Table 2
Theoretical and experimental values of the magnetic moments for the two lower levels in Pm^{149}

State, keV	μ_{sp}	μ_{qp}	μ_0	μ_1	μ_2	μ_{theor}	μ_{exp}
114 ($5/2^+$)	4,79	3,65	1,51	0,75	0.29	2.55	2,20 ±0,20
270 ($7/2^-$)	1,72	2,19	0,75	0,97	0,35	2.06	2,17 ±0,21

Knowing the exactly established values of the spins of the levels 114 and 270 keV, we can determine their magnetic moments:

and

$$\mu(114) = (2{,}20 \pm 0{,}21) \text{ n.m.}$$
$$\mu(270) = (2{,}17 \pm 0{,}21) \text{ n.m.}$$

The Schmidt model predicts for levels with spin $I^\pi = 5/2^+$ and $I^\pi = 7/2^-$, in nuclei with an odd proton, magnetic moments 4.79 and 1.72 nuclear magnetons, respectively, which do not agree with our results. This points to the presence of impurities in these states, i.e., they are not purely single-particle. We have therefore attempted to explain the characteristics of the nuclei by using the Kisslinger and Sorensen model of paired plus quadrupole forces [6]

$$\mu(I_j) = (C^j_{j00})^2 \mu_{qp}(I_j) + \mu_1 + \mu_2 \quad ,$$

where C^j_{j00} is the non-phonon component of the magnetic moment, μ_1 and μ_2 are the single-phonon and two-phonon corrections, and $\mu_{qp}(I_j)$ is the quasiparticle magnetic moment of the state under consideration.

Table 2 shows and compares the obtained data for 114 and 270 keV states with the theory. It follows from Table 2 that the experimental and theoretical values are in good agreement. This in turn indicates that the assumption 114 and 270 keV level are mixtures of single-particle and phonon state is correct.

[1] R. B. Begzhanov et al., in: Elektromagnitnye perekhody v yadrakh (Electromagnetic Transitions in Nuclei), Fan, 1966, p. 205.
[2] K. Gopunothan, Phys. Rev. 141, 1185 (1966).
[3] A. G. Soensson et al., Nucl. Phys. 89, 348 (1966).
[4] R. Arus and M. Wiedenbeck, Phys. Rev. 111, 1631 (1958).
[5] R. B. Begzhanov, Dzh. Gaffarov, and K. T. Salikhbaev, DAN UzSSR, No. 12 (1968).
[6] L. S. Kisslinger and T. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

CONDENSATION OF EXCITON GAS IN GERMANIUM

V. M. Asnin and A. A. Rogachev
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted 24 February 1969
ZhETF Pis. Red. 9, 415-419 (5 April 1969)

In [1 - 3] we reported observation of metalization of exciton gas in germanium, manifest by a sharp increase of the electric conductivity when a certain critical value of the exciton density is reached. These experiments, however, did not make it possible to explain the mechanism of such a transition. It is possible in principle that the transition is the result of a more or less gradual collapse of the energy gap between the exciton levels and the states

of the continuous spectrum. On the other hand, it may turn out that the metallization of the excitons is a first-order phase transition [4, 5]. If this is so, we can expect regions, in which the excitons are either in the dielectric or in the metallized state, to be formed in the sample. An important distinguishing feature of this case could be the appearance of a constant concentration in the metallized regions.

The present paper is devoted to preliminary results of an experimental investigation of this question. It was observed in [3, 6, 7] that the form of the absorption edge of direct transitions in germanium depends strongly the concentration of the free carriers, and it was shown that the change of the form of the absorption edge is the result of the screening of the Coulomb interaction of the electrons and holes produced by the light. This effect is manifest in the modulation of the light transmitted through the sample with a wavelength near the absorption edge when free carriers appear in the sample. The form of the modulation spectrum is determined by the concentration of the carriers produced in the semiconductor. In this investigation, similar measurements were used to determine whether the metallization of the excitons is a first-order phase transition. Indeed, in the case when the sample breaks up into regions in which the concentration of the free carriers is constant and regions where there are practically no free carriers, then the form of the modulation spectrum can be expected to be constant[1)]. To the contrary, a gradual increase of the concentration of the free electrons and the holes leads to an appreciable change of the form of these spectra [7].

The experiments were made with p-type germanium samples (ρ = 25 ohm-cm) 6 μ thick, placed in liquid helium. To reduce the rate of surface recombination, the samples were bright-dipped. The electron-hole pairs were produced by light from an ISSh-100 flash lamp with pulse duration 15 μsec. Monochromatic light in the wavelength region corresponding to the edge of the direct transitions was passed simultaneously through the sample. The intensity-modulation signal resulting from the pulsed illumination was received by a germanium photodiode with a time constant $\sim$ 1 μsec and was registered by a pulsed synchronous detector, which made it possible to measure the modulation signal at a variable time delay relative to the exciting pulse. Since the lifetime of the electron-hole pairs in the temperature interval from 77 to 1.7° K was much longer than the duration of the exciting-light pulse, the electron and hole concentration averaged over the sample[2)] could be determined from the forms of the modulation spectra at liquid-nitrogen temperature. The dependence of the absorption coefficient near the direct exciton on the free-carrier concentration was calibrated by using samples doped with antimony and gallium and having a known carrier density.

Figure 1 shows the transmission spectra of the sample, obtained at different excitation levels, while Fig. 2 shows the dependence of the integral transmission on the concentration of the electron-hole pairs averaged over the sample. The modulation of the light in the sample becomes manifest when the concentration of the electron-hole pairs exceeds 10^{15} cm^{-3}. It is

---

1) It is assumed here that the sample is sufficiently thin, and that the changes of the absorption coefficient are sufficiently small.

2) We have in mind the total concentration of free electron-hole pairs and those bound in excitons.

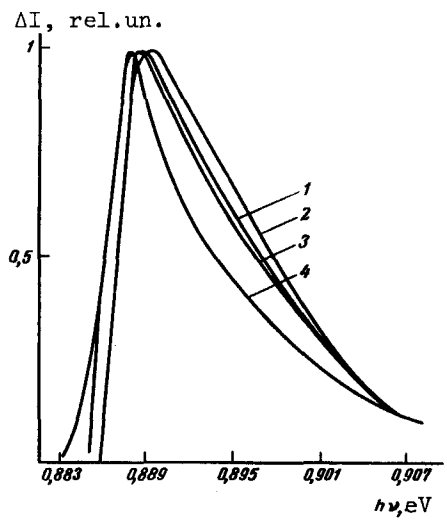

Fig. 1

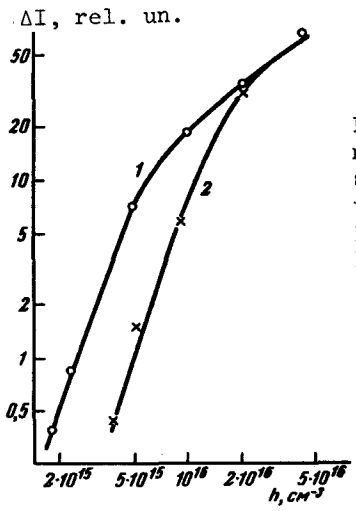

Fig. 2

Fig. 1. Transmission spectra of germanium in the region of direct transitions at different sample excitation levels, T = 4.2°K, and n = 3.5×10^{15} cm^{-3}(1), 5.5×10^{15} cm^{-3}(2), 1×10^{16} cm^{-3}(3),and 2×10^{16} cm^{-3}(4).

Fig. 2. Integral transmission vs. electron-hole pair concentration averaged over sample: 1)T = 4.2°K, 2) T = 1.7°K.

significant that the form of the modulation spectrum remains practically constant over the entire section of sharp growth of the modulation, starting from the instant when the modulation appears (curves 1 - 3, Fig. 1).

It follows therefore that the sample contains individual regions in which the excitons are in a metallized state with a constant density independent of the excitation level. The increase of the local concentration becomes possible only after these regions fill the sample completely. The filling of the sample by metallized excitons occurs apparently near the point of cessation of the sharp growth of the modulation on Fig. 2, since an appreciable change in the form of the modulation spectrum is observed at larger concentrations (curve 4, Fig. 1). It should be noted that this is precisely the concentration region we observed a broadening of the luminescence spectra near the direct transitions; this obviously is a reflection of the growth of the Fermi energy. At the same time, in the luminescence spectra remained practically unchanged in the preceding section of sharp modulation growth.

The foregoing facts allow us to conclude that the observed metallized regions constitute "drops" of condensed excitons.

In another series of experiments, the concentration of the electron-hole pairs was varied by changing the time of delay of the spectrum measurements and the magnitude of the modulation. The decrease of the concentration with time can be approximately described by the relation $n = n_0 (1 - e^{-t/\tau})$, where τ is the lifetime[3)], and therefore each value of the delay t corresponds to a definite concentration of the electron-hole pairs. In such an experiment, there is no section of sharp modulation growth, but the experimental modulation spectra retain the same form in the corresponding concentration region. The results of these experiments probably characterize the kinetics of the formation of the "drops" of the exciton condensate. At small average concentrations, only a small fraction of the excitons has time

[3)]The dependence of the concentration on the time can be evaluated from the character of the relaxation of the photo luminescence of the samples at the same excitation levels.

to condense into "drops" during the exciton lifetime. This fraction, however, increases rapidly when the concentration approaches the critical value equal to the concentration in the "drop." As the carriers gradually die out, the volume of the "drops" decreases gradually, leading to a smoother dependence of the modulation on the concentration. It follows from the experimental data presented here that the density of the electron-hole pairs in the metallic phase is approximately equal to 10^{16} cm^{-3} and increases somewhat with decreasing temperature.

The authors thank S. M. Ryvkin for support and interest in the work and L. V. Keldysh for a fruitful discussion of questions pertaining to the collective properties of large-radius excitons.

[1] V. M. Asnin, A. A. Rogachev, and S. M. Ryvkin, Fiz. Tekh. Poluprov. 1, 1742 (1967) [Sov. Phys.-Semicond. 1, 1447 (1968)].
[2] V. M. Asnin and A. A. Rogachev, ZhETF Pis. Red. 7, 464 (1968) [JETP Lett. 7, 360 (1968)].
[3] A. A. Rogachev, Proc. 9th Internat. Conf. on Physics of Semiconductors, Moscow, 1968, p. 407, Leningrad, 1968.
[4] N. F. Mott, Phil. Mag. 6, 287 (1961).
[5] L. V. Keldysh and A. A. Rogachev, Paper at Session of Division of General Physics and Astronomy AN SSSR, September, 1968.
[6] V. M. Asnin and A. A. Rogachev, Phys. Sol. Stat. 20, 755 (1967).
[7] V. M. Asnin, A. A. Rogachev, and G. P. Eristavi, ibid. 29, 443 (1968).

LIFETIME OF NEUTRAL PION

V. I. Kryshkin, A. G. Sterligov, and Yu. P. Usov
Nuclear Physics Research Institute, Tomsk Polytechnic Institute
Submitted 20 January 1969; resubmitted 25 February 1969
ZhETF Pis. Red. 9, No. 7, 420-424 (5 April 1969)

In the present paper we report preliminary results of an experiment aimed at the investigation of photo production of π^0 mesons in the Coulomb field of the nucleus (the "Primakoff effect") [1].

The connection between the cross section of the "Primakoff effect" and the neutral-pion lifetime was used in [2 - 5] to determine the lifetime τ_{π^0} of the π^0 meson. The accuracy of this method is limited essentially by the angular resolution of the apparatus, at best 0.5° [4].

Our experimental setup is shown in Fig. 1. The bremsstrahlung beam from the "Sirius" electron synchrotron with maximum energy 1.1 GeV was fed through a collimator (1) or 1 mm diameter to a lead target (2) 0.1 mm thick. The target was placed in the field of a magnet (3). The gamma quanta from the decaying meson passed through a conical opening with aperture angle 32° in a lead shield (4). Located 51 cm from the target was placed a spark chamber SC_1 with two 1-cm gaps, and spark chamber SC_2 with

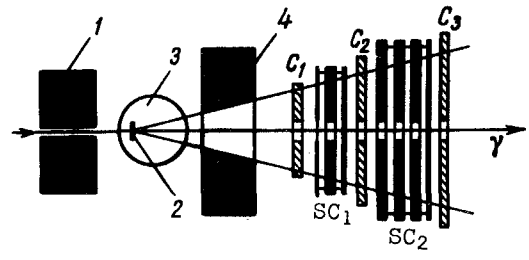

Fig. 1. Arrangement of apparatus