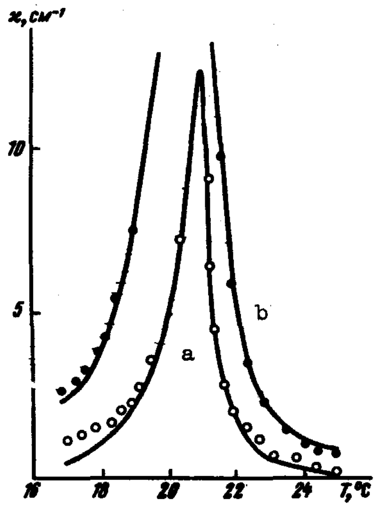

Temperature dependence of the USW absorption coefficient $\kappa(T)$ of SbSI: a - at 10 MHz (light circles); b - 30 MHz (dark circles). The solid curves represent the theoretical calculations.

dependences of the USW absorption and of the specific heat.

We have attempted to compare the temperature dependence of the anomalous absorption of USW in SbSI [5] with the jump of the specific heat given in [11]. Assuming that Eq. (3) holds up to 10 MHz, we calculated κ and obtained quite good agreement with experiment (curve a in the figure). By choosing $\gamma = 3.8 \times 10^7$, $\chi = 0.1$, and $A = 3.4 \times 10^{-6}$ cgs esu, and by using formula (2), we can obtain good agreement also at 30 MHz (Fig. b). At 30 MHz the experimental points are displaced 0.4°C towards the lower temperatures, since such an error in the measurement of the absolute temperature was quite possible. In the ferroelectric phase, the experimental values of κ are somewhat larger, but this is understandable, since the domain scattering was not taken into account in this case.

Such an agreement between the experimental and theoretical results in the case of SbSI promises an interesting theoretical study of the change of the specific-heat and USW absorption in ferroelectrics.

[1] K.A. Minaeva and A.P. Levanyuk, Izv. AN SSSR ser. fiz. 24, 96 (1965).
[2] K.A. Minaeva, A.P. Levanyuk, B.A. Strukov, and V.A. Koptsik, Fiz. Tverd. Tela 9, 1220 (1967) [Sov. Phys.-Solid State 9, 950 (1967)].
[3] L.D. Landau and I.M. Khalatnikov, Dokl. Akad. Nauk SSSR 96, 469 (1954).
[4] A.P. Levanyuk, Zh. Eksp. Teor. Fiz. 49, 1304 (1965) [Sov. Phys.-JETP 22, 901 (1966)].
[5] V.I. Samulionis and V.F. Kunigelis, Fiz. Tverd. Tela 11, 844 (1969) [Sov. Phys.-Solid State 11, 696 (1969)].
[6] V. Dvorak, Can. J. Phys. 45, 3903 (1967).
[7] K. Tani and H. Mori, Progr. Theor. Phys. 39, 876 (1968).
[8] K. Kawasaki, Phys. Lett. 26A, 543 (1968).
[9] K. Kawasaki, Phys. Lett. 29A, 406 (1969).
[10] I. Hatta, T. Ishiguro, and N. Mikoshiba, J. Phys. Soc. Japan 28, Suppl. 211 (1970).
[11] T. Mori, H. Tamura, and E. Sawaguchi, J. Phys. Soc. Japan 20, 281 (1965).

ELECTROPRODUCTION IN COLLIDING-BEAM EXPERIMENTS

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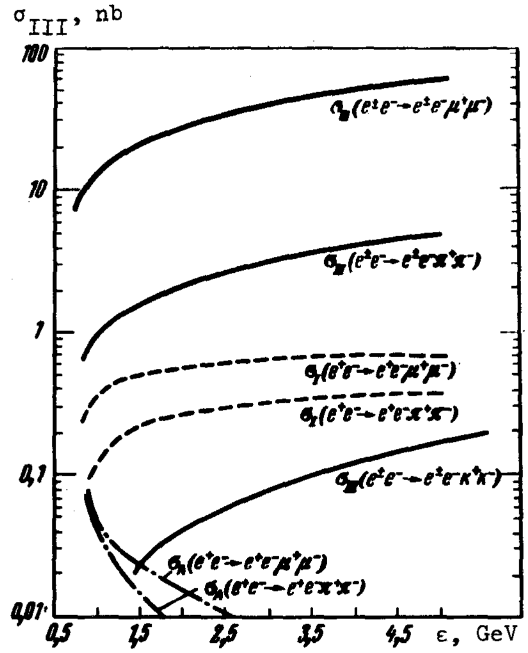
The process of electroproduction in colliding beam experiments ($e^{\pm}e^- \to e^{\pm}e + N$) has been frequently discussed recently, particularly at the Kiev Conference [1 - 3]. In the region of realistic energies ($\varepsilon < 5$ GeV in the foreseeable future), pair electroproduction processes ($\pi^+\pi^-$, $\mu^+\mu^-$, etc.), will apparently predominate, and these lend themselves most readily to a theoretical analysis (large-angle e^+e^- pair electroproduction was recently observed in Novosibirsk at $\varepsilon = 500$ MeV [4, 5]). To estimate the total cross sections, variants of the method of equivalent photons were used in [1, 2], and analytic expressions for the cross sections were calculated in [3] for the case of arbitrary masses in the doubly-logarithmic approximation. We present here a more complete analysis of the pair-electroproduction process, for the purpose of comparing it with the results of the latest experiments with colliding-beam experiments.

In the lowest order of perturbation theory in the electromagnetic interaction, the electroproduction process is represented by two types of diagrams: a) the final states are produced by two photons (two-photon); 2) the final states are produced by one photon (bremsstrahlung). Belonging to the same types are the exchange diagrams (for e^-e^- collisions) and the annihilation diagrams (for e^+e^- collisions), which we shall consider separately.



The contribution of the two-photon diagrams is predominant, and when $\varepsilon >> \mu$ it has with singly-logarithmic accuracy the form:

$$\sigma_{III}^{(s_f)} = \frac{\alpha^4}{27\pi\mu^2}\left[g_1^{(s_f)} L_p\left(L^2 - \frac{L_p^2}{3}\right) - g_2^{(s_f)}(L^2 - L_p^2) - g_3^{(s_f)} L L_p + g_4^{(s_f)} L + g_5^{(s_f)} L_p\right], \tag{1}$$

where $L = \ln(4\varepsilon^2/m^2)$, $L_p = \ln(4\varepsilon^2/\mu^2)$, $\varepsilon(m)$ is the energy (mass) of the initial particle, $\mu(s_f)$ is the mass (spin) of the particles of the produced pair,

$$g_1^{(0)} = 6,\ g_2^{(0)} = 51/2,\ g_3^{(0)} = 19,\ g_4^{(0)} = 569/6 - 4\pi^2,\ g_5^{(0)} = -\frac{979}{6} + \pi^2,$$

$$g_1^{(1/2)} = 42,\ g_2^{(1/2)} = 192,\ g_3^{(1/2)} = 178,\ g_4^{(1/2)} = \frac{5855}{6} - 28\pi^2, \tag{2}$$

$$g_5^{(1/2)} = -\frac{6925}{6} + 7\pi^2.$$

The cross section $\sigma_{III}^{(s_f)}$ is shown in the figure, where account is also taken of the terms containing μ/ε. At high energies ($\varepsilon > 3$ GeV for μ and π mesons), Eq. (1) is valid directly. It is important that the terms cubic in L and L_p in Eq. (1) are cancelled out to a considerable degree by the quadratic terms (at $\varepsilon = 5$ GeV, the cross section $\sigma_{III}^{(0)}$ is half as large as the cubic term[1]). In a

[1]The cross section $\sigma_{III}^{(0)}$ given in [2] corresponds to the term L_pL^2 in (1) and has an incorrect numerical coefficient. The cross sections σ_{III} shown in the figure for $\mu^+\mu^-$ and $\pi^+\pi^-$ differ from the corresponding cross sections in [2] by a factor 1.5 - 2.5.

rather wide region near the threshold ($\varepsilon \lesssim 5\ \mu$), the expansion of the cross section in powers of L and L_p is not adequate (nor is it in the photoproduction problem), and incidentally the cross sections are small in this region. In the case of production of π and K mesons, the cross section $\sigma^{(0)}_{III}$ should be regarded as being model-derived, since only the Born term is taken into account in it. However, since the main contribution is made by the region where the invariant mass of the produced pair $\Delta^2 \equiv (p_+ + p_-)^2 \sim 4\mu^2$, it is perfectly possible that this term describes the physical situation satisfactorily. Great interest attaches to the interaction between the produced hardons in the final state (ℓ even, C = 1), information concerning which can be obtained from a comparison of the observed cross section with the one calculated at fixed Δ^2, for which we have, omitting the terms linear in L_p,

$$\frac{d\sigma^{(0)}_{III}}{dx} = \frac{\alpha^4\beta}{\pi\mu^2}\left\{d_1\left[L_x\left(L^2 - \frac{L_x^2}{3}\right) - \frac{3}{2}(L^2 - L_x^2) - 4L\left(L_x + \frac{\pi^2}{6} - \frac{39}{16}\right)\right] + L\left[d_2(L_x - 2) + \frac{2}{3}d_3\left(L_x - \frac{11}{6}\right)\right]\right\}, \tag{3}$$

where

$$x = \frac{4\mu^2}{\Delta^2},\quad \beta = \sqrt{1-x},\quad L_x = \ln\frac{\epsilon^2}{\mu^2}x,\quad d_1 = \frac{1}{2}\left[1 + x - x\left(1 - \frac{x}{2}\right)\ell_0\right],$$

$$d_2 = -3 - \frac{x}{2} + \left(1 + x - \frac{x^2}{4}\right)\ell_0,\quad d_3 = \frac{1}{2}\left[1 - x - \left(1 - \frac{3}{2}x + \frac{x^2}{2}\right)\ell_0\right], \tag{4}$$

$$\ell_0 = \frac{1}{\beta}\ln\frac{1+\beta}{1-\beta}.$$

In the region that makes the main contribution to σ_{III}, the transverse momentum of all the final particles is $p_{f\perp} \lesssim \mu$, and the final electrons are deflected through a small angle (distribution $d\theta/\theta$, $(m\mu^2/\varepsilon^3) \ll \theta \ll (\mu/\varepsilon)$), and their energy is $\sim\varepsilon$. When $\varepsilon \sim \mu$, the angular distribution of the produced particles is smooth, and when $\varepsilon \gg \mu$ their spectrum is given by $(d\omega/\omega)$ ($\omega = \varepsilon_+ - \varepsilon_-$), so that at $\varepsilon_\pm \sim \mu$ their angular distribution is smooth, and at $\varepsilon_\pm \gg \mu$ it is elongated ($\Delta^2 \sim 4\mu^2$) in the direction of the initial particle whose energy is received by the pair.

The bramsstrahlung diagrams make equal contributions $\sigma_I = \sigma_{II}$ for each of the electron lines:

$$\frac{d\sigma_I^{(s_f)}}{dx} = \frac{\alpha^4\beta}{9\pi\mu^2}\psi^{(s_f)}\left[\ln\frac{4\mu^2}{m^2x}\ln\frac{2\epsilon^4x^{3/2}}{m\mu^3} + \frac{1}{3}\ln\frac{8\epsilon^2m^8x^5}{(2\mu)^{10}}\right]\left|F\left(\frac{4\mu^2}{x}\right)\right|^2. \tag{5}$$

where $\psi^{(1/2)} = 1 + x/2$, $\psi = (1 - x)/4$, and $F(\Delta^2)$ is the electromagnetic of the produced particles (F = 1 for muons). In the case of hadron production, the interaction in the final state is well known from experiments on annihilation in the one-photon channel. For the pairs $\pi^+\pi^-$ and K^+K^-, the bremsstrahlung of the $\rho(\phi)$ meson predominates in the cross sections $\sigma_{I,II}$ (its contribution to the cross section exceeds the cross section for pointlike particles by 6 - 7 (3 - 4) times). The contribution σ_A of the annihilation diagrams, which decreases like ε^{-2} (for e^+e^- collisions) was considered in [6], and it should be taken into account only far from the threshold. The total cross sections $\sigma_I = \sigma_{II}$ and σ_A (with allowance for the terms $\sim\mu/\varepsilon$) are shown in the figure. We see that $\sigma_I + \sigma_{II}$ constitutes an appreciable fraction of the total cross section of the process ($\sigma = \sigma_I + \sigma_{II} + \sigma_{III} + \sigma_A$) at $\varepsilon < 1$ GeV and that the relative contribution of these diagrams decreases with increasing ε. The distribution of the produced hadrons is determined by the decay properties of the $\rho(\phi)$ meson and by its motion. When $\varepsilon \sim m_\rho$, the ρ meson has low velocity, and when $\varepsilon \gg m_\rho$ the meson moves in the direction of the electron that produced it with the following angular and energy distributions:

$$d\epsilon_\rho \, d\theta_\rho^2 / \epsilon^3 [\theta_\rho^2 + \epsilon^{-3} m\rho^2 (\epsilon_{\rho\, max} - \epsilon_\rho + \epsilon m^2 m\rho^{-2})]^2 ,$$

where $\varepsilon_{\rho max} = \varepsilon + (m\rho^2/4\varepsilon)$. The bremsstrahlung electron loses practically all the energy (the distribution is $d\varepsilon_B/[\varepsilon_B + \varepsilon(m^2/m_\rho^2)]$), and the recoil electron loses an energy m_ρ^2/ε and is emitted in an angle $\lesssim m_\rho/\varepsilon$.

We note that by analyzing the produced particle we can identify the process also without observing the final electrons, as was done in [4].

It was reported at the Kiev Conference that events in which the momenta of the final particles were not collinear and the angle between the production planes (the non-complanarity angle) was $\phi_{nc} > 5 - 20°$), were observed in colliding-beam experiments in Novosibirsk and in Frascati at 0.6 GeV $< \varepsilon < 1.0$ GeV. These events were interpreted as multiple production of particles [7, 8]. The total cross section for these events is $\sigma_m \sim 10^{-31}$ cm^2, and they may be due to electroproduction. It is seen from our results, however (see the figure), that the total electroproduction cross sections are several times smaller than is required to explain the results, let alone the fact that the large-angle cross section for non-complanar events is much smaller than the total cross section, and contains only the first power of L [5]. It remains to evaluate the processes that imitate hadron production. Foremost among these is the process of electroproduction of e^+e^- pairs at large angles, for which the imitation cross section (i.e., the cross section at real angles, at real energy thresholds of registration, etc., recalculated in terms of the total cross section under the same very simple assumption as the experimental one) is $\sigma_{e^+e^-} \sim 10^{-32}$ cm^2 [5]. The cross section for the electroproduction of two e^+e^- pairs when two or more of the particles have an energy $\varepsilon_\pm > \varepsilon_0$ and are emitted at large angles, does not exceed $(m/\varepsilon_0)^2\sigma_t$ (in the region of the main contribution, all the momenta are $\lesssim m$). For this reason, the imitation cross section is $\sigma_{2(e^+e^-)} < 10^{-34}$ cm^2, thus refuting the explanation proposed in [9], where part of the observed events was ascribed to this process.

The authors are grateful to A. Onuchin for a discussion of the experimental situation and to S. Eidel'man for help in the numerical calculations.

[1] V.E. Balakin, V.M. Budnev, and I.F. Ginzburg, Kiev Conference, 1970; ZhETF Pis. Red. 11, 559 (1970) [JETP Lett. 11, 388 (1970)].
[2] S. Brodsky, T. Kinoshita, H. Terezawa, Kiev Conference, 1970; Phys. Rev. Lett. 25, 972 (1970).
[3] V.N. Baier and V.S. Fadin, Kiev Conference, 1970; Lett. Nuovo Cimento 5, No. 10 (1971).

[4] V.E. Balakin, A. Bukin, E. Pachtusova, et al., Phys. Lett., 1971 (in print).
[5] V.N. Baier and V.S. Fadin, Phys. Lett., 1971 (in print).
[6] V.N. Baier, V.A. Khoze, and V.S. Fadin, Zh. Eksp. Teor. Fiz. 50, 156 (1966) [Sov. Phys.-JETP 23, 104 (1966)].
[7] V.E. Balakin, G.I. Budker, et al., Kiev Conference, 1970.
[8] B. Bartoly et al., G. Barbellini et al., Kiev Conference, 1970.
[9] J. Sakurai, Acta Phys. Hung., 1971 (in print).

LIGHT SCATTERING BY DROPS OF THE CONDENSED PHASE OF NONEQUILIBRIUM CARRIERS IN GERMANIUM

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It was noted in [1] that a direct confirmation of the existence of a condensed phase of nonequilibrium carriers in semiconductors, in the form of droplets, would be the observation of scattering of light by such droplets. In fact, drops of an electron-hole plasma of radius r_0 with a concentration p_0 of nonequilibrium carriers, have a complex refractive index m, which differs from the refractive index n of the crystal lattice of the semiconductor as a result of the absorption of the light by the carriers:

$$m = n - in^* ; \quad n^* = Sp_0 \lambda / 4\pi . \tag{1}$$

Here S is the cross section for the absorption of the light by the carriers, and λ is the wavelength of the light in vacuo. If $n^*/n \ll 1$ and $Sp_0r_0 \ll 1$, then the Rayleigh-Gans scattering theory is valid [2]. If furthermore, the dimension of the drops is large, $2\pi r_0 \gg \lambda/n$, then scattered at small angles will predominate. In this case the strength of the light scattering in the sample at an angle θ/n and emerging through a flat face of the crystal at an angle θ to the beam of incident light, can be represented in the form [2]

$$u_p(\theta) = I_0 d(2\pi)^2 NV^2 \lambda^{-4} (n^*)^2 G^2(r_0\theta),$$
$$G(r_0\,\theta) = 3\left(\sin\frac{2\pi}{\lambda}r_0\theta - \frac{2\pi}{\lambda}r_0\theta\cos\frac{2\pi}{\lambda}r_0\theta\right)\left(\frac{2\pi}{\lambda}r_0\theta\right)^{-3}. \tag{2}$$

Here I_0 is the flux of the sounding light, $V = 4\pi r_0^3/3$ is the volume of the drops, N is their concentration, and d is the thickness of the layer in which the scattering takes place. Integrating (2) with respect to θ and assuming that the bulk of the nonequilibrium carriers is concentrated in the condensed phase, $NVp_0 = g\tau_0$, we obtain, when account is taken of (1), the integral flux of the scattered light

$$I_p = \frac{3}{8} I_0 dS^2 p_0 r_0 g\tau_0 \tag{3}$$

Here g is the excitation rate, and τ_0 the lifetime of the condensate. The light flux absorbed by the carrier in the condensed phase can be written in the form

$$I_n = I_0 dS g\tau_0 \tag{4}$$

from which it follows that

$$I_p/I_n = \frac{3}{8} Sp_0 r_0 . \tag{5}$$