On the Problem of Anti-Protons in the Primary Stream of Cosmic Rays

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Analysis of data on the measurement of the east-west asymmetry of cosmic rays at high altitudes demonstrates that it is thoroughly impermissible to exclude the possibility of the presence of a certain proportion (up to 13%) of negatively charged particles in the primary flow. Computation shows that in the primary flow of cosmic rays, the proportion of anti-protons formed in interstellar space cannot exceed 0.2%, and apparently the presence of anti-protons cannot explain the results of measurement of east-west asymmetry.

COMPARISON of the intensity of cosmic rays measured at high altitudes arriving from the west with the intensity of cosmic rays arriving from the east, provides, as is generally known, the possibility of determining the sign of the charge on the particles in primary cosmic radiation. The magnitude of east-west asymmetry is characterized by the equation

$$A_{W-E} = \frac{2(I_W - I_E)}{I_W + I_E}, \quad (1)$$

where I_W, I_E is the intensity of the cosmic rays arriving, respectively from the west and the east. If k is the percentage of negatively charged (negative) particles present in the primary radiation, then

$$A_{W-E} = A^{+}_{W-E}(1 - 0.02\,k), \quad (2)$$

where A^{+}_{W-E} is the magnitude of east-west asymmetry when the cosmic rays consist solely of positively charged (positive) particles. Equation (2), which is valid if it is assumed that the energy spectra of particles of both signs are identical, makes it possible to find the proportion of negative particles in the primary stream of cosmic rays.

In 1949, Vernov, Grigorov, and others[1] carried out measurements of east-west asymmetry in the stratosphere and determined that for the hard component (passing through 8 cm of Pb) this magnitude comprises approximately 70%. This demonstrated that the dominant role in the primary stream of cosmic rays is played by positive particles. An analogous result was later obtained in other researches[2-6]. However, there is a definite divergence between measured east-west asymmetry and the asymmetry to be expected on the basis of purely positive primary articles. The integral energy spectrum of primary particles at definite energy intervals can be represented in the form of an exponential function $E^{-\gamma}$, where the exponent varies from $\gamma \approx 1$ in the range of energy near 1.4×10^9 ev, to $\gamma \approx 2.5$ at energies greater 10^{13}ev. If the expected east-west asymmetry A^{+}_{W-E} is calculated and compared with the results of experiment[1] ($A_{W-E} \approx 70\%$), then from Eq. (2) it is possible to find that proportion of negative particles which would make it possible to clarify the observed divergence. The magnitudes of A^{+}_{W-E} and k are given in the following table as calculated on the basis of various assumptions as to the size of the exponent γ.

γ	1	1.2	1.3	1.5
A^{+}_{W-E} in %	96	111	118	131
k in %	13.5	18.5	20	23

Even for a very "hard" ($\gamma = 1$) spectrum of primary particles, the results of measurement do not exclude the possibility of the presence of

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approximately 13% of negative particles in the primary cosmic ray stream. This result can vary somewhat, if the cascading of primary particles in the stratum of air above the instrument (order of magnitude of 15 g/cm²) is taken into consideration. No correction for this cascading effect is required for measurements carried out beyond the boundaries of the atmosphere. Such measurements[5,6] showed $A_{W-E} \approx 40\% \pm 10\%$ while the expected figure was $A^{+}_{W-E} = 84\%$. From this we obtain $k \approx 26$. Consideration of possible reverse flow of the particles ("albedo" of the cosmic rays) reduces the value of k to approximately 22, if the albedo (the ratio of the magnitude of reverse flow to the full magnitude of the measured flow) is taken as equal to 15%, and can explain the entire divergence observed only if it is assumed that the albedo attains 52% at an angle of 45°, while direct measurements[7] permit a magnitude of the albedo not exceeding 10%.

Since direct experiments[8] point to the absence of any significant number of electrons of great energy in the primary cosmic ray stream, it is natural to assume that negative particles in the primary stream, if they are actually present there, are anti-protons. It is just such a conclusion in categorical form which is given by Bhowmik[4].

It is most natural to assume that anti-protons in cosmic rays (see Feinberg[9]) can form during the collision of nucleons of high energy. At the present time there is no conclusive theory dealing with the interaction of particles at high energies, but considerations developed by Fermi[10] and Landau[11] make it possible to carry out certain evaluations of the possible quantity of anti-protons in the primary stream of cosmic rays. Since we are interested in the upper limit for the number of anti-protons in the primary cosmic ray stream, we will make use of the results of the researches of Fermi, although these results, as can be seen from the remarks of Pomeranchuk[12] and Landau[11], definitely give inflated values for the number of nucleons and anti-nucleons which form.

It is reasonable to assume that the formation of anti-nucleons occurs solely in interstellar space and not in the primary sources of the cosmic rays, since the acceleration period for particles in the primary source is definitely less than the period between collisions leading to the appearance of anti-nucleons. For this reason the proportion of anti-protons ap in the primary stream of cosmic rays must be much less than the proportion of protons p, which are created in the main by the primary sources of the cosmic rays (for example, by super-novae[13]) or as a result of the breakdown of heavy nuclei.

Considering that the anti-protons in cosmic rays are in equilibrium with the protons, and ignoring the effect of ionization losses on the variation in the flow of anti-protons, we can write the balancing equations

$$\int_{E_{th}}^{\infty} N_p(E)\,\sigma_p\,(E)\,\mu\,(E)\,dE$$

$$= \int_{E_0}^{\infty} N_{ap}(E_1)\,[\sigma_{coll}^{ap} + \sigma_{ann}]\,dE_1$$

$$= -\int_{E_{th}}^{\infty} N_{ap}(E)\,\sigma_p^{ap}(E)\,\mu^{ap}(E)\,dE,$$

where $\mu(E)$ and $\mu^{ap}(E)$ are the average number of anti-protons with an energy greater than E_0, formed, respectively, from a proton and an anti-proton of energy E; $N_p(E)dE$ and $N_{ap}(E)dE$ are the differential spectra of the protons and anti-protons; $\sigma_p(E)$ and $\sigma_p^{ap}(E)$ are the effective cross-sections of the processes p–p and $ap - p$ with the formation of nucleon pairs; σ^{ap}_{col} is the total cross-section of the process $ap - p$, and σ_{ann} is the cross-section of the annihilation of nucleonic pairs; $E_{th} \approx 10Mc^2$ is the minimum (threshold) energy at which the formation of nucleonic pairs is possible.

Making use of the equations taken from the work of Fermi, at $E < 500\,Mc^2$ we will have $\sigma_p < 0.02\sigma_{geom}$ and $\mu(E) \leq 0.75$, and at $E_{th} < E < 50\,Mc^2$, $\sigma_p < 0.01\sigma_{geom}$ and $\mu(E) \leq 0.5$. Naturally we must consider $\mu^{ap}(E) = \mu(E)$ and $\sigma_p^{ap} = \sigma_p$, and at $E > 1.8Mc^2$, $\sigma_p^{ap} = \sigma_p \approx \sigma_{geom}$. In conformity with reference 14, for the cross section of annihilation at $E > 10Mc^2$ we have $\sigma_{ann} < 0.002\sigma_{geom}$ and at

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$E = 1.8Mc^2$, $\sigma_{ann} \approx 0.05\sigma_{geom}$.

In view of the fact that there are no particles with a momentum of less than $1.5Mc$ (see reference 15) in the primary stream of cosmic rays, we will now consider the quantity of anti-protons with $E > 1.8Mc^2$. Here, $E_0 = 1.8\ Mc^2$ and in Eq. (3) it is possible to ignore the cross section of annihilation in comparison with the cross section of collision.

The spectrum for the protons, in accordance with Neher[16], is written in the form

$$N_p(E)\,dE = N_0\,\varepsilon^{-3/2}[1 + 0.09\,\varepsilon^{4/3}]^{-3/2}\,d\varepsilon, \qquad (4)$$

where N_0 is a certain constant, $\epsilon = E/Mc^2$, M is the mass of the proton at rest.

The spectrum for the anti-protons is written, hypothetically, in the form of the exponential function

$$N_{ap}(E)\,dE = A\varepsilon^{-\xi}\,d\varepsilon.$$

Under the conditions given above, for $\xi = 2$, Eq. (3) is transformed into the inequality

$$N_{ap}(E > 1.8\ Mc^2) < 0.0027\ N_0\,Mc^2.$$

In the case of a "softer" spectrum ($\xi > 2$) the upper limit for the number of anti-protons in the primary stream of cosmic rays will be still lower. From Eq. (4) we find the entire number of protons with an energy of $E > 1.8\ MC^2$

$$N_p(E > 1{,}8\ Mc^2) \sim 1{,}6\ N_0\,Mc^2.$$

From this we find that the proportion of anti-protons in the primary stream of cosmic rays comprises

$$k < 0.0027\,/\,1.6 \approx 0.17\,\%.$$

For an energy $E > 10Mc^2$, which corresponds to measurements in the zone of the equator, we have

$$N_{ap}(E > 10\ Mc^2) < 0.0005\ N_0\,Mc^2,$$

$$N_p(E > 10\ Mc^2) \sim 1.4\ N_0\,Mc^2$$

and

$$k < 0{,}0005\,/\,1.4 \approx 0{,}04\,\%.$$

Although the factor k thus found is evidently excessive in value, even this factor does not conform with modern results of the measurement of east-west asymmetry ($k \sim$ 13-20%).

It is most probable, that in processing available experimental data with the aim of determining the proportion of negative particles, it is necessary to take more completely into consideration such effects as cascading in the atmosphere, reverse current, etc. Thus, the actual quantity of negative particles in the primary stream of cosmic rays is apparently small. However, in view of the importance of this problem, it appears expedient to carry out experiments with a view to the exact determination of the permissible proportion of these particles in primary cosmic rays. If it turns out that the proportion of anti-protons in the primary stream of cosmic rays comprises 0.1%, we may hope to set up special experiments that will isolate these particles

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