constants in Eq. (1). This relation holds very well for all the elements[1] for which these constants are known.

We would like to use this opportunity to correct a statement in our previous article.[1] Dr. D. E. Mapother pointed out that on cooling through the transition temperature in a magnetic field a superconducting shell does not expel flux lines. Therefore our measurements were performed in the earth's magnetic field.

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THREE-LEVEL MASERS AS HEAT ENGINES*

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The purpose of this note is to demonstrate that three-level masers[1,2] can be regarded as heat engines. The principal conceptual difference between these and conventional heat engines is that in the 3-level maser one is concerned with the discrete energy levels of a particle's internal energy whereas in a conventional heat engine one is concerned with the continuous spectrum of energies associated with external motion of the working substance. In treating a 3-level maser as a prototype of heat engine, a particular advantage is, in our opinion, the resulting conceptual simplicity. Especially, it is easily shown that the limiting efficiency of a 3-level maser is that of a Carnot engine.

Consider the system shown in Fig. 1. A three-level system is assumed with all transitions allowed and with no appreciable relaxation processes. The usual 3-level maser terminology is introduced by correlating transition $1 \leftrightarrow 3$ with pump frequency ν_p, $1 \leftrightarrow 2$ with signal frequency ν_s, and $2 \leftrightarrow 3$ with idler frequency ν_i. As a further convention, the length of each energy level line is drawn proportional to its population.

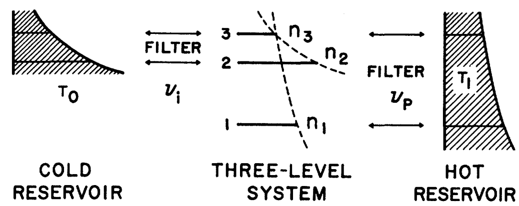

FIG. 1. Three-level system in thermal contact with two heat reservoirs.

The levels 1 and 3 are in thermal contact, through a filter passing frequencies in the vicinity of ν_p and rejecting frequencies in the vicinity of ν_i and ν_s, with a heat reservoir at temperature T_1. The temperature is indicated in the figure by showing schematically the Boltzmann distribution of this heat reservoir. Levels 2 and 3 are in thermal contact with a reservoir at a lower temperature T_0 through a filter which passes frequencies in the vicinity of ν_i but rejects those close to ν_p and ν_s.

Experimentally, the high-temperature reservoir might be realized by a gas noise lamp and the filter by a wave guide cutting off the lower frequencies. For practical purposes, however, the single mode present in a wave guide does not provide good thermal contact. The assumed coupling situation to the low-temperature reservoir, on the other hand, was closely approximated by experimental conditions in some maser experiments.[3] There, the idler transition of the gadolinium three-level system was coupled, through spin-spin interaction at frequency ν_i, to a transition of the same frequency of cerium ions within the same crystal. Thus, through the resultant short spin-lattice relaxation time, good thermal contact to the lattice heat reservoir at T_0 was established.

In the system described, for each quantum $h\nu_p$ supplied by the hot reservoir, the energy $h\nu_i$ is passed to the cold reservoir. The smaller quantum $h\nu_s$ can be extracted at the signal transition if maser action prevails, that is if $n_2/n_1 \geqslant 1$. Thus the efficiency of this idealized system in maser operation is

$$\eta_M = \nu_s/\nu_p. \tag{1}$$

From the Boltzmann factors involved, we find

$$\frac{n_2}{n_1} = \frac{n_2}{n_3}\frac{n_3}{n_1} = \exp\left(\frac{h\nu_i}{kT_0}\right) \times \exp\left(-\frac{h\nu_p}{kT_1}\right). \tag{2}$$

After rearrangement, this becomes

$$\frac{n_2}{n_1} = \exp\left[\frac{h\nu_S}{kT_0}\left(\frac{\nu_p}{\nu_S}\,\frac{T_1 - T_0}{T_1} - 1\right)\right]. \qquad (3)$$

In this formula, one recognizes the maser efficiency η_M and the efficiency of the Carnot cycle,

$$\eta_c = (T_1 - T_0)/T_1. \qquad (4)$$

Using these, the condition for maser action is

$$\eta_M \leq \eta_c. \qquad (5)$$

This may be regarded as another formulation of the second law of thermodynamics. Maser efficiency equals that of a Carnot engine if the signal transition is at the verge of inversion, $n_2 - n_1 \rightarrow +0$ or $T_{\text{sig}} \rightarrow -\infty$.

As any heat engine, this system should be reversible so that it acts as a refrigerator. This is indeed the case. Suppose a quantum $h\nu_s$ is applied to the signal transition. It causes an ion to go from state 1 to 2. The ion may further jump to state 3 if the energy $h\nu_i$ is supplied by the cold reservoir. The cycle is finally completed when the ion returns from state 3 to state 1 while the energy $h\nu_p$ is communicated to the hot reservoir. In this process, energy is extracted from the idler transition, that is from the cold reservoir, so that it is refrigerated. The scheme outlined here, however, requires the signal transition to be absorptive. Otherwise the first step, application of $h\nu_{\text{sig}}$ to the signal transition, would not have been possible. Thus the refrigeration scheme is possible if $n_2/n_1 \leq 1$. Again, the limiting efficiency of the refrigerator is that of a Carnot engine and it is realized with $n_2 - n_1 \rightarrow -0$ or $T_{\text{sig}} \rightarrow +\infty$.

It seems probable at this time that generation of microwaves through thermal excitation by two temperatures will be possible experimentally. Such a scheme should be very attractive for high microwave signal frequencies. Refrigeration experiments, on the other hand, as applied to interacting nuclear and electronic spin systems have been suggested by the theoretical work of Overhauser.[4] A thermodynamical analysis of the Overhauser effect has been given by Brovetto and Cini[5] and Barker and Mencher.[6]

Finally, we should like to point out that the possibility of treating masers as heat engines sets a fundamental distinction between these and parametric amplifiers. Three-level masers are capable of operating with noise-like excitation in all three transitions. Parametric amplification requires some phase coherence, that is, monochromatic excitation is necessary for at least one of the three frequencies involved. This statement excludes heat as the source of energy for parametric amplification.

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GAMMA-RAY ACTIVATION OF CARBON*

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A direct measurement of photonuclear reaction cross sections can be accomplished by the use of the monochromatic capture gamma rays of the $T(p,\gamma)He^4$ reaction.

If the gamma-ray energy be varied by changing the energy of the captured particle, the photonuclear cross section can be determined as a function of photon energy. The capture of protons in tritium produces a high-energy gamma ray of $(19.82 + \frac{3}{4}E_p)$-Mev energy, where E_p is the proton energy. This gamma ray has a smooth yield curve with no resonances, but it is of rather low intensity. Nevertheless, by using a highly effective detector we have measured the direct photoactivation of carbon by the $C^{12}(\gamma,n)C^{11}$ reaction in the photon energy range 20.2 to 21 Mev.

The tritium was absorbed in a thin layer of zirconium evaporated on a silver backing[1] which was water cooled. The thickness of the target for 1-Mev protons was measured to be 70 kev by observing the $T(p,n)$ threshold and comparing with very-thin-target differential curves.[2]

The carbon was reactor-grade graphite in the form of an annular ring surrounding the tritium target. The carbon subtended the angles from 90° to 102° with respect to the proton direction which corresponds to a range of photon energies