FEASIBILITY OF AN EXPERIMENT IN WHICH HADRONS ARE PRODUCED BY TWO PROTONS FROM THRESHOLD TO EXTREMELY HIGH ENERGIES

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1. The cross sections of the customarily observed and investigated processes of hadron production by a single photon decrease rapidly with increasing total effective mass of the reaction products. We wish to call attention to a mechanism of hadron production by photons ("condensation" of photons), which is amenable to observation in accelerators with opposing e^-e^- or e^+e^- beams, and the cross section of which is practically independent of the total effective mass of the reaction products, and increases like $\ln^2 E/m$ with increasing beam energy E.

The colliding electrons (for concreteness, we shall deal with e^-e^- beams) are decelerated and emit bremsstrahlung photons, which in turn condense into hadrons (see Fig. 1). The total photon-condensation cross section, in analogy with all total cross sections involving hadrons, should be practically constant at high energies.

2. The scheme for calculating the observable quantity is similar to that used to extract data on the total γp-scattering cross section from electroproduction [cf. [1], where references to earlier literature can be found).

For colliding beams $p_1^0 = p_2^0 = E$, the energy of the final electrons is $p_i'^0 = E_i$, and there scattering angles are θ_i -- see Fig. 1. Then (m is the electron mass)

$$q_i = p_i - p_i'; \quad r_i = p_i + p_i'; \quad q_i^2 = -4EE_i \sin^2\frac{\theta_i}{2} - m^2\frac{(E-E_i)^2}{EE_i} \; (i = 1,2);$$

$$s = (q_1 + q_2)^2;$$

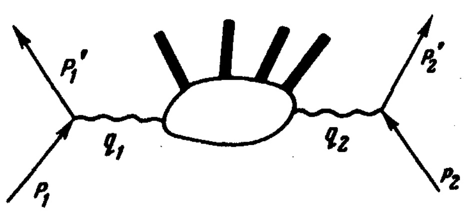

Fig. 1

After summing over all the hadron states, the result is expressed in terms of the absorptive part of the 6-amplitudes of the forward γγ scattering. Since $q_i^2 \neq 0$, a scalar photon polarization S is possible besides the transverse one T. The 4-amplitudes are expressed in terms of the total cross section $\sigma_{TT}^{\gamma\gamma}$, $\sigma_{TS}^{\gamma\gamma}$, $\sigma_{ST}^{\gamma\gamma}$, and $\sigma_{SS}^{\gamma\gamma}$ (the first index indicates the polarization of the first photon) and two amplitudes τ_{TT}^{ex} and τ_{TS}^{ex} corresponding to processes with change of helicity of the individual photons, but with conservation of the total helicity. This question will be dealt with in a separate paper. As a result we have for small scattering angles θ_i, when $|q_i^2| \ll s$,

$$\frac{d^4\sigma}{dE_1 d\Omega_1 dE_2 d\Omega_2} = \left(\frac{\alpha}{2\pi^2}\right)^2 \frac{1}{q_1^2 q_2^2} \frac{E_1}{E} \frac{E_2}{E} \frac{(E_2^2 + E^2)(E_1^2 + E^2)}{(E - E_1)(E - E_2)} \sigma_{exp}^{\gamma\gamma}, \tag{2}$$

$$\sigma_{exp}^{\gamma\gamma} = \sigma_{TT}^{\gamma\gamma} + \epsilon_1\sigma_{ST}^{\gamma\gamma} + \epsilon_2\sigma_{TS}^{\gamma\gamma} + \epsilon_1\epsilon_2\left(\sigma_{SS}^{\gamma\gamma} + \frac{\tau_{TT}^{ex}}{4}\cos 2\phi\right) + \epsilon_3\tau_{TS}^{ex}, \tag{3}$$

$$\epsilon_1 = \frac{2EE_1}{E^2 + E_1^2}; \quad \epsilon_2 = \frac{2EE_2}{E^2 + E_2^2}; \quad \epsilon_3 = \frac{(E+E_1)(E+E_2)E\sqrt{E_1E_2}\cos\phi}{8(E^2+E_1^2)(E^2+E_2^2)}. \tag{4}$$

Here ϕ is the angle between the electron scattering planes.

3. At small values of q_i^2 we have $s \approx 4(E - E_1)(E - E_2)$, and the quantity $\sigma_{exp}^{\gamma\gamma}(s;\, q_1^2;\, q_2^2)$ differs little from the total cross section for the scattering of light by light $\sigma_{TT}^{\gamma\gamma}(s;\, 0;\, 0)$. The asymptotic values $\sigma^{\pi p} \approx 25$ mb and $\sigma^{\gamma p} \approx 100$ μb differ by approximately $2/\alpha \approx 250$ times. This is approximately the factor by which $\sigma^{\gamma\gamma}$ should be smaller than $\sigma^{\gamma p}$, i.e., $\sigma^{\gamma\gamma} \sim (0.3 - 1) \times 10^{-30}$ cm^2 $\approx (\alpha/m_\pi)^2$. The maximum $2\gamma \to 2\pi$ cross section calculated in scalar electrodynamics has about the same value. Integrating (2) over the entire spectrum of the secondary electrons, we obtain $\sigma \sim [(\alpha/\pi)\ln(E/m)]^2\sigma_{exp}^{\gamma\gamma} \sim 10^{-33}$ cm^2. On the other hand, if we confine ourselves in (2) to integration in the range of scattering angles θ_i from 0 to $\theta_m < 1$, and in the range of energies E_i from 0 to $E_m < E$, assuming that σ_{exp} is constant, then

$$\Delta\sigma|_{\theta_i \leqslant \theta_m,\, E_i \leqslant E_m} \approx \sigma_{exp}^{\gamma\gamma}\left[\frac{\alpha}{\pi}\frac{E_m}{E}\ln\frac{E_m\theta_m}{m}\right]^2. \tag{5}$$

When $E = 3.5$ GeV, $E_m/E = 0.2$ and $\theta_m = 0.2$, the range of q_i^2 is from 0 to 0.007 GeV, that of s is from 30 to 50 GeV, and $\sigma \sim (1 - 4) \times 10^{-36}$ cm^2.

4. Since the electron scattering angles are small in the proposed experiments, the photon momenta are directed along the initial momenta. Therefore the condensed hadrons should form, in the main, two bunches traveling along the initial beams. The average transverse momentum of the hadrons in these bunches should be of the order of 300 - 500 MeV (as in all hadron processes). A significant part of these bunches should carry away a unit angular momentum, i.e., they should contain many vector mesons (ρ, ω, ϕ, ...). It is very important to ascertain the fraction of processes in which hadrons emitted at large angles reproduced. The dependence of the cross sections in q_i^2 is also of great interest.

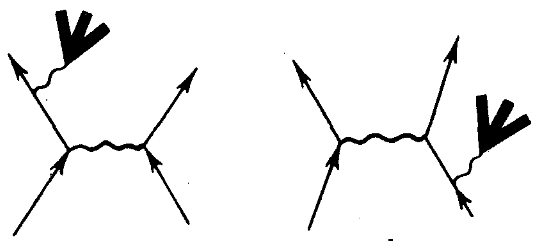

Fig. 2

5. In hadron interactions, the cross sections of the low-energy ($\lesssim 1$ GeV) elastic or almost-elastic processes are of the same order as the asymptotic total cross sections, while a (at resonance) is larger by one order of magnitude. The proposed scheme can therefore be used also to study the following low-energy processes: a) $2\gamma \to 2\pi$, from which data can be extracted on the $\pi\pi$-scattering s-wave, i.e., on the wavelengths and on the ε meson (the σ meson) and perhaps also on the f-meson, etc. We know that the required calculations are already under way, see also [2]. b) $2\gamma \to \pi^0\eta$, which is a very interesting system for various symmetry schemes. In particular, the resonances $\eta'(X^0)$, π^N, A_2, etc. are of interest.

6. To distinguish this process from ordinary annihilation into hadrons, it is nece-sary to separate the final electrons. This can be done with the aid of

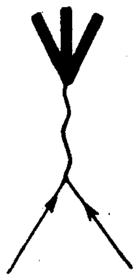

Fig. 3

a magnetic field at the point of encounter even at a zero scattering angle. An important competitor of the two-photon production is the hadron "bremsstrahlung" process (Fig. 2), which likewise does not decrease with increasing energy. This process can be calculated fully if the cross sections for single-photon annihilations into hadrons is known (Fig. 3). It is important here that the amplitudes of the processes in Figs. 1, 2a, and 2b do not interfere pairwise.

The existence of these methods of hardon production must be taken into account in the interpretation of colliding-beam experiments.

Thus, accelerators with colliding electron and (or) positron beams can be used as sources of colliding photon beams, i.e., for the study of the "condensation" of photons into hadrons at high energies. The characteristic cross sections of such processes are 10^{-33} - 10^{-34} cm^{-2}.

[1] F.I. Gilman, Preprint, SLAC-PUB-674, 1969.
[2] P.C. DeCelles and I.F. Goehl, Phys. Rev. 184, 1617 (1969).

ANOMALOUS VIBRATIONAL EXCITATION OF THE CO^+ ION PRODUCED UPON COLLISION OF NOBLE-GAS IONS WITH CO MOLECULES

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Recent papers [1 - 3] have reported deviations from the Franck-Condon law upon population of the vibrational levels of excited electronic states of diatomic molecular ions produced in slow collisions of ions with molecules in the electronic ground state. In [1, 2] there was observed an increase of the population of vibrational levels with vibrational quantum numbers v' = 1, 3, and 3 of the state $B^2\Sigma_g^+$ of the molecular ion N_2^+ excited by collision of different ions of velocity $v < 1 \times 10^8$ cm^2/sec with N_2 molecules.

A deviation from the Franck-Condon principle was observed in [3] upon population of the vibrational levels v' = 0, 1, 2, 3, 4, and 5 of the excited electronic state $A^2\Pi$ of the CO^+ ion produced in collisions between Ar^+ ions of energy 1 keV with CO molecules.

It was of interest to study the effect of anomalous population of the vibrational levels of the $A^2\Pi$ state of the CO^+ ion produced by collisions of various ions having velocities $v < 1 \times 10^8$ cm/sec with the CO molecule. In the present investigation, the molecular ion CO^+ in the state $A^2\Pi$ was produced in collisions between He^+, Ne^+, and Ar^+ ions of energy 0.16 - 30 keV with CO molecules. The experimental setup used for the measurements is described in [1]. The effective cross sections σ for the productions of the $CO^+(A^2\Pi)$ ions in different vibrational states were determined in relative units by measuring the intensities of the bands of the system of comet tails, emitted in $A^2\Pi$ -- $X^2\Sigma$ transitions ($X^2\Sigma$ is the ground state of the CO^+ ion). The functions $\sigma(v)$ were determined for the bands of the comet-tail systems with vibrational transitions (0, 1), (1, 0), (2, 0), (2, 1), (1, 1), (3, 0), and (4, 2). Figure 1 shows the functions $\sigma(v)$ for the (2, 0) band, excited by collisions with He^+, Ne^+, and Ar^+ ions. The functions for the other bands of the $A^2\Pi$ -- $X^2\Sigma$ system were similar. The measured effective excitation cross sections of $A^2\Pi$ -- $X^2\Sigma$