[1] P.E. Zil'berman, Fiz. Tverd. Tela 12, 1014 (1970) [Sov. Phys.-Solid State 12, 796 (1970)].
[2] P.E. Zil'berman, ibid. 12, 2839 (1970) [12, No. 10 (1971)].
[3] Yu.M. Gal'perin and V.D. Kagan, Zh. Eksp. Teor. Fiz. 59, 1657 (1970) [Sov. Phys.-JETP 32, No. 5 (1971)].
[4] P.E. Zil'berman, ibid. 60, No. 6 (1971) [33, No. 6 (1971)].

POSSIBILITY OF PRODUCING INVERTED POPULATION IN ATOMIC BEAMS BY CHARGE EXCHANGE OF PROTONS WITH ATOMS

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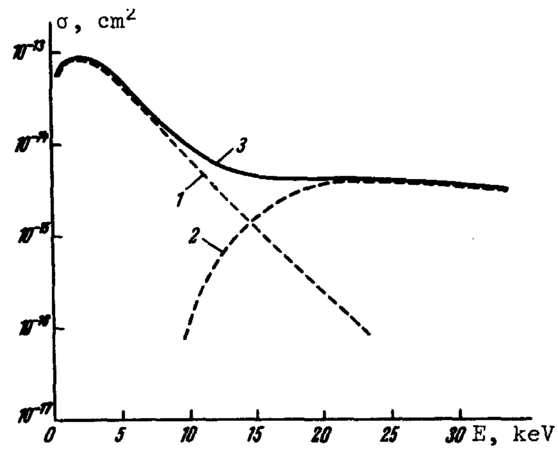
The charge exchange of protons with atoms (the reaction $p + A \rightarrow H + A^+$) is in many cases a very effective method of producing excited atoms and ions. By way of an example, the figure shows the effective cross section of charge exchange with Cs atoms. At collision energies up to 10 - 15 keV, the electron is captured with overwhelming probability in the 2p and 2s states of the hydrogen atom, and the cross section for charge exchange in the 2p state is approximately three times larger than in the 2s state. The large value of the cross section is due to the quasiresonant character of the process: the ionization potential of the Cs atom is close to the binding energy of the electron in the H atom with principal quantum number n = 2. The capture of the electron in the ground state of the H atom in the indicated energy region is smaller by two orders of magnitude, and charge exchange in all states with n > 2 has a total cross section smaller by a factor of 20 than the cross section for charge exchange in the 2p state. At collision energies higher than 20 keV, the capture of an optical electron becomes ineffective, and the principal role is assumed by charge exchange on the inner shells of the Cs atom [1]. In this case, an excited Cs^+ ion ($5p^5 6s$) is produced, and the H atom is predominantly in the ground state. Calculation of the charge-exchange cross section (see the figure) was carried out within the framework of the method of strong coupling of several states [2]. The result agrees with the available experimental data [3, 4]. Similar properties are possessed by the cross sections for the charge exchange of protons with K and Rb atoms.



Effective cross section for the charge exchange of protons with Cs atoms: 1 - cross section for capture of an outer electron of the Cs atom in the H-atom state with n = 2: $p + Cs \rightarrow H\ (n = 2) + Cs^+(5p^6)$; 2 - cross section for the capture of a 5p electron of the Cs atom: $p + Cs \rightarrow H + Cs^+ (5p^5 6s)$; 3 - total cross section of the charge exchange $p + Cs \rightarrow H + Cs^+$.

An inverted medium (H atoms in a state with n = 2) can be produced when a beam of atomic cesium is intersected by a beam of protons having an energy less than or equal to 10 keV (proton velocity $v_p \simeq 10^8$ cm/sec). At a Cs atom density on the order of $10^{16} - 10^{17}$ cm^{-3}, the proton beam exchanges charge over a path $10^{-2} - 10^{-3}$ cm. The emission of the L_α line ($\lambda = 1215.85$ Å) occurs over a path 0.2 cm. At a proton beam cross section of 1 cm^2 the working volume is 0.2 cm^3. Since the temperature in most proton sources is of the order of 1 eV, the emitted line will have a Doppler width $\Delta\omega \approx 10^{12}$ sec^{-1}. Taking into consideration the ratio of the statistical weights of the 2p and 1s states of the H atom, and also the fact that one-quarter of all the protons exchange charge in the 2s states, it is easy to verify that for the L_α line the gain is $K_{L_\alpha} \gtrsim 1$ if the proton density in the beam is $N_p \geq 5 \times 10^{13}$ cm^{-3}. In this case we can neglect the loss due to the photoionization of the H and Cs atoms, since the corresponding cross sections do not exceed 10^{-18} cm^2 [5, 6], and also the quenching collisions of the excited hydrogen with the Cs atoms or ions (the cross section does not exceed 10^{-17}cm^2). Under these conditions, the emission of the L_α line can be realized in a continuous regime with a power $W \approx 8 \times 10^3$ J/sec. We note that for a given spectral region it is possible to use at present mirrors (say aluminum coated with MgF_2) with reflection coefficients up to 80%.

With increasing proton energy, charge exchange with capture of an electron from an inner shell of the Cs atom becomes effective (see the figure). In the energy region from 20 to 40 keV, excited ions (electron configuration $np^5(n + 1)s$) are produced in a beam of an alkali-element atom (K, Rb, Sc), and there are practically no ions in the ground state (configuration np^6). We note that, unlike in the situation investigated by Rozanov [7] as applied to photoionization of atoms in an immobile volume, the short lifetime at the upper level of the resonance line of the ion leads, under conditions of intersecting beams, not to the stringent requirements imposed on the growth rate of the pump, but to a relative smallness of the working volume. The ordinary sources of alkali-element atoms ensure at present an atom velocity in the beam not larger than $10^5 - 10^6$ cm/sec. The inverted population in the continuous regime is therefore realized in a volume whose dimension along the direction of the atomic beam does not exceed 10^{-4} cm. The two other dimensions are determined by the geometry of the beams and by the particle densities in the proton and atom beams. Since the Doppler width of the lines does not exceed the natural line in this case, the gain for the resonance line of Cs^+ ($\lambda \approx 912$ Å) can exceed unity if the proton density in the beam is $N_p \geq 10^{12}$ cm^{-3}.

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[1] A.V. Vinogradov, L.P. Presnyakov, and V.P. Shevel'ko, ZhETF Pis. Red. 8, 449 (1968) [JETP Lett. 8, 275 (1968)]; A.V. Vinogradov and V.P. Shevel'ko, Zh. Eksp. Teor. Fiz. 59, 593 (1970) [Sov. Phys.-JETP 32, 323 (1971)].
[2] I.A. Poluektov and L.P. Presnyakov, Zh. Eksp. Teor. Fiz. 54, 120 (1968) [Sov. Phys.-JETP 27, 67 (1968)]; Trudy FIAN 51, 62 (1970).
[3] R.N. Il'in, V.A. Oparin, E.S. Solov'ev, and N.V. Fedorenko, ZhETF Pis. Red. 2, 310 (1965) [JETP Lett. 2, 197 (1965)]; R. Il'in et al., Zh. Tekh. Fiz. 36, 1241 (1966) [Sov. Phys.-Tech. Phys. 11, 921 (1967)].
[4] I.A. Sellin and L. Granoff, Phys. Lett. 25A, 484 (1967).
[5] B.I. Volkov, D.P. Grechukhin, and E.I. Karpushkina, IAE Preprint No. 873, 1965.
[6] I.L. Beigman, L.A. Vainshtein, and V.P. Shevel'ko, Opt. spektrosk. 28, 425 (1970).
[7] V.B. Rozanov, ZhETF Pis. Red. 12, 486 (1970) [JETP Lett. 12, 340 (1970)].