R_i - R)$, where $R_j = R_0 A_j^{1/3}$ and $R_i = R_0 A_i^{1/3}$ are the radii of the bombarding nucleus (j) and target-nucleus (i), and $R = 1.17\ R_0$ ($R_0 = 1.45 \cdot 10^{-12}$ cm). The thus computed paths coincide with those measured experimentally within the limits of 10%. We utilized the following values of paths: group L) 15 cm of emulsion, group M) 13.5 cm and group H) 10 cm. These quantities agree well with the mean values obtained from experimental data of [7 –10].

Paths for the Annihilation of $\tilde{A}$. - When computing these paths we started from the data according to which the path $\tilde{p}$ in nuclear matter is of the order $(0.6 - 0.7) \cdot 10^{-13}$cm, i. e. it is very small by comparison with the dimensions of nuclei ($\sim 10^{-12}$ cm) and consequently, all $\tilde{p}$ must annihilate in the superficial layer of the nucleus [11, 12].

During the interaction $\tilde{p}$–nucleus ($Z \geqslant 4$), the latter constitutes an "absolutely black" (absorbing) sphere of radius $R_{eff} = R_{1/2} + \eta$, where $R_{1/2} = 1.08\ A^{1/3} \cdot 10^{-13}$ cm is the radius of the nucleus corresponding to half-density $\rho = (1/2)\rho_0$, and $\eta = 2 \cdot 10^{-13}$ cm is the effective thickness of the diffusive surface of the nucleus, practically identical for all nuclei with $A > 4$. By way of analogy, when computing the paths for the annihilations of A in the emulsion ($\lambda_{ann} = 1 / \Sigma n_i \sigma_i$) is the radius R_i in the cross-section $\sigma_i = \pi R_i^2$ was determined by is as the sum of two effective radii of the bombarding nucleus (j) and the target-nucleus (i) (for nuclei with $Z = 4$ of group L the radius of the bombarding nucleus was defined as $R = r_0 A^{1/3}$, where $r_0 = 1.35 \cdot 10^{-13}$ cm, and the target-nucleus as $R_{eff(i)}$):

$$R_i = R_{eff(j)} + R_{eff(i)},$$

where $R_{eff\,(j,\,i)} = R_{1/2(j,\,i)} + \eta$. Paths for annihilation in the emulsion (the composition of the latter being known) were estimated for all the groups L, M and H.

Utilizing the obtained values of paths for deceleration, interaction and annihilation we may estimate $N_{\tilde{A}} / N_A$ is the ratio of the numbers of antinuclei and nuclei which, having decelerated, may stop in our emulsion chamber. Thus was obtained the value $k = N_{\tilde{A}} / N_A = 0.48$. Therefore, for identical energy and charge spectra hitting the chamber, the number of antinuclei at rest will be two times less than the standard multi-charge nuclei. When determining the upper limit of A in cosmic rays, this coefficient must be taken into account.

2. ANNIHILATION OF $\tilde{A}A$

The above estimates show that in the presence of $\tilde{A}$ in primary cosmic rays there exists a probability of detecting them among the number of stopped nuclei.

The form of tracks of $\tilde{A}$ and A at rest in the emulsion is sharply different. The standard nuclei form at stops a characteristic strongly narrowing track (after thickness maximum), which is conditioned by a decreasing energy of δ-electrons (in proportion of energy loss by the nucleus), and over the very last portion of the path by the decrease of the effective charge of the nucleus (capture of atomic electrons of the medium).

During deceleration in the emulsion and prior to attaining a velocity equal to the velocity of atomic electrons, antinuclei form a track analogous to that of the standard nucleus. No electron capture can take over the last portion of the path. At stop the antinucleus will necessarily annihilate from the bound ($\tilde{A}A$) state.

Thus an annihilation star must be observed for a track of an antinucleus at rest after thickness maximum and further narrowing.

Estimates carried out by A. Z. Dolginov and D.A. Varshalovich for A and $\tilde{A}$ with $Z \geqslant 4$ have shown that during annihilation "antinucleus-nucleus" ($A > \tilde{A}$) at rest (or at small kinetic energy) only $\sim$ 30 to 40 percent of antinucleons from the antinucleus will annihilate. The forming π-mesons ($5\pi^0\pm$-mesons for each pair $\tilde{N}N$ as an average) must undergo the usual interactions with nucelons and antinucleons of nuclei – residues, such as elastic and inelastic scattering and absorption (most probably on a pair of nucleons).

As a result of these processes cascade (fast) N and $\tilde{N}$ will be observed, and the residues of nucleus and antinculeus, having remained excited, will vaporize the slow nucleons and antinucleons.

According to the estimate $\sim$ 30% of all antinucleons will be slow (vaporizable) and 30% will be fast. The slow $\tilde{N}$ may be revealed among products of fission in annihilation stars during stops.

3. ESTIMATES OF THE UPPER LIMIT OF $\tilde{A}$ IN COSMIC RAYS

Whwn looking over the area of the relativistic emulsion which was irradiated by cosmic rays at 300 km ("Kosmos-4"), all ending multi-charge particles ($Z \geqslant 3$) and all interactions induced by multi-charge particles were registered. 474 ends and 325 interactions were revealed in all. Each multi-charge particle forming fission or stopping in the emulsion was tracked to the entry of the emulsion chamber. Among the ending particles, multi-charge ones had a secondary origin in 122 cases (25.8%), i. e. they formed in stars under tee action of cosmic rays. Thus, 352 cases were revealed of primary multi-charge particles having stopped in the emulsion. The tracks of such particles had the f shape of "carrots", very characteristic for the stops of standard multi-charge particles.

Moreover, we investigated all the interactions induced by multi-charge particles. Studied first was the ionization of the track during the transit of the multi-charge particle from the emulsion camera inlet to the place of formation of interaction. Secondly, we investigated all tracks with the view of ascertaining in their composition the existence of slow antinucleons and annihilation π-mesons; this was done in fissions induced by multi-charge particles of low energy (< 200 Mev/nucleon).

Not a single case was revealed that would satisfy the enumerated singularities of annihilation "antinucleus-nucleus".

Making use of these data we may evaluate the upper limit of antinucleus content in the composition of primary cosmic rays, taking into account all the noted corrections. The quantity

$$n_{\tilde{A}} < 1 \,/\, N_{emch}\, k,$$

where $N_{emch} = 352$ is the number of primary multicharge nuclei ending in the emulsion, and the coefficient $k = 0.48$ takes into account the difference in the interaction cross-sections of $\tilde{A}$ and A in the emulsion (see Section 1).

Hence we obtain $n_{\tilde{A}} < 0.59\%$ of the multi-charge component of primary cosmic rays. The estimates available in literature of the upper limit $n_{\tilde{A}} < 1\%$ [1], $n_{\tilde{A}} < 0.1\%$ [2] and $n_{\tilde{A}} < 0.23\%$ [3] were apparently obtained without taking into account the corrections. If we borrow the experimental data of the works by N. L. Grigorov et al [3], where the case statistics are closer to our own (442 ends of multi-charge particles), and if we introduce the corrections a) for the secondary origin of a certain part of stopping multi-charge particles (25.8%) and b) for the difference in the cross-sections of interactions of $\tilde{A}$ and A in the emulsion ($k = 0.48$), we shall obtain

$$n_{\tilde{A}} < \frac{1}{(442 - 442 \cdot 0{,}26)\, 0{,}48} = 0{,}63\,\%,$$

which is close to our own value.

The data obtained show that for the admitted assumptions about the charge and energy spectra of antinculei, their number in the composition of cosmic rays and near-ground space is in any case less than 0.6% of the number of standard multi-charge cosmic particles (the investigated energy region for nuclei stopping in our chamber is ≤ 1.4 Bev/nucleon).

However, we still cannot estimate on the basis of these data the upper limit of antinuclei in the Galaxy, and the more so in the Universe. Our knowledge of the sources of cosmic rays, of acceleration mechanisms and propagation of cosmic rays are still too incomplete to allow any reliable conclusion in this direction.

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***** THE END *****

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