[1] M. A. Azimov, V. G. Kolesnik, V. S. Pantuev, L. V. Sil'vestrov, and M. N. Khachaturyan, JINR Preprint R-2436, Dubna, 1965.
[2] V. S. Pantuev and M. N. Khachaturyan, PTE, No. 3, 51 (1965).
[3] I. Manelli, A. Bigi, R. Karara, M. Wahlig, and L. Sodickson, Phys. Rev. Lett. 14, 408 (1965).
[4] A. V. Stirling, P. Sonderegger, J. Kirz, P. Falk-Vairant, O. Guisan, C. Bruneton, P. Borgeaut, M. Yvert, J. P. Guillaud, C. Cavarzasio, and P. Amblard, ibid. 14, 763 (1965).
[5] G. Hohler and J. Giesecke, Phys. Lett. 12, 149 (1964).
[6] M. A. Wahlig, I. Manelli, L. Sodickson, O. Fackler, C. Ward, T. Kan, and E. Shibata, Phys. Rev. Lett. 13, 103 (1964).

THE CROSS SECTION OF QUARK GENERATION

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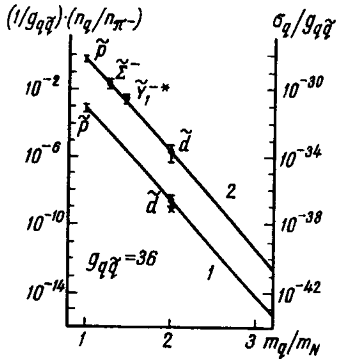
The absence of quarks from pN collisions in accelerators or cosmic rays has led to the conviction that their mass m_q is much higher than the generation threshold, $m_q \sim (8 - 16)m_N$ and more (m_N is the nucleon mass); it is furthermore assumed that their generation cross section σ_q can not be much smaller than $\sim(10^{-3} - 10^{-4})\sigma_0$, where $\sigma_0 \approx 30$ mb is the cross section of inelastic NN collision. We shall show, however, that both independent experiment and the theory lead to $\sigma_q \sim \exp(-2m_q/\mu)$, where μ is the pion mass, so that any increase of m_q by an amount equal to m_N reduces σ_q by ~5 orders of magnitude. Even when $m_q = 2.5m_N$ we get $\sigma_q \sim 10^{-10}\sigma_0$. The experiments performed mean only that $m_q > 2.5m_N$, and the detection of quarks is exceedingly difficult. The reason for this is the competition of the channels with π generation; there is a much larger statistical probability of emission of $2m_q/\mu$ pions than of a $q\tilde{q}$ pair. We assume here (and this is of fundamental significance) that at distances $\sim m_N^{-1}$ to μ^{-1} the qN or qπ interaction is essentially the usual one for NN and πN: inasmuch as the virtual decay $q \to q + (q + \tilde{q}) \equiv q + \pi \to q$ is possible, the q should have the usual pion shell (and the other usual shells of smaller radius).

1. Experiment. The dependence of the cross section for the generation of pairs of heavy strongly-interacting particles on their mass can be deduced from accelerator experiments on the generation of $\tilde{p}$ and $\tilde{d}$, and also $\tilde{\Sigma}^-$ and $\tilde{Y}_1^{-*}$. For the ratio of their numbers $n_{\tilde{p}}$ and $n_{\tilde{d}}$ to the number of pions n_{π^-} in the p-Be collision act (which is practically the same as for the pN collision), and for $d^2\sigma_{\tilde{d}}/d\Omega dp$ for $\tilde{d}$ on Be, for example at $E_{lab} = 30$ GeV, an emission angle $\theta_{lab} = 4.5°$, and a secondary pion momentum p = 5 GeV/c, we get [1,2]

$$\frac{n_{\tilde{p}}}{n_{\pi^-}} = (1 \pm 0.1) \times 10^{-2}; \quad \frac{n_{\tilde{d}}}{n_{\pi^-}} = (5.5 \pm 1.5) \times 10^{-8}; \quad \frac{d^2\sigma_{\tilde{d}}}{d\Omega dp} = 7 \times 10^{-33}\ \text{cm}^2\text{sr}/(\text{GeV/c}).$$

From this we estimate the generation cross sections $\sigma_{\tilde{p}}$ and $\sigma_{\tilde{d}}$ in pN collision (the uncertainty in the values of n_{π^-}, of the angular and momentum distributions of $\tilde{p}$, $\tilde{d}$, and π^-, and the nuclear dimensions can change the results by one order of magnitude, whereas we are concerned with much larger effects). However, $\sigma_{\tilde{d}}$ differs from σ for the generation of a pointlike particle of the same mass by only a factor $\lesssim 6$ [3]: the $\tilde{N}$ are emitted in the c.m.s. with p ~ 200 MeV and readily produce $\tilde{d}$ (cf. the large cross section of the $p + p \to \pi + d$ reaction at ~ 300 MeV). Therefore, taking into account the spin and isotopic factors $g_{\tilde{p}N} = 2 \times 4 = 8$, $g_{\pi^-} = 1$, $g_{q\tilde{q}} = (g_q^2) = 6 \times 6 = 36$, and $g_{\tilde{d}NN} = 3 \times 4 \times 4 = 38$, we get:

$m_q/m_N =$	1	2
$n_{\tilde{q}}g_{\pi^-}/n_{\pi^-}g_{q\tilde{q}} =$	$n_{\tilde{p}}g_{\pi^-}/n_{\pi^-}g_{\tilde{p}N} = (1 \pm 0.1) \times 10^{-3}$	$(1 - 6)n_{\tilde{d}}g_{\pi^-}/n_{\pi^-}g_{\tilde{d}NN} = (0.1 - 1) \times 10^{-8}$
$\sigma_q/g_{q\tilde{q}} =$	$(6 - 2) \times 10^{-29}$ cm^2	$(0.5 - 5) \times 10^{-34}$ cm^2



In the figure we have drawn through the pair of points $m_q/m_N = 1$ and 2 interpolation curves of the type:

$$1)\ \frac{n_q}{g_{q\tilde{q}}n_{\pi^-}} = A\left(\frac{m_q}{T_k}\right)^3 \exp(-2m_q/T_k);\quad A = 6,\ T_k = 0.93\ \mu$$

$$2)\ \frac{\sigma_q}{g_{q\tilde{q}}} = a\left(\frac{m_q}{T_k}\right)^3 \exp(-2m_q/T_k);\quad a = 4 \times 10^{-25}\ \text{cm}^2,\ T_k = 0.94\ \mu$$

The experimental data presented have been divided by the appropriate spin and isospin factors (e.g., $\sigma_{\tilde{p}}/g_{\tilde{p}N}$ etc.). We have also determined the pairs of constants A(a) and T_k. We also indicate σ_Y [4] for $\tilde{\Sigma}^-\Sigma^-$ and $\tilde{Y}_1^{-*}Y_1^{-*}$.

2. Theoretical considerations. An indication of the possibility of the factor $\exp(-2m_q/\mu)$ follows already from the statistical weight Ω_n of the final state with a large number n of particles: $\Omega_n \sim n!V^n \sim \exp[n \ln(nV)]$. Replacement of n by $\Delta n = 2m_q/\mu$ (replacement of the $q\tilde{q}$ pair by a number of pions of equivalent energy) changes the probability by a factor ~ $\exp(2m_q/\mu)$. Owing to the uncertainty in the "generation volume" V, this reasoning can be only used for illustration. A more rigorous derivation is obtained when account is taken of the fact that the particles produced in the multiple generation move apart, interact, and experience transformation so long as their mutual distances do not exceed the force radius μ^{-1}, when a system of many weakly-interacting particles is produced, i.e., a gas of temperature $T_k \sim \mu$. The mass (and momentum) distribution is given by Bose and Fermi statistics. This is the main idea of the Heisenberg-Landau hydrodynamic theory, which is valid for the decay of any strongly-interacting aggregate, for example in a central NN collision or for a center that is strongly excited by peripheral collision. We need here no other features or details of this theory - neither the multiplicity, nor the scattering dynamics, nor the equation of state. From this we can obtain n_q/n_{π^-}. It is necessary to distinguish between the case $n_q \gg 1$, dis-

cussed by Belen'kii [5], and $n_q \lesssim 1$, when the probability of a rare fluctuation is calculated. We obtain ($F_-(z)$ is tabulated in [5], $F_-(1) \approx 2$):

$$n_q = \frac{g_q}{g_\pi} \frac{\sqrt{\pi/2}}{F_-(\mu/T_k)} \left(\frac{m_q}{T_k}\right)^{3/2} \exp(-m_q/T_k), \quad n_q \gg 1 \; ; \tag{1}$$

$$n_q = \left(\frac{g_q}{g_\pi}\right)^2 \frac{(\pi/2)\; n_\pi^2}{[F_-(\mu/T_k)]^2} \left(\frac{m_q}{T_k}\right)^3 \exp(-2m_q/T_k), \; n_q \lesssim 1. \tag{2}$$

The figure corresponds to $n_q \lesssim 1$. It is obvious that the agreement with experiment is very good: T_k is actually close to μ and $A_{theor} \approx 1$ (for $n_{\pi^-} \approx 2 - 3$). All this corresponds to a central collision. Its cross section is $\sim 0.1\ \sigma_0$ (for example, processes of the type $\tilde{p}p \to \tilde{\Sigma}^+\Sigma^+$, which proceed via exchange of a strange meson and have characteristics of peripheral charge exchange [4], are not included here).

Even for very large $n_\pi \sim 500$, for example in collisions of a Ca nucleus with energy $E_{lab} > 10^{12}$ eV/nucleon in emulsion [6], we get (using (1) for $n_q \gg 1$ and (2) for $n_q \lesssim 1$) $n_q \approx 12$, 0.6×10^{-3}, and 1×10^{-9} for $m_q/m_N = 1$, 2, and 3, respectively.

3. Conclusions. The relation derived is general: the decay of any excited center into pions is always more convenient, and (1) and (2) are again applicable to it. The same holds also for electric generation, and in general for any diagram vertex in which a $q\tilde{q}$ pair is produced. However, there are no experimental points for $m_q > 2m_N$, and the statistical analysis may not be accurate, since it presupposes that the system is homogeneous and in equilibrium. Actually, for such small values of σ_q ($\sigma_q < 10^{-10}\sigma_0$), an important role may be played by side effects such as "leakage" of particles from the aggregate, etc.

In this connection, the following possibility is especially important. If the cross section for the interaction of q with π and the cross section of $q\tilde{q}$ annihilation are for some reason noticeably smaller than σ_0 (it is possible that a decrease by 1 - 2 orders of magnitude is sufficient), then the probability of "leakage" of the generated q becomes ~1. A paradoxical situation arises: the strongly interacting q are generated, as already shown, with very small cross section. On the other hand, if the quarks interact weakly at a distance $\sim m_N^{-1} - \mu^{-1}$, then they can have a large production cross section, starting with a certain critical energy (as an estimate, $E_c \sim (m_q/\mu)^2 m_N$).

[1] W. F. Baker et al., Phys. Rev. Lett. 7, 101 (1961).

[2] D. E. Dorfan et al., ibid. 14, 1003 (1965).

[3] R. Hagedorn, Nuovo Cimento 25, 1017 (1962).

[4] B. Musgrave et al., ibid. 35, 735 (1965).

[5] S. Z. Belen'kii and L. D. Landau, UFN 56, 309 (1955).

[6] K. Rybicki, Nuovo Cimento 28, 1437 (1963).