ciently optical excitation of a maser working in the visible region. The use of electron impact excitation of the working medium would reduce the practical difficulty of obtaining a sufficient density of excited atoms, and the use of a discharge in the medium itself is suggested. In a medium containing a single gas or vapor, the possibility of obtaining the required excess population in the upper of two levels exists in cases where there is a favorable lifetime ratio, i.e., a long-lived upper state and a short-lived lower state. As an example of this, the 6678A line in helium I is due to a transition between the $3\,^1D_2$ state, mean life 1.5×10^{-8} sec, and the $2\,^1P_1$ state, mean life 4.3×10^{-10} sec. Many processes exist in a discharge which may disturb the relative population of such levels from the value implied by these lifetime values, and it may be possible to choose conditions which maintain a high population in the upper state.

Detection of the onset of continuous oscillation in the optical maser working in the visible region would be particularly simple. The Fabry-Perot étalon, used as the "cavity" of the maser, gives a concentric fringe system at infinity when the light source is placed between the plates, similar to the conventional case when the étalon is used by transmission. Using highly reflecting plates, of which only one need transmit a small percentage of the light, and a spacing of several centimeters, the width of the observed rings would normally be larger than the instrumental width. If maser oscillation were taking place, due to the presence of an adequate excess population in an upper level in the medium between the plates, the light due to this process would have an extremely small frequency width, and lines of the instrumental width would appear superimposed on the broader lines due to spontaneous emission. To confine oscillation to only one order, or mode, the aperture of the étalon could be restricted to reduce the number of effective beams in those orders in which the light is not normal to the plates. The order in which maser oscillation would be most likely to occur would then be the central, or normal, order.

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*On leave from the Clarendon Laboratory, Oxford, England.

[1] A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958).

POSSIBILITY OF PRODUCTION OF NEGATIVE TEMPERATURE IN GAS DISCHARGES

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(Received June 3, 1959)

In a recent paper[1] Schawlow and Townes have discussed a possibility for obtaining maser action in the optical region. In their proposed scheme, negative temperature is obtained by optical pumping. One may expect also that under favorable conditions the excitation of atomic levels by electrons in a discharge can lead, in principle, to a state of negative temperature. However, severe restrictions exist if densities of the excited atoms as large as those needed for maser action are required. The present Letter considers briefly these limitations and certain types of systems which appear to be most favorable for practical application of this proposal. Pure gases behave quite differently than certain kinds of gas mixtures. First let us consider the former case.

For the purposes of rough estimates of various discharge conditions as described below, let us make a simplifying assumption that the main source of population of an excited state is due to collisions of the first kind between the electrons and atoms in the ground state leading directly to the excited level under consideration. It can be shown that, at least in cases discussed below, other details such as cascade processes and collision of electrons with other excited atoms do not appreciably effect our order-of-magnitude estimates.

In the following, the indices 0, 1, and 2 refer to the ground, the lower, and the upper states of the maser levels, respectively. If $1/\theta_{0i}$ is the rate of excitation of the ith excited state by electron impact with the atoms in the ground state and $1/\theta_{i0}$ is the rate for the reverse process, for a Maxwellian distribution of electrons at a temperature T_e, the relationship

$$\theta_{0i}/\theta_{i0} = \exp(E_i/kT_e)$$

will hold;[2] where E_i is the energy of the ith excited state. For θ_{i0} much shorter than the radiative lifetimes of the ith excited state, T_i, it can be shown that $N_i/N_0 = \exp(-E_i/kT_e)$, which means a Boltzmann equilibrium for population distribution of the excited state at the electron temperature T_e. For $\theta_{i0} \gg T_i$, however, one obtains

$$N_i/N_0 = (T_i/\theta_{i0}) \exp(-E_i/kT_e). \tag{1}$$

The ratio T_i/θ_{i0} is a measure of departure from the Boltzmann equilibrium. Such a departure is necessary for the problem under consideration. The factor $1/\theta_{i0}$ is proportional to the electron density in the discharge. It is therefore clear that excessively large electron densities should be avoided in order to satisfy $\theta_{i0} \gg T_i$, so that

$$N_2/N_1 = (T_2/T_1)(\theta_{10}/\theta_{20}) \exp[-(E_2 - E_1)/kT_e]$$

may be larger than unity, giving a negative temperature.

If the nature of the excited levels to be used for the maser action permits, it is very desirable to operate at a large gas pressure consistent with practical considerations. This is evident since for a given number of atoms in an excited state an effective temperature as determined from the ratio of this number to that of the atoms in the ground state is lower at larger pressure.

At a large pressure, however, the trapping of resonant radiation becomes an important factor. Consider a level which is optically connected to the ground state. At a pressure where the resonant photons arising from this transition are trapped, the effective radiative lifetime of this level will be increased and determined by its decay into the other available low-lying levels. This effect can best be taken to the advantage if the upper maser level is optically allowed to the ground state. In such a situation, in addition to an increased lifetime of the upper maser level at a large pressure, one expects also a more favorable ratio of θ_{10}/θ_{20}. This is evident since a level which is optically connected to the ground level, as a rule, has a large excitation cross section by electron impact with the atoms in the ground state. Furthermore, due to the nature of the electrical dipole matrix elements, only one of the maser levels may be optically connected to the ground level.

For a typical example of levels which allow operation at a large pressure, let us consider the case of Ne. The $2s_4$ and $2p_{10}$ (in Paschen notation)[3] considered as the upper and the lower maser levels, respectively, meet the required conditions. At a pressure where the ultraviolet photons arising from the transition $2s_4$ to the ground state are completely trapped, the lifetime of this state is estimated to be at least a factor of 60 larger than that of the $2p_{10}$ level. The latter level is known to have a mean life of 10^{-8} sec due to its radiative decay into some of the lower excited states. Let us consider 10 mm of Hg as a typical gas pressure. For production of $N_2 = 10^{10}/\text{cm}^3$, one obtains from Eq. (1), $T_2/\theta_{20} = 3 \times 10^{-5}$, assuming an electron temperature at $kT_e = 2.9$ ev. The cross section for electron excitation of the above Ne level is not known. Let us assume a reasonable value of $\sigma = 10^{-17}$ cm^2 for an average of this cross section over the electron energy distribution. From the above value of T_2/θ_{20} and $T_2 = 6 \times 10^{-7}$ sec, one obtains an electron density of $n_e = 5 \times 10^{10}/\text{cm}^3$.

The numbers obtained above are intended to represent only rough estimates and indicate that, in practice, the necessary discharge conditions are obtainable. Considerations such as departure from Maxwellian energy distribution of the electrons at the high- and low-energy limits may show appreciable effects. However, with view to the possibility of operating at somewhat of a higher electron temperature, no serious consequences are expected.

In the above scheme, the presence of a large density of the metastable Ne should be avoided to prevent the trapping of the red Ne line which may lead to an extended lifetime for the $2p_{10}$ level. Furthermore, the collision of the first kind of the electrons with the Ne metastables may give rise to an unfavorable population of the excited levels. This can be prevented by introducing a very small amount of a quenching gas such as argon to decrease the lifetimes of the longer lived excited atoms such as the metastables.

It may be of interest to compare the above system with a case which does not permit operation at large pressure. In He the $3\,^1D$ and $2\,^1P$ levels have a lifetime ratio of $T_2/T_1 = 35$. The lower level, $2\,^1P$, has a short lifetime due to its radiative decay into the ground level. An estimate of θ_{10}/θ_{20} indicates that this ratio may be as large as 1/15. Thus, a negative temperature may still be expected if appreciable excitation of these levels by electron impact with the metastable He can be prevented. On the basis of the known cross section for electron excitation of the $3\,^1D$

level and manipulations similar to those presented above, the following rough estimate of the discharge condition may be obtained: At a pressure of 5×10^{-3} mm and for $kT_e=5$ ev, the electron density for production of $N_2=10^9/\text{cm}^3$ is roughly $n_e=10^{12}$ or about 1% ionization of the total number of atoms. Although such a condition is not outside of the range of practical possibility, however, it indicates the difficulties encountered in this case. It is likely that a more favorable situation of this type may be found in a different atom with a larger electron excitation cross section, thus resulting in a reduced number for the required electron density.

An alternative scheme is the use of transfer of excitation between excited states of two different atoms in a gas mixture. Consider a long-lived state of an atom (such as a metastable state). This state can be populated appreciably at moderate electron densities. If an excited state of a second atom happens to lie very close in energy to that of the level of the first atom, a large cross section is expected to exist for an inelastic collision resulting in a transfer of excitation from the metastable state to the excited state of the other atom and vice versa. Due to the nonadiabatic nature of the process of collision, the levels of the second atom which differ in energy considerably from that of the metastable level of the first atom do not show appreciable cross sections for transfer of excitation.

If the rate at which such transfer of excitation takes place is larger than the rate of the radiative decay of the excited states, the metastable level serves to increase the contact between the temperature of the excited level of the other atoms and that of the electrons. In this case, it can be shown that $(G^*N^*/GN)=(g^*n^*/gn)f$, where the capital letters refer to one atomic species and the small letters to the other. The letters with asterisks denote the excited states, and those without asterisks, the ground states; G and g are the statistical weights of the levels involved and N and n are the populations of the levels. The factor f in this equation is given by $f=e^{\Delta E/kT}$, where T is the temperature of the gas as determined by thermal kinetic energies of the atoms and ΔE is the resonance defect and is the difference between the excitation energy of the level corresponding to n^* minus that corresponding to N^*.

This relationship does not hold if ΔE is appreciably large, resulting in reduced rate of transfer of excitation.

In order to take full advantage of the above effect, large differences in the partial pressures of the two atoms are desirable. Otherwise, due to reduction in electron temperature and various quenching mechanisms, the population of the metastable level will be decreased.

As an example, a mixture of Kr and Hg with Kr at about 10 to 50 mm of Hg pressure and Hg at about 10^{-3} mm of Hg pressure can be used for obtaining an abnormally large population of the $9\,^1P$ and $6\,^1F$ of Hg. These two levels lie very close to $5s_5$ metastable Kr. A negative temperature at the transition originating from these levels to $6\,^1D$ may then be expected. It is expected that the levels $6\,^1D$ and $6\,^1P$ may also show a negative temperature because of the cascade transition from the $9\,^1P$ and $6\,^1F$ into $6\,^1D$ level.

The $^3S_1$ metastable of He also lies in energy fairly close to the excitation energy of the upper maser level of Ne discussed above. The presence of a partial pressure of He is expected to enhance considerably the negative temperature in the levels of Ne.

The transfer of excitation of the type described above may play an appreciable role within the levels of the same atom. An important example of this is expected to occur in the levels of Ne. Let us consider the group of four levels $2s_5$, $2s_4$, $2s_3$, and $2s_2$. The level $2s_4$ is the one emphasized in the above for the upper of the two maser levels. These four levels all fall fairly close in energy. The level $2s_2$ is also allowed for an optical transition to the ground state. The transfer of excitation within these levels is expected to result in particular built up of large population in the level $2s_5$, this level having the lowest energy within this group. Thus, an even more favorable transition in Ne appears to be the $2s_5\rightarrow 2p_{10}$. This transition lies at 10343 wave number.

Details of the above proposals will be published upon their experimental verifications.

I would like to acknowledge helpful discussions with Dr. W. R. Bennett, Jr., Dr. S. J. Buchsbaum, Professor C. H. Townes, Dr. J. P. Gordon, and Dr. A. L. Schawlow.

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[1] A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958).

[2] See, for instance, Rudolf Ladenberg, Revs. Modern Phys. 5, 243 (1933).

[3] In the LS designations the levels $2s_4$ and $2p_{10}$ correspond to $(2p^5 4s)\,^3P_1$ and $(2p^5 3p)\,^3S_1$, respectively.