quired for this purpose could be generated by lasers. In this connection we note that lasers often generate several frequencies rather than a single frequency.[7,8] One expects that combination frequencies would be generated under these conditions.

*The idealization in which we consider only three levels of the entire system of levels is completely justified since the other levels can be neglected in most cases.

†The Bloembergen equations,[3] in which the off-diagonal elements of the density matrix are not considered, are frequently used in maser calculations. It will be evident that these equations can not give the effect considered here nor a number of other features of maser operation. The reference made by Bloembergen[4] to the calculation by Clogston,[5] in which off-diagonal terms in the density matrix are included, is not well taken because the latter work[5] contains an error in that the author has not taken account of all the resonance terms in the density matrix. A similar error appears in a paper by one of the present authors.[6]

[1] R. Karplus and J. Schwinger, Phys. Rev. **73**, 1020 (1948).

[2] A. N. Malakhov and V. M. Faĭn, Izv. Vuzov, Radiofizika (News of the Colleges, Radiophysics) **1**, 66 (1958).

[3] N. Bloembergen, Phys. Rev. **104**, 324 (1956).

[4] N. Bloembergen and S. Shapiro, Phys. Rev. **116**, 1453 (1959).

[5] A. Clogston, J. Phys. Chem. Solids **4**, 271 (1958).

[6] V. M. Faĭn, JETP **33**, 1290 (1957), Soviet Phys. JETP **6**, 991 (1958).

[7] P. P. Sorokin and M. J. Stevenson, Phys. Rev. Letters **5**, 557 (1960).

[8] Javan, Bennett, and Herriott, Phys. Rev. Letters **6**, 106 (1961).

Translated by H. Lashinsky
170

NEGATIVE CONDUCTIVITY IN INDUCED TRANSITIONS

N. G. BASOV, O. N. KROKHIN, L. M. LISITSYN, E. P. MARKIN, and B. D. OSIPOV

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

Submitted to JETP editor July 13, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 988-989 (September, 1961)

A number of methods for producing negative temperatures in semiconductors[1-3] have been proposed in recent years.

It has been noted[3] that in indirect transitions the concentration of carriers for which a negative temperature is produced with respect to interband transitions is relatively small, being several orders of magnitude smaller than the concentration at which a negative absorption coefficient is obtained for photons with energies comparable to the width of the forbidden band. In order to obtain a negative absorption coefficient the probability for induced emission of photons in an interband transition must be appreciably greater than the probability of photon absorption in the inverse process, so as to compensate for absorption in internal transitions. However, internal absorption processes have essentially no effect on conductivity since they cause no change in the total number of free carriers; on the other hand, induced interband transitions due to photons incident on a semiconductor in a negative temperature state reduce the number of free current carriers and cause a reduction in conductivity.

Thus, a semiconductor in a negative temperature state with respect to an interband transition should exhibit a negative photoconductivity when irradiated by photons with energies approximately equal to the width of the forbidden band. Measurement of the spectral dependence of the photoconductivity of a semiconductor should allow us to find negative temperature states even if a negative absorption coefficient is not produced.

We have carried out experiments to produce and observe negative temperatures in silicon. Samples maintained at a temperature of 4° K were irradiated by light at wavelengths smaller than $0.7\,\mu$ and exhibited an appreciable increase in conductivity. When irradiated by weak monochromatic light in a narrow wavelength band close to $1.1\,\mu$, however, a number of samples exhibited reduced conductivity (negative photoconductivity).

It can be assumed that this reduction in conductivity is due to a negative temperature state, although we have not completely ruled out other explanations for the observed effect, for example, impurity photoconductivity.

[1] Basov, Vul, and Popov, JETP **37**, 587 (1959), Soviet Phys. JETP **10**, 416 (1960).

[2] Basov, Krokhin, and Popov, JETP **38**, 1001 (1960), Soviet Phys. JETP **11**, 720 (1960).

[3] Basov, Krokhin, and Popov, JETP **40**, 1203 (1961), Soviet Phys. JETP **13**, 845 (1961).

Translated by H. Lashinsky
171

WHAT IS HEAVIER, "MUONIUM ONE" OR "MUONIUM TWO"?

L. B. OKUN' and B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor August 10, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 989-991 (September, 1961)

SOME years ago it was noted[1] that muonium [the atomic system $M \equiv (\mu^+e^-)$] can spontaneously transmute in vacuum into antimuonium $\bar{M} \equiv (\mu^-e^+)$. The oscillations $M \rightleftarrows \bar{M}$ would be analogous to the transmutation $K^0 \rightleftarrows \bar{K}^0$.[2]

Recently several papers devoted to this problem have appeared in the literature.[3-6] The aim of the present paper is to emphasize that the analogy between the oscillations $M \rightleftarrows \bar{M}$ and $K^0 \rightleftarrows \bar{K}^0$ is even more complete than noted earlier in that the decay of the states which are even and odd in combined parity (i.e., under PC), viz., $M_1 = (M + \bar{M})/\sqrt{2}$ and $M_2 = (M - \bar{M})/\sqrt{2}$, proceeds via different channels, as in the case of K_1^0 and K_2^0. Here M_1 and M_2 are the muonium states which are stationary in vacuo.

Let us investigate the case where only one kind of neutrino exists and there is no direct $(\mu e)(\mu e)$ interaction.[1] One would expect this case to correspond to reality if there would hold in nature the so called "Kiev symmetry," i.e., invariance of all weak interaction processes under the substitution $\mu \to \Lambda$, $e \to n$, $\nu \to p$. If $K^0 \rightleftarrows \bar{K}^0$ oscillations exist this symmetry points to a possibility of $M \rightleftarrows \bar{M}$ oscillations. In any case the transmutation would in this case be due to the same interaction which is responsible to the decay of the free muon $\mu^+ \to e^+ + \nu + \bar{\nu}$. Naturally the question arises: in what respect do the even and odd muonium states differ? The decay channels of the odd state M_2 will be

$$e^+_{\text{fast}} + \nu + \bar{\nu} + e^-_{\text{slow}}, \qquad (1)$$

$$e^-_{\text{fast}} + \nu + \bar{\nu} + e^+_{\text{slow}}, \qquad (2)$$

$$\nu + \bar{\nu}. \qquad (3)$$

We are considering here muonium with spin 1, since a system with spin 0 can not decay into a neutrino pair in view of the neutrino helicity. The even system M_1, also with spin 1, can decay via channels (1) and (2) but the decay via channel (3) is forbidden. The circumstance that the spin-1 even system can not decay into the pair $\nu + \bar{\nu}$ is similar to the case of spin-0 odd K_2^0 meson which can not decay into two π mesons. By means of Lehman's theorem[8] one can show that the mass of M_2 is greater than that of M_1. As is well known, one cannot decide the question of which is heavier, the K_1^0 or the K_2^0 meson, on theoretical grounds,[3] because of the difficulties associated with the strong interactions.

In contrast to the $K_1^0 - K_2^0$ case, the difference in the decay characteristics of the systems M_1 and M_2 is rather small. Physically this is associated with the large size of the atomic system: even though strictly speaking the decaying objects are M_1 and M_2, in the overwhelming number of cases it is the "free" muon which decays in the atomic system. In principle, however a difference still exists between the decay channels of M_1 and M_2. It was thought worthwhile to point this out even if only for pedagogic reasons.

The above arguments about the difference in the decay channels of M_1 and M_2 remain true also if there exists a direct $(\mu e)(\mu e)$ interaction.[1] However, then the mass difference obviously will be determined by the $(\mu e)(\mu e)$ interaction[10] and we then will not be able to say anything about the sign of the mass difference of M_1 and M_2.

We now assume that there exist in nature two neutrino types: ν_e and ν_μ.[11] If e and ν_e on the one hand and μ and ν_μ on the other hand have different additive quantum numbers (charges) then the transition $M \rightleftarrows \bar{M}$ is strictly forbidden and it makes no physical sense to talk about M_1 and M_2.

We now shall discuss the recently proposed[12,13] possibility that there might exist multiplicative quantum numbers. In that case the decay of the free meson is given by

$$\mu^+ \to \begin{cases} e^+ + \nu_e + \bar{\nu}_\mu \\ e^+ + \bar{\nu}_e + \nu_\mu \end{cases},$$

and the transmutation $M \rightleftarrows \bar{M}$ is due to the direct $(\mu e)(\mu e)$ interaction. Then there does not exist a difference in the decay channels of the even and odd muonium states. Both M_1 and M_2 can decay through the channels

$$e^+_{\text{fast}} + \nu_e + \bar{\nu}_\mu + e^-_{\text{slow}}, \quad e^-_{\text{fast}} + \nu_e + \bar{\nu}_\mu + e^+_{\text{slow}}$$

$$e^+_{\text{fast}} + \bar{\nu}_e + \nu_\mu + e^-_{\text{slow}}, \quad e^-_{\text{fast}} + \bar{\nu}_e + \mu_\mu + e^+_{\text{slow}}$$

$$\nu_e + \bar{\nu}_\mu, \quad \nu_e + \nu_\mu.$$