EFFECTS OF ADDED CESIUM ON POPULATION INVERSION IN A RECOMBINING LITHIUM PLASMA

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In recent years, there have been many papers dealing with the scope for lasing in the recombination of supercooled plasmas from numerous elements [1-3]. It has been shown that a multicomponent plasma is more promising for the production of quantum amplifiers and lasers [4, 5]. In [5], a numerical analysis was performed on the populations of the levels of Li I in the recombination of a dense supercooled Li–Cs plasma. The Li–Cs interactions were incorporated, particularly as regards the effects on the populations of the Li I levels, and it was shown that low cesium concentrations, $N_{Cs} = (10^{-2}-10^{-3})\cdot N_{Li}$, can increase the inversion on the 3p → 3s, 4s → 3p transitions by 2-3 orders of magnitude. However, the variation in the major plasma parameters (electron concentration N_e and temperature T_e) on adding the cesium was not established, nor were the effects on the populations of the lithium levels.

The addition of a readily ionized substance to a recombining plasma may substantially increase the electron concentration and the recombination fluxes for the atomic levels, and this can provide a promising method of increasing population inversions in a plasma for an element of high ionization potential, where low electron densities are produced. It is therefore of interest to consider a recombining Li–Cs plasma in a numerical analysis of the lithium-level populations with allowance for the combining effects of the readily ionized Cs on the populations due not only to changes in the plasma parameters (N_e and T_e) but also because of inelastic atomic collisions.

Calculation Method. Consider the time relaxation of a spherically expanding Li–Cs plasma whose initial parameters vary within the following limits: $N_{Li} = 10^{14}-10^{18}$ cm^{-3}, $N_{Cs} = 10^{12}-10^{18}$ cm^{-3}, $T_e = T_0 = 0.25$ eV. The initial expansion time is $t_0 = 10^{-7}$ sec. The initial ion concentrations are defined by the Saha–Boltzmann formula. See [1, 6] for a system of differential equations describing the population relaxation in the lithium and cesium levels as well as the changes in the major parameters (electron temperature T_e, heavy-particle temperature T_0, electron concentration N_e, and atom concentration N_0). The method of [1] was used to derive the time dependence of the populations: The differential equations for the slowly varying plasma parameters (the populations of the ground states of lithium and cesium N^0_{Li}, N^0_{Cs}, N_e, T_e, T_0) were integrated numerically by the Runge–Kutta method with automatic step choice, while the populations of the excited levels were found in the stationary-sink approximation as functions of N^0_{Li}, N^0_{Cs}, N_e, T_e, T_0.

The number of atomic levels that had to be incorporated into the system was determined from the sink bottleneck [4]: The 15 lowest levels were incorporated for lithium, and 14 for cesium. The lithium levels with principal quantum numbers from n = 7 to n = 10 were included in the quasiequilibrium spectrum, and their populations were calculated from the Saha–Boltzmann formula. The oscillator strengths were taken from [7, 8]. Any lacking oscillator strengths were calculated from the tables of [9]. The calculations were for a plasma with a sufficiently high electron concentration, so the electron velocity distribution was taken as Maxwellian [4]. For the same reason, three-particle recombination predominates in the recombination processes in the low-temperature plasma, and this was incorporated into the calculations.

We now discuss the methods of calculating the cross sections for the electron–atom and atom–atom collisions at low energies. Figure 1a shows that Drawin's method [10], which has been used to determine ionization cross sections (solid curves), agrees well with experimental results [11] in this energy range (dashed curves). The electron-impact excitation cross sections near threshold are most accurately described by the strong-coupling method. However, it is fairly laborious to calculate cross sections by this method, and the system of differential equations in [1] for the level populations included about 100 cross sections for the ex-

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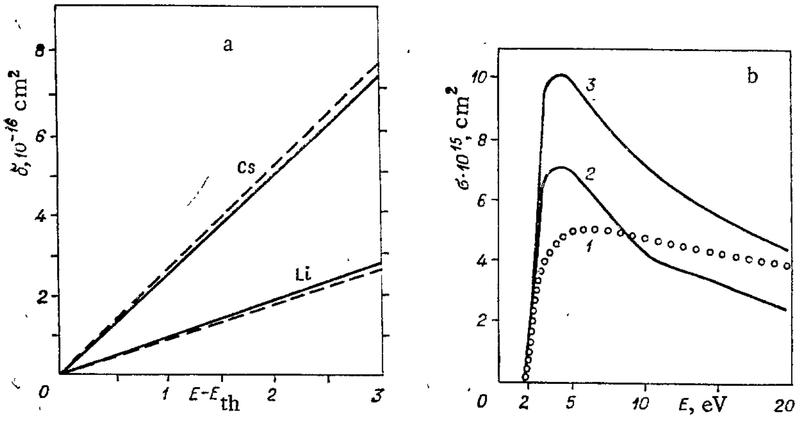

Fig. 1

citation of spectral transitions. This makes it virtually impossible to compute the plasma parameter relaxation. Therefore, one calculates the excitation cross sections for a relaxing plasma usually either by means of the modified Bethe formula [12] or by means of the Vainshtein–Sobel'man–Yukov formula [9], which produce a standard overestimation of the cross section at the maximum by a substantial factor. Figure 1b compares calculations on the total excitation cross sections for the $2^2P_{1/2,3/2}$ level of Li I from the ground state via Bethe's formula (curve 2) and via Vainshtein's formula (curve 3) with the experimental data [13] (curve 1). In this calculation, we used Bethe's formula, since it gives values of the effective cross sections for excitation levels in the energy region below 10 eV closer to the experimental results (Fig. 1b). In that case, the contributions from the excitation to the level populations will be somewhat overestimated. We performed additional calculations on the relaxation with excitation cross sections altered by an order of magnitude. This did not substantially affect the results, since the main contribution to populating the levels in a low-temperature plasma comes from recombination.

The cross sections for excitation transfer in atomic collisions were calculated from Stuckelberg's formula [14], which agrees better with the measurements than do other methods.

The cross section for endothermic charge transfer in an Li–Cs plasma was extrapolated to thermal collision velocities on the basis of the experimental data of [15]. Allowance was made for the fact that this cross section tends linearly to zero when the velocities of the colliding particles tend to zero. At thermal velocities, the cross section for exothermic charge transfer increases as 1/E, as is evident from experiment [16, 17]. This course for the cross section is not described by standard methods of calculating charge transfer such as in [18], and therefore we analyzed the experiments of [16, 17] to derive an empirical formula $\sigma = \text{const}\cdot 1/E$. We normalize σ at the point $E = E_A$ on the endothermic charge-transfer cross section [15], with E_A determined from Massey's criterion. As the exothermic charge-transfer cross section was only estimated, we also calculated the relaxation with the cross sections in this reaction increased by a factor 10.

The following collision reactions have the largest cross sections in an Li–Cs plasma:

$$\mathrm{Li}(2p) + \mathrm{Cs}^+ \rightarrow \mathrm{Cs}(6s) + \mathrm{Li}^+ + 0.3508\ \mathrm{eV}; \tag{1}$$

$$\mathrm{Cs}(0) + \mathrm{Li}^+ \rightarrow \mathrm{Li}(2p) + \mathrm{Cs}^+ - 0.3508\ \mathrm{eV}; \tag{2}$$

$$\mathrm{Cs}^*(5d) + \mathrm{Li}(0) \rightarrow \mathrm{Cs}(0) + \mathrm{Li}^*(2p) + 0.05\ \mathrm{eV}; \tag{3}$$

$$\mathrm{Li}^*(3p) + \mathrm{Cs}(0) \rightarrow \mathrm{Cs}^*(19p) + \mathrm{Li}(0) - 0.002\ \mathrm{eV}; \tag{4}$$

In the exothermic transfer of (1), we obtained a cross section of $1.58\cdot 10^{-15}$ cm^2 at E = 0.1 eV, while for (2) we found $6.3\cdot 10^{-17}$ cm^2. For excitation transfer as in (3) and (4), we found $\sigma = 1.8\cdot 10^{-17}$ and $5.74\cdot 10^{-14}$ cm^2 from the formula of [14] for E = 0.1 eV. We also estimated the scope for the formation of ions in the collisions of excited atoms as in $\mathrm{Li}^* + \mathrm{Cs} \rightarrow \mathrm{Li} + \mathrm{Cs}^+ + e$ and $A^* + A \rightarrow A_2^+ + e^-$ (where A is an Li or Cs atom). As Li and Cs do not have low-lying long-lived levels, these processes play only a secondary part in the relevant range of plasma parameters.

Results. The kinetic calculations on the lithium level populations showed that about 10 transitions in Li I are inverted in a pure lithium plasma and in a lithium–cesium one,

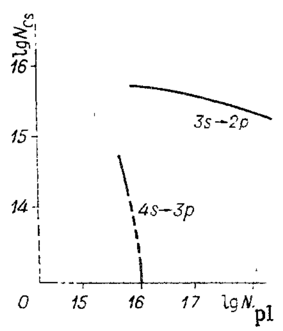

Fig. 2

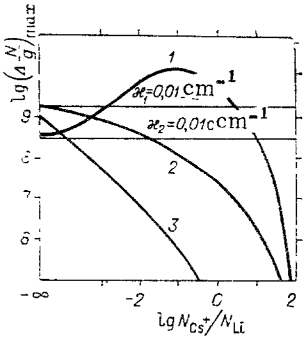

Fig. 3

where the 3s → 2p, 4s → 3p, 5s → 3p transitions are the most important as regards the absolute magnitude of the inversion. If we take the initial cesium concentration as small (or zero), the inversion on a given transition in lithium occurs from the time when the electron temperature becomes less than a certain critical temperature T_e^c, which was the same for all forms of the calculation. If on the other hand the Cs concentration is high, the cesium can effectively clear the lower working level via reactions (1)-(4) under certain conditions and T_e^c does not exist. The occurrence of T_e^c, which determines the start of population inversion on the ns → mp transition, indicates that the recombination flux becomes sufficient to produce a population inversion only at a fairly low T_e^c. Our calculations show that T_e^c = 0.14 eV for the 3s → 2p transition in a lithium plasma, while inversions are produced on the 4s → 3p and 5s → 3p transitions at critical temperatures of 0.12 and 0.05 eV correspondingly.

1. Highly Ionized Cesium. The addition of readily ionizable cesium to a lithium plasma may substantially increase the electron concentration and recombination fluxes. Therefore, the population inversions in a lithium plasma increase with the cesium concentration. However, during the relaxation the cesium readily recombines and heats the electrons. If the cesium-ion concentration is high, the electron temperature is reduced so slowly that the recombination proceeds slowly in spite of the increase in N_e, and the inversions are less than in pure Li plasma. There is thus a certain optimum concentration of ionized cesium that substantially increases N_e and the population inversions in a lithium plasma but does not alter T_e appreciably. Figure 2 shows the optimum cesium concentrations for Li—Cs plasmas of various densities. The optimal concentrations are $<5 \cdot 10^{15}$ cm^{-3} for the 3s → 2p transitions at the Li—Cs plasma densities used in the calculations, as against $<10^{15}$ cm^{-3} for the 4s → 3p transition. There is no optimum cesium concentration for the 5s → 3p transitions, because T_e^c at which an inversion can be formed on this transition is small (T_e^c = 0.05 eV) and even very small cesium concentrations raise T_e so much that the inversion on the 5s → 3p transition is much reduced. Figure 3 shows how the inversions on the 3s → 2p, 4s → 3p, 5s → 3p transitions vary with the initial concentration of ionized cesium in an expanding Li—Cs plasma having an initial density for the lithium plasma of $0.5 \cdot 10^{16}$ cm^{-3} and an initial temperature of 0.25 eV (the transitions correspond to curves 1-3). The effects of the cesium on the lithium level populations via N_e and T_e^c are much greater than those of the collisions (1)-(4). As the optimum cesium concentration is less than $5 \cdot 10^{15}$ cm^{-3} for the 3s → 2p transition in an Li—Cs plasma of any density, the relative contribution from the cesium to the inversions in the lithium decreases as the Li—Cs plasma concentration increases, and the highly ionized cesium does not produce a considerable increase in the inversions at high plasma densities (Fig. 4).

2. Weakly Ionized Cesium. We consider how weakly ionized cesium affects the population in a lithium plasma. Figure 5 compares the calculated time curves for the populations, electron concentration, and temperature in a Li—Cs plasma (points) with those for a one-component Li plasma (solid lines). In both cases, the initial parameters were as follows: $N_e = 10^{15}$ cm^{-3}, $T_e = T_+ = 0.3$ eV, $N_{Li} = 10^{16}$ cm^{-3}, $N_{Li}^+ = 10^{15}$ cm^{-3}. In the Li—Cs plasma, $N_{Cs} = 0.9 \cdot 10^{19}$ cm^{-3}, $N_{Cs}^+ = 10^5$ cm^{-3}. It is evident that N_e varies in time in much the same way in these forms, whereas the T_e curves differ appreciably. Over the time interval 0.10-0.15 msec, T_e for the Li—Cs plasma is less than that for the Li one, since some of the electron energy is consumed in ionizing the cesium atoms. In the time interval 0.15 μsec to 0.45 μsec, T_e is raised somewhat in the Li—Cs plasma, since the cesium ions recombine rapidly and heat the plasma as the electron temperature begins to fall. Then the recombination processes in the Li—Cs plasma are substantially retarded, and the lithium level populations are reduced. In

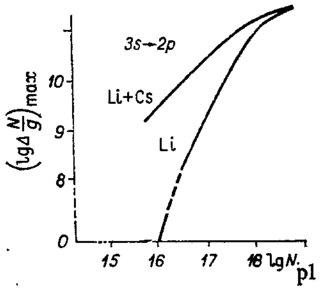

Fig. 4

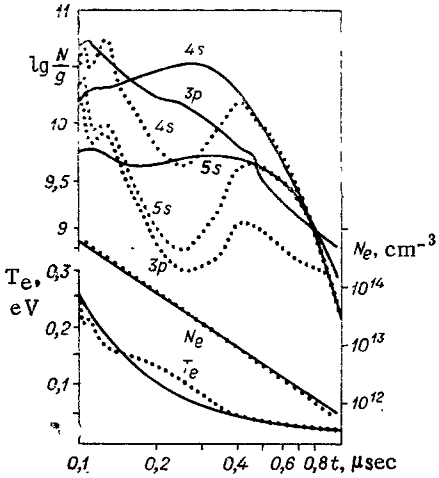

Fig. 5

a plasma having a high neutral cesium atom concentration, reaction (4) occurs rapidly, which clears the lower working level in the 5s → 3p, 4s → 3p transitions in Li I. As a result, inversions are formed on these transitions throughout the relaxation time interval, and there are no N_e and T_e^c that restrict the inversion existence time (Fig. 5).

One concludes that weakly ionized cesium increases the inversions in the lithium for a short time, but subsequently the recombination deteriorates and the populations in the lithium levels are reduced. Therefore, this way of increasing the inversions in lithium is not promising. A considerable increase in the inversions in the lithium can be attained by introducing highly ionized cesium in the optimum concentration. The inversions found in the calculations can be used on the assumption of a Doppler line broadening mechanism to estimate the gains on the 4s → 3p and 3s → 2p transitions in Li I.

Figure 3 shows that the gain $\varkappa$ for the optimum cesium concentration substantially exceeds 10^{-2} cm^{-1}, and the value is quite sufficient to provide a recombination Li–Cs laser on 3s → 2p transition. The inversion increases almost linearly with the concentration of the Li–Cs plasma (Fig. 4), so even higher gain may be attained by increasing the density.

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POSSIBLE EFFECTS IN SOLIDS IN ULTRASTRONG MAGNETIC FIELDS

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The history of solid-state theory and the detection of major interactions in solids are closely related to research on the effects of external magnetic fields on characteristics such as the magnetization, volume, specific heat, conductivity, thermal conductivity, spectral parameters, and so on, since almost all of these are affected by magnetic fields. Advances in producing fields of 100-300 kOe have been accompanied by improvements in research methods since the pioneering studies by Kapitsa [1], in which the law of linear increase in magnetoresistance was discovered for various metals, and there have since been numerous physics researches in this range of magnetic fields. Anomalies in magnetization have been observed [2] along with the magnetocaloric effect [3], magnetooptic effects [4], and other features. A very important discovery was that of the gap-free state in a solid [5], which represents an essentially new type of ordering in condensed media at low temperatures in strong magnetic fields. Naturally, the region of even stronger fields, up to 10^7 G, should reveal new effects or special features in known ones. Here we examine some possible phenomena related to the action of fields up to 10^7 G on the condensed state.

The magnetocaloric effect is a major one to be considered in experiments with pulsed magnetic fields. In fact, the field increases under adiabatic conditions, and the changes in internal magnetic energy are considerable, and they may attain the energies of the spin-orbit and exchange interactions or the energies of the crystalline field at about 10^4 cm^{-1} per ion. As the total entropy is conserved (magnetic plus phonon), while the magnetic entropy tends to zero in the external field under ordinary conditions, the phonon component increases considerably, which increases the temperature. To calculate the rise, it is necessary to solve a system of equations consisting of Shroedinger's equations and the equations of statistical thermodynamics:

$$\hat{H}\Psi_n = E_n\Psi_n,\ S_{\rm m}(T_0, 0) + S_{\rm ph}(T_0) = S_{\rm m}(T_{\rm k}, H) + S_{\rm ph}(T_{\rm k}),$$
$$S_{\rm m} = -n_{\rm m}S_p\left[\left(e^{-\hat{H}/T}/z\right)\ln\left(e^{-\hat{H}/T}/z\right)\right],\quad S_{\rm ph} = 3n\left\{-\ln\left(1-e^{-\Theta/T}\right) + 12\,(T/\Theta)^3\int\limits_0^{\Theta/T}\frac{z^3dz}{e^z-1}\right\}$$

being the magnetic and phonon entropies of the specimen per formula unit, while n_m and n are the numbers of magnetic ions and of all ions in the formula unit, and Θ is the Debye temperature. These formulas give a large temperature rise $\Delta T = T_k - T_0$. Figure 1 shows the calculated value of ΔT in metallic Tb in a field of 1.5 MG. The Néel temperature is 230°K, while the Debye temperature is 177°K. It is evident that the largest value ΔT = 120°K occurs in the region of a magnetic phase transition. One can estimate the limiting value of ΔT as follows. For $T \gg \Theta/4$ with H = 0, $S_m = n_m \ln(2J + 1)$, where J is the momentum quantum number and $S_{ph} = 3n \ln T + c$. In a limiting strong field, where $s_m = 0$, the adiabatic equation takes the form

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