rotate the spin of the i-th nucleon by an angle π about the direction **q**. This allows to determine the transformation properties of various spin characteristics when R^j is replaced by $R^{(3)j}$. For example, this exchange leads to a change in the sign of the polarization P which takes place in the collision of unpolarized nucleons.

We finally remark that changing the sign of all the phase shifts (taking the complex conjugate of R^j) leaves the cross section unchanged, and changes the sign of $\mathbf{P}_0$. Thus a simultaneous application of this transformation with the transformation R^j into $R^{(3)j}$ leaves unchanged the cross section as well as the polarization. Therefore the two sets of elements of R obtained from one another by means of the indicated transformation, cannot be distinguished through the simplest polarization experiments (double scattering).

[1] S. Minami, Progr. Theor. Phys. **11**, 213 (1954).
[2] Hayakwa, Kawaguchi, and Minami, Progr. Theor. Phys. **12**, 355 (1954).
[3] R. Ryndin and Ia. Smorodinskii, Dokl. Akad. Nauk SSSR **103**, 69 (1955).

Translated by M. A. Melkanoff
101

RESONANCE ABSORPTION OF ELECTROMAGNETIC WAVES BY AN INHOMOGENEOUS PLASMA

N. G. DENISOV

Gor'kii State University

Submitted to JETP editor November 28, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 528-529 (February, 1958)

THE phenomenological description of the propagation of electromagnetic waves in a plasma is based on the possibility of introducing an index of refraction for the medium. A magneto-active plasma is usually characterized by two indices of refraction. It is well known that at certain values of the electron concentration one of these indices becomes infinite (neglecting the collisions of electrons with heavy particles). This may be called a resonance effect since the singularity in the index of refraction is related to the resonance properties of the plasma.[1,2]

In the resonance region, an electromagnetic wave incident on an inhomogeneous layer is partially or totally absorbed. The first of these effects has been discussed by Ginzburg (cf. Ref. 1, §79, and Ref. 2) for the case of quasi-longitudinal propagation. A calculation of absorption in the region of the singularity in the index of refraction has been carried out by Budden[3] using a simplified model of an inhomogeneous layer. The complete solution of the problem can be obtained in the case in which the plasma is not highly inhomogeneous. The results of an analysis of this kind are given below.

In a weakly inhomogeneous medium, except for one case which is discussed below, the interaction between the ordinary and extraordinary waves can be neglected. For simplicity, we consider transverse propagation although the final results can be generalized quite easily. In transverse propagation the index of refraction for the extraordinary wave has a singularity, the dependence of which on electron concentration is given by the following:

$$n^2(v) = 1 - \frac{v(1-v)}{1-u-v} \qquad \left(v(z) = \frac{4\pi e^2 N(z)}{m\omega^2}; \quad u = \frac{\omega_H^2}{\omega^2}\right) \quad (1)$$

(the wave propagates along the z axis, and the electron concentration N depends on z). The function $n^2(v)$ has two zeros, $v_1(z_1) = 1 - \sqrt{u}$ and $v_2(z_2) = 1 + \sqrt{u}$, and a pole at $v_3(z_3) = 1 - u$. We consider the case $u < 1$, in which the resonance region ($v = v_3$) lies between the zeros of the function $n^2(v)$. The solution for the reflection of waves from such a layer by the "standard-equation" method[4] shows[5] that the reflection coefficient for the region $(v_1 v_2)$ is

$$|R|^2 = 1 - 4e^{-\delta}(1 - e^{-\delta})\sin^2 s, \quad (2)$$

where δ and s are defined by the expressions

$$\delta = 2ik_0 \int_{z_1}^{z_3} \sqrt{n}\, dz; \qquad s = k_0 \int_{z_3}^{z_2} \sqrt{n}\, dz; \qquad \left(k_0 = \frac{\omega}{c}\right). \quad (3)$$

Equation (2) indicates that the maximum value of the absorption coefficient $(1 - |R|^2)$ is approximately 35 per cent.

In calculating absorption in the resonance region it is necessary to take account of the interaction between the different waves only in the case of quasi-longitudinal propagation. In this case, in the region $v \sim 1$ (in the vicinity of which the resonance is found) the index of refraction for the ordinary wave $n_1(\epsilon)$ and for the extraordinary wave $n_2(\epsilon)$ $(\epsilon = 1 - v)$ assume values which are approximately the same and two waves exhibit a strong interaction effect.[2]

If an ordinary wave is incident on the interaction region from below, it produces a reflected wave of the same type, characterized by a reflection coefficient $|R_1| = (1 - e^{-2\delta_0})$. The transmission of the wave is characterized by a transmission coefficient $|D_2| = e^{-\delta_0}$ (cf. Ref. 6). In this case the mean absorbed energy is

$$1 - |R_1|^2 - |D_2|^2 = e^{-2\delta_0}(1 - e^{-2\delta_0}). \quad (4)$$

The real quantity δ_0 is defined by the integral

$$\delta_0 = -\frac{1}{4} ik_0 \oint (n_2 - n_1)\, dz. \quad (5)$$

The integral is taken over a path which encloses the two singularities of the integrand at which $n_1 = n_2$. If, however, an extraordinary wave is incident on the interaction region from above, it is not reflected but is scattered into two waves in the interaction region. The amplitudes of these two waves are (cf. Ref. 5)

$$d_1 = e^{-\delta_0}; \qquad d_2 = (1 - e^{-2\delta_0})^{1/2}. \quad (6)$$

The factor d_1 characterizes the transmission of the ordinary wave. The factor d_2 characterizes the extraordinary wave which is produced in the interaction region and holds in the direction of the pole of the functions $n_2^2(\epsilon)$. This wave is then completely absorbed. The absorption $(|d_2|^2)$ is small only when δ_0 is small. When $\delta_0 \gg 1$, $d_2 \sim 1$ and the wave which is incident from above is almost completely absorbed in the region of high $n_2^2(\epsilon)$.

Because of the thermal motion of the electrons,[2] a wave traveling in the direction of the pole of the function $n_2^2(\epsilon)$ is converted into a plasma wave, the energy of which, in the final analysis, is dissipated in heating the plasma. Thus the absorption effect being discussed is related to the conversion of electromagnetic waves into plasma waves.

Finally we may note that in experiments in which the ionosphere is "sounded" by pulses the interaction mechanism being considered here may explain the fact that only three pulses are observed. The incident wave is presumably split into an extraordinary wave and an ordinary wave. The extraordinary wave is reflected at a level corresponding to $\epsilon = \sqrt{u}$ (first signal); the ordinary wave is reflected in the interaction region ($\epsilon = 0$) (second signal) and partially penetrates as an extraordinary wave into the region $\epsilon < 0$. The extraordinary wave reflected from the point corresponding to $\epsilon = -\sqrt{u}$ passes through the interaction region without reflection and reaches the point of observation as an ordinary wave (third signal). Thus, multiple-reflection effects are impossible.

The author is indebted to V. L. Ginzburg for discussion of the results of this work.

[1] Al'pert, Ginzburg, and Feinberg, Распространение радиоволн (Propagation of Radio Waves), GITTL, 1953.

[2] Gershman, Ginzburg, and Denisov, Usp. Fiz. Nauk **61**, 561 (1957).

[3] K. G. Budden, "Physics of the Ionosphere," Reports on the Physical Society Conference, 320 (1955).

[4] S. C. Miller and R. G. Good, Phys. Rev. **91**, 174 (1953).

[5] N. G. Denisov, Радиотехника и электроника (Radio Engineering and Electronics) (in press).

[6] N. G. Denisov, Труды Физ.-техн. ин-та и mm радиофакультета Горьковского ун-та, серия физич. (Trans. Phys. Tech. Inst. and Radio Faculty, Gor'kii State University, Phys. Series) **35**, 3 (1957).

Translated by H. Lashinsky
102

RECOMBINATION CAPTURE OF MINORITY CARRIERS IN N-TYPE GERMANIUM BY LATTICE DEFECTS FORMED UPON IRRADIATION BY FAST NEUTRONS

A. V. SPITSYN and V. S. VAVILOV

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor November 29, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 530-531 (February, 1958)

In an earlier work[1] an estimate was made of the cross-section for recombination capture of minority carriers by radiation defects in the crystal structure of N-type germanium, produced by irradiation with fast neutrons. The following relations were used in the calculations

$$1/\tau - 1/\tau_0 = n_d v_p \theta, \quad (1)$$

$$n_d = n_{Ge} N_n \bar{N}_d \sigma. \quad (2)$$

Here τ is the lifetime of the minority carriers after irradiation, τ_0 the lifetime of the minority carriers before irradiation, n_α the concentration of the radiation lattice defects, v_p the thermal velocity of the minority carriers (holes), n_{Ge} the number of germanium atoms per cm^3, N_n the integral dose of neutrons (expressed in neutrons per