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THE PROBLEM OF QUARKS IN COSMIC RAYS*

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THE problem of the reality of quarks, of their separate existence in a free state, is one of the most interesting questions of elementary-particle physics.

How did the very idea of quarks arise? We shall explain its origin with a crude example.

Let us suppose that we knew nothing about the existence of electrons and had not begun the study of atomic shells with the simplest atom with one electron, but had at the beginning had available only many-electron atoms. Studying their properties, we would have noted that the shell of such an atom has definite values of the angular momentum and its projection, would have found some regularities in the locations of the levels, and so on, and in the final analysis would have learned, for example, that with regard to these matters the wave function of the shell system of an atom with nuclear charge Ze, in various states of excitation, behaves like a higher-order (rank Z) spinor $\psi^{\alpha_1\alpha_2\ldots\alpha_Z}$, where each of the Z indices α_i can have two values. We would not know that the functions could have as arguments the coordinates $\mathbf{r}_i$ of particles. In general the coordinates are not separated in the wave function of the shell structure, but we could expand this function in terms of products of ordinary spinors of rank unity (for simplicity we confine ourselves to states with zero orbital angular momentum):

$$\psi^{\alpha_1\ldots\alpha_Z} = \sum a_{\alpha_1\alpha_2\ldots\alpha_Z}\psi^{\alpha_1}\psi^{\alpha_2}\ldots\psi^{\alpha_Z},$$

and in the crudest approximation, neglecting exchange, we could assume that the sum reduces to only one term $\psi^{\alpha_1}\ldots\psi^{\alpha_Z}$.

Then undoubtedly the thought would arise: does not the shell structure of the atom indeed consist of Z individual particles, each of which is described by a spinor of the first rank—that is, does it not consist of particles with spin $1/2$? We would thus arrive at the idea of electrons, would guess at their individual existence, and thereafter would discover them experimentally as separate particles.

In the systematization of the properties of elementary particles it has been noted that many regularities can be explained from the point of view of SU(3) symmetry, namely by assuming that in the space of isotopic spin and strangeness the particles can be grouped in such a way that certain sets of particles, for example the baryons, are described by wave functions which transform under coordinate transformations in this space like a spinor of third rank, $\psi^{\alpha\beta\gamma}$, where each of the indices α, β, γ runs through two values. Naturally here also the question arises: Is not this wave function the product of three spinors which belong to the various subparticles which make up the entire particle in the same way as electrons make up an atomic shell? This idea (Gell-Mann, Zweig) is reinforced by the fact that the mesons also form systems with similar symmetry structures, and their wave functions can be expressed in terms of products of pairs of functions of the same basic spin particles—the quarks. Such particles must have electric charges $\pm e/3$ and $\pm 2e/3$, and at least some of them should be stable (for details see [1]).

For the electrons in an atomic shell, however, the interaction is weak, and we can suppose that the electrons in a shell and the free electron do not differ much in their properties, and even that the properties of a set of electrons described by individual functions are nearly the same as those of the whole shell. In the case of strongly interacting particles, on the other hand, such a replacement may seem meaningless. It may be that the properties of a baryon cannot be reduced to those of the three particles which constitute it—the quarks taken separately—with small corrections to their properties caused by their interaction. It may also be that each of these particles does not exist by itself.

In fact, we know the history of attempts to construct a neutrino theory of light. Starting from the fact that from the point of view of its transformation properties the vector field that describes electromagnetic quanta is equivalent to a combination of two spinor fields, as early as thirty years ago some theorists tried to explain light quanta as combinations of two neutrinos. This is quite permissible from the point of view of the tensor structure of the electromagnetic field functions on the one hand and of those for neutrinos on the other. This formulation is, however, impossible because of other, more physical, properties of these fields.

Therefore it is also quite possible that quarks do not exist, even if the approximate SU(3) structure or some similar symmetry of the elementary particles is a definite fact.

But there is a problem here, and a most interesting

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*Fuller form of a report at the All-Union Conference on Cosmic Rays, Alma-Ata, October, 1966.

one. Therefore we must not hold back from investigating it thoroughly.

2. SEARCHES MADE WITH ACCELERATORS

During the last few years there have been many serious attempts to find quarks among the products from the collision of nucleons coming from accelerators, i.e., having energies up to 30 GeV. These attempts were in vain.[2] We shall start from the assumption that quarks nevertheless exist. Then the negative result of the searches made with accelerators may mean that the energies of the accelerators are simply insufficient, because quarks are heavy—that their mass m_q is more than $5m_N$, five nucleon masses, and that nucleon energies of 30 GeV are too low to produce quark pairs $q\tilde{q}$ even when the motion of the nucleons in a nucleus is taken into account. On the other hand, the results of these experiments may merely mean that though the quark mass is not so large, the cross section for their production is for some reason very small.

The question of the production of quark pairs can be studied theoretically, but only if we make some quite concrete assumption about the properties of quarks. It turns out that it suffices to make an assumption about the forces with which they interact with pions and nucleons.

Quarks grouped in threes form nucleons, and a quark-antiquark pair forms a meson. This means that, at least at small distances of the order of particle sizes, they interact very strongly with each other, so that the mass defects in mesons are larger than $\sim m_q$, and $m_q > m_N/3$ (otherwise three quarks would not form a baryon with mass m_N). But how does a quark interact with a baryon, which also consists of quarks? Evidently, as to order of magnitude, as a baryon interacts with a baryon.

We take this as our starting point; that is, we shall assume that as to order of magnitude a quark interacts with pions and baryons as strongly as does an ordinary strongly interacting particle.

We note that this is not an unquestionable conclusion, though it is a very natural one. It could be that quarks interact strongly with each other only at ultrasmall distances, inside a proton or a meson, when their speeds are extremely high, and that at distances of the order of $1/\mu$, where μ is the pion mass, and at not very large kinetic energies, their interaction is small. This assumption, however, looks very extravagant, and we shall for the present rely on our first conclusion.

Then we can derive the cross section for production of a pair $q\tilde{q}$ with masses m_q if we find a regularity in the production of other pairs of strongly interacting particles—proton-antiproton ($p\tilde{p}$) and deuteron-antideuteron ($d\tilde{d}$) pairs. There are experimental data for these cases [unfortunately, for pairs of heavier particles—triton-antitriton ($t\tilde{t}$)—the data are very uncertain].

If we try to calculate the probabilities for production of these pairs in NN collisions by a statistical theory, we find excellent agreement with experiment. This is not very surprising. The production of such pairs is possible only in collisions with very large momentum transfer, i.e., central collisions. Precisely for these the statistical theory must be good. A calculation shows that the cross section, or more exactly the ratio of the number $n_{q\tilde{q}}$ of heavy pairs produced to the number n_π of pions produced simultaneously in the same act, is

$$\frac{n_{\tilde{q}q}}{n_\pi} = \frac{g_{q\tilde{q}}}{g_\pi^2}\,\frac{\pi}{2}\,n_\pi\,\frac{1}{[F_-(\mu/T_c)]^2}\left(\frac{m_q}{T_c}\right)^3 e^{-2m_q/T_c}\,. \tag{1}$$

Here $g_{q\tilde{q}}$ is the isotopic and spin weight of the pair $q\tilde{q}$ (for $p\tilde{p}$ this is $2 \times 2 = 4$, for $d\tilde{d}$ it is $3 \times 3 = 9$, and for quarks $g_{q\tilde{q}} = 6 \times 6 = 36$); F_- is a tabulated function, $F_-(1) \approx 2$; T_c is an indeterminate parameter which has the meaning of a critical temperature for the system (formed in a central collision), at which the system breaks up into pions and other particles.* From this we can also get the cross section σ_q. In the figure we have shown the experimental data for the production of $p\tilde{p}$ and $d\tilde{d}$ and have drawn interpolation curves of the type

$$\sigma_{\tilde{q}q} = g_{\tilde{q}q}\cdot a\left(\frac{m_q}{T_c}\right)^3 e^{-2m_q/T_c}, \quad a = 4\cdot 10^{-25}\ \text{cm}^2, \quad T_c = 0.94\ \mu.$$

It can be seen that these curves are in excellent agreement with the experimental data. The value of T_c determined from this comparison of the theoretical formula with experiment is quite reasonable from the point of view of the statistical theory (one expects $T_c \sim \mu$).†

We see that when the mass of the particle increases by m_N the cross section for production falls off by 5 to $5\frac{1}{2}$ orders of magnitude. This holds for p and d, and has a simple explanation: Statistically it is much more favorable to produce $\sim 13m_q/m_N$ pions than to produce a pair of total mass $2m_q$. This competing process depresses the production of heavy pairs.

If we apply this formula to the production of a pair of quarks, we see that already for $m_q = 3m_N$ the cross section falls to $\sim 10^{-38}$ cm^2 and is beyond, the reach of the experiments done so far with accelerators. Therefore these experiments do not exclude the possibility that $m_q \sim (2.5-3)\,m_N$. It follows that in general it is remarkably hard to produce a $q\tilde{q}$ pair in collisions of nucleons. But also in any other process, for example in electromagnetic production, the production of many

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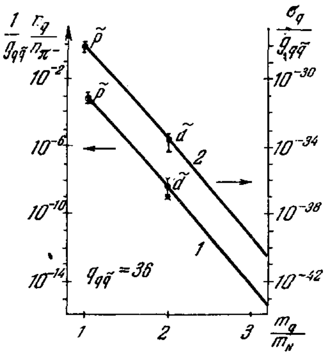
*It is assumed in this formula that $n_{q\tilde{q}} \ll 1$. For $n_{q\tilde{q}} \gg 1$ a simpler formula (used, in particular, in [5]) would hold, but in our case this latter formula is unsuitable.

†See preceding footnote.

pions can depress the production of quarks, so that this conclusion holds in general.

There is one possible loophole in this argument. If $m_q | \gtrsim 3m_N$, the cross section for production becomes so small that small side effects which we have not taken into account may begin to be important. For example, quarks arising in the first stage of the existence of the statistical system (when its temperature is high, $T \gg T_c$) can slip out of a system which is of small size, and never get into thermal equilibrium with the system at all. Then the drop of the curve in Fig. 1 will be slower, and it may even flatten out into a plateau.



In general, if our original assumption that quarks interact with nucleons and pions just as strongly as ordinary strongly interacting particles is incorrect, if for some reason they interact more weakly, then they can also slip out of the statistical system in early stages of the expansion, and not get annihilated with the formation of many pions as the temperature falls, and consequently the cross section for their production will be larger than the calculated value. Of course it is paradoxical that with a weaker interaction the particles should have a larger cross section for production, but this follows from the thermodynamic picture.

Calculations of the cross section for quark production have also been made by other methods, for example by the consideration of certain peripheral diagrams with form-factors. They seem to us less reliable.[7] The estimate from diagrams in which there is exchange of a quark also gives a small cross section, although in it the dependence on m_q is algebraic (with a high power, for example m_q^{-12} [7]) instead of exponential. Sometimes also diagrams with exchange of a pion are considered.[8,9] Then, however, one should include the form-factor at a vertex containing the pair $q\tilde{q}$. It has either been omitted altogether or has been taken from experiments in which a pair $N\tilde{N}$ was produced (instead of $q\tilde{q}$).

Meanwhile it is precisely this factor that gives the exponential decrease with the mass of the particle, and therefore the results of the calculations is which it is not correctly taken into account give much too high values, cross sections of the order 10^{-30} cm^2.[8]

3. SOURCES OF QUARKS IN COSMIC RAYS

The lack of success in attempts to produce quarks with accelerators has increased the interest in searches for quarks in cosmic rays. Here the usual starting point is the fact that in cosmic rays there are particles with such high energies that a threshold $\sim 5m_N$ can be surmounted. In the light of what has been said, however, the situation is more complicated. If the cross section σ_q is as small as our estimate indicates, there is not much hope that quarks are produced by cosmic rays in the atmosphere (or in special filters). Only if Eq. (1) and the assumptions on which its derivation is based are not entirely reliable could we look for any success in this direction.

Meanwhile there is another source of quarks, of an entirely different nature.

At the present time we can regard it as almost assured that in the process of its expansion our universe has been in the past in a state of high density and temperature, and that then, in thermodynamic equilibrium, there were present in it large numbers of pairs of arbitrarily heavy particles and other quanta. Along with the expansion and cooling of the system their concentrations decreased in accordance with equilibrium. Thereafter, owing to the rapidity of the expansion a stage was reached in which, because of the low concentration, the pairs no longer had enough time to be annihilated. The number that had been preserved up to this stage was conserved also in the future stages; the relative fraction of each type of particle was "frozen in," and in general remained unchanged in the further expansion. The correctness of this conception has been proved by radioastronomical observations in the last year and a half, when an isotropic distribution of radio waves at wavelengths 20, 7, 3, and 0.25 cm was found. Its intensity is in good agreement with the assumption that it is the equilibrium thermal radiation filling space at a temperature ~3°K. This is the most direct, though not the only, proof that the universe really evolved as described during the last $\sim 10^{10}$ years. But along with this relic of the radio waves space must be filled with other relics of quanta, and in particular with quarks and antiquarks. The calculation of their exact present concentration is extraordinarily difficult and is based on estimates, not always very reliable, of various factors such as the frequency with which matter has passed from cold regions into hot ones (stellar interiors) and back: in the hot regions the rate of annihilation of quarks is greatly increased—they are "burned up."

Such a calculation has been made in a well known paper by Ya. B. Zel'dovich, L. B. Okun', and S. B. Pikel'ner,[10] and led to the estimate $Q \sim 10^{-9}$—10^{-18}

quarks per nucleon in the cold regions of the universe (outer shells of stars, and so on).

New data on the residual radio waves allow us to improve the original model (to choose the so-called "hot model" of the universe), and this leads Ya. B. Zel'dovich to estimate the number of quarks as $Q \sim 10^{-10}$—10^{-13} per stable nucleon. These residual quarks must be very slow, corresponding to their temperature $\sim 3°$K. Therefore they are looked for primarily in various media by mass-spectrometric methods, in experiments of the Millikan type, and so on.

These slow quarks can also give a quark flux in cosmic rays. In fact, the quarks, since they occur in heavenly bodies on an equal footing with nucleons and nuclei, and especially since they are electrically charged, can undergo the same accelerations as the nucleons and nuclei that make up the cosmic rays. Therefore they can be present in cosmic rays in a proportion which is determined by two factors: first, their initial, residual distribution Q, and second, the difference between the effectiveness of their acceleration and the acceleration of nucleons and nuclei.[12]

This second source of quarks in cosmic rays can be more important than their production in the atmosphere.

4. POSSIBLE FLUXES OF ACCELERATED RESIDUAL QUARKS

Let us pass on to the question of possible mechanisms of acceleration of the residual quarks.

First of all we must note that the only acceleration mechanisms that can be of interest are those that function in cold regions of the universe—in interstellar gas and in the nonconvective shells of cold stars. Acceleration in the outbursts of novas and supernovas could be of importance for our purpose in cases in which they occur in cold outer layers of the stars in question.

On the other hand, however, we must keep in mind that many acceleration mechanisms that are regarded as ineffective for ordinary cosmic rays can be important for quarks. We shall give an example.

The Fermi statistical mechanism (of second order) gives particles of energy $E = E_0 e^{\alpha t_0}$, where E_0 is the initial energy of the particles, $E_0 \approx m_q$, and α is the acceleration coefficient in the formula $dE/dt = \alpha(v/c)E$. If we take the usual values, $l \sim 3 \times 10^{19}$ cm for the size of the clouds in the interstellar medium and $u \sim 10^{-4}c$ for their speed, we have $\alpha = u^2/cl \sim 10^{-17}$ sec^{-1}. Even during the present age of the universe, $t_0 \sim 3 \times 10^{17}$ sec, we get an acceleration only to energy $E \sim e^3 E_0 \sim 20 m_q$. With $m_q = m_N \sim 1$ GeV this is of course altogether insufficient to explain the observed flux of cosmic rays. In our case, on the other hand, this means only that the quarks will have relatively small energies. The only essential thing is that an effective injection mechanism must exist. The situation is improved by the fact that the threshold kinetic energy of injection for quarks is lower than that for protons and nuclei:

$$E_{\text{kin. inj.}} \sim 7 \cdot 10^{-9} \frac{Z^2 n}{c\alpha}$$

(n is the concentration of atoms in the medium).

Since for quarks of charge e/3 we have $Z^2 = (1/3)^2 \sim 1/10$, the conditions are better for the quarks than for protons and nuclei. Even if the raising of the energy to the range above the injection threshold occurs by such a simple mechanism as Coulomb collisions with cosmic rays, we get as an estimate of the ratio of the quark flux I_q to the total cosmic ray flux $I_{\text{c.r.}}$

$$\xi = \frac{I_q}{I_{\text{c.r.}}} \sim 10^{-4} \frac{m_N}{m_q} Q,$$

where Q is the equilibrium concentration of cold quarks and $Q \sim 10^{-10}$—10^{-15}. Of course there can also be other, more effective, injection mechanisms, and also cold regions with values of α large than 10^{-17} sec^{-1}.

If there is an acceleration mechanism without injection[13]—and this possibility finds support in the fact that the content of heavy nuclei in the primary cosmic rays (at the time of their production in the source) is remarkably high—an important part will be played by the parameter Z^2/m, where Ze and m are the charge and mass of the particle undergoing acceleration. For quarks with $Z = 1/3$ it is smaller by a factor $\sim 10 m_q/m_N$ than even for the proton, and therefore in this case also the conditions for the acceleration of quarks are more favorable than for the ordinary cosmic rays.

The cosmic rays produced in the nonconvective layers of the Sun (and of other stationary stars) form a small fraction ($\sim 10^{-3}$—10^{-5}) of all cosmic rays, and moreover have small energies. The acceleration mechanism exists, however, and accordingly there can be quarks so produced with energies $E_{\text{kin}} \lesssim m_q$, making up a fraction $\xi \gtrsim (10^{-3}$—$10^{-5})Q$ of the cosmic ray flux.

Similar arguments can also be given for the mechanism of acceleration by plasma waves.

Accordingly, the fraction of accelerated residual quarks in the cosmic ray flux may be about the same as the fraction of quarks in the cold state, $\xi \sim Q$, or it may be a few orders of magnitude smaller [the Fermi mechanism with Coulomb injection as already indicated, a quite certain mechanism, already gives as a lower limit $\xi \sim 10^{-4}(m_N/m_q)Q$]—but it is possible that ξ is even larger than Q.

Consequently, the possibility that a measurable number of quarks is present in cosmic rays is determined primarily by the stationary concentration Q of cold quarks in the sources.

It is well known that terrestrial searches for cold quarks have so far been unsuccessful. Even the old experiments of Millikan give Q much smaller than the figure that has been indicated, $Q \sim 10^{-10}$—10^{-13}. A recent repetition of these experiments for iron meteorites, air, and water gave the upper limits: $Q_{\rm met} < 10^{-17}$, $Q_{\rm air} < 5 \times 10^{-27}$ and $Q_{\rm water} < 3 \times 10^{-29}$.[14] (The water was evaporated and introduced into the apparatus as vapor.) One could, however, regard this as the result of the Earth's being in a sense unfortunate: perhaps during its history it passed through a stage in which all of its matter was hot and all of the quarks were burned out.

5. THE RESULTS OF SEARCHES FOR QUARKS IN COSMIC RAYS

All of the investigation made so far have been directed to the search for cosmic rays with too-small charges. We give a table of the results.

Charge criterion for selection	Height above sea level, m	Upper limit on flux of quarks, $cm^{-2}sr^{-1}sec^{-1}$	Authors
$\frac{1}{3}e$	0	$20 \cdot 10^{-8}$	Sunyar et al. 15
$\frac{1}{3}e$	2500	$1{,}6 \cdot 10^{-8}$	Bowen et al. 16
$\frac{2}{3}e$	500	$5 \cdot 10^{-8}$	Massam et al. 2
$\frac{1}{3}e$	2500	$8{,}7 \cdot 10^{-9}$	De Lise et al. 17
$\frac{2}{3}e$	2500	$18{,}0 \cdot 10^{-9}$	» » » » 17
$\frac{1}{3}e$	500	$1.5 \cdot 10^{-9}$	Bühler-Broglin et al. 18
$\frac{2}{3}e$	500	$1.4 \cdot 10^{-9}$	» » » 18

All of the data are given at the 90 percent confidence level. In addition, a paper of the Argonne group[19] gave $I_q < 4.5 \times 10^{-10}$ at the 80 percent confidence level. After reduction to the same confidence level this figure is practically the same as the data of [18].

We may further mention the report at the All-union Conference on Cosmic Rays (Alma-Ata, 1966) of work by A. V. Khrimyan, V. V. Avakyan, and G. V. Khrimyan, in which masses of particles in cosmic rays were determined. To 10^{-5} μ mesons one particle of mass larger than 7 GeV was found. The probability that such a particle was simulated by an alpha particle was estimated as $< 10^{-4}$.

A special case is a paper by the American physicists Leipuner, Kasha, and Adair,[20] which reports a sensational result: in observations on cosmic rays these authors detected, against the background of large numbers of particles with the usual ionizing power, particles with charges e/3 and 2e/3:

$$I_q\left(\frac{1}{3}e\right) = (2.6^{+2.1}_{-1.3}) \cdot 10^{-9};$$

$$I_q\left(\frac{2}{3}e\right) = (2{,}1^{+1.8}_{-1.5}) \cdot 10^{-9}.$$

This paper, however, after being sent to the press in May 1966, was not discussed at the Thirteenth International Conference on Elementary Particle Physics in Berkeley (September, 1966). It can be seen that the values for the fluxes do not exceed twice the error, and it would be premature to attach great significance to them.

Accordingly, the problem of looking for quarks in cosmic rays is a still unsolved and important one.

In judging the promise of such searches, we should keep in mind two important comments which were made at the conference in Alma-Ata in October, 1966.

The first comment is due to S. N. Vernov, who pointed out that a search for quarks in cosmic rays at low altitudes has a chance of success only if quarks are not strongly interacting particles. Only if this is the case can the primary quarks incident on the boundary of the atmosphere remain in the cosmic-ray flux, which has had many encounters with nuclei in matter in getting down to the altitude of the observations. On the other hand, as has been emphasized, it is only in this case that they can be produced in the atmosphere by ordinary cosmic-ray particles. Therefore the negative result of the searches, as displayed in the table may only mean that the quarks interact strongly and that one must look for them at much higher altitudes.

The second remark, made by N. L. Grigorov, emphasizes that if the upper limits for the content of slow quarks in water and in air given in [14] are correct, the negative result of that paper also means that the flux of fast quarks in the primary cosmic rays is vanishingly small. In fact, on being slowed down stable quarks do not disappear, but are retained in the soil and the atmosphere. During the time that the Earth's crust has existed, $T \sim 10^9$ years $\sim 3 \times 10^{16}$ sec, with a flux $2\pi I_q$ of quarks on 1 cm^2 each second, the number of quarks striking each square centimeter of the Earth's surface has been $2\pi I_q \cdot T \sim 2 \times 10^{17} I_q$. Becoming mixed with the soil or the water of the oceans, they should give, for example in the sea if we assume an average depth of 1 km = 10^5 cm, about

$$\frac{2 \cdot 10^{17} I_q}{10^5 \cdot 6 \cdot 10^{23} \cdot \frac{1}{18} \cdot 18} \sim 3 \cdot 10^{-12} I_q$$

quarks per stable baryon. According to the measurements[14] this number is not larger than 3×10^{-29}. Consequently

$$I_q < 10^{-17}\ \mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}}.$$

For quarks slowed down in the atmosphere and remaining in it, analogous arguments give a similar figure. These values, however, are by no means beyond question. In the processing of the results of the measurements in [14] many assumptions were used which could lead to underestimation of Q, and consequently of the values just given for I_q, by an unknown number of orders of magnitude. Apart from the fact that the physico-chemical methods of selecting the material (for example, evaporation of sea water) can lead to a lowering of the quark content in the specimens studied, other possible sources of large errors can be found in this work (for details see [21]). The authors of the paper themselves say that the work is being continued. We note that more fundamental studies, in which the search was made for quarks in small grains of graphite,[22] give much higher limits for Q. The upper limits for I_q derived from them are still large enough so that we do not have to take them into account for the point of interest here.

Accordingly, as the investigations develop there is an accumulation of negative evidence. It supports the point of view that quarks are only an auxiliary mathematical concept, and not real particles capable of independent existence. The problem is of such fundamental importance, however, that it must be studied experimentally to a final conclusion.

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