Cross sections for characteristic x-ray emission in collisions of C^{6+}, N^{6+}, N^{7+}, and O^{8+} ions with hydrogen atoms

V. V. Afrosimov, E. D. Donets, A. N. Zinov'ev, S. Yu. Ovchinnikov, and M. N. Panov

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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The cross sections for x-ray emission in the transitions $\Sigma_n(np\text{–}ls)$ and $2p\text{–}ls$ have been measured during the decay of excited states formed in collisions of C^{6+}, N^{6+}, N^{7+}, and O^{8+} ions with H atoms at collision velocities in the range $(3\text{–}12)\times 10^7$ cm/s. The cross sections for the transitions $\Sigma_n(np\text{–}ls)$ are approximately equal to the total cross sections for electron capture.

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In collisions of multiply charged ions with atoms, electrons are captured to highly excited states of a lower-charge ion which results from a charge exchange. The subsequent cascade of radiative transitions terminates in the emission of characteristic x radiation. This process contributes to the ionization balance of the ions and to the emission of hot plasmas, which always contain impurities of the nuclei of light elements and hydrogen atoms, which enter the plasma from the wall or which are formed through photorecombination. The same process turns out to be extremely important in the injection of intense beams of hydrogen atoms into a plasma to heat it, in which case collisions with impurity ions ionize the beam atoms and cause their capture at the plasma boundary, thereby lowering the efficiency at which the central part of the plasma is heated.[1] Furthermore, whether information is available on the cross sections for the emission of radiation determines whether local diagnostics of the impurity concentration in a plasma can be carried out. This diagnostic method makes use of the emission of these ions which arises upon the injection of an atomic beam into a plasma.[2]

In this letter we report the first measurements of the cross section for x-ray emission in collisions of C^{6+}, N^{6+}, N^{7+}, and O^{8+} ions with hydrogen atoms at collision velocities in the range $(3\text{–}12)\times 10^7$ cm/s, corresponding to the particle velocities in the plasmas in advanced fusion-research devices. The beams of multiply charged ions were produced in the Krion-2 source, developed at the Joint Institute for Nuclear Research, Dubna.[3] An ion beam of the appropriate charge, singled out by a magnetic mass monochromator, was injected into the chamber, where it intersected a target consisting of a jet of hydrogen atoms. The jet was produced by admitting into vacuum thermally dissociated hydrogen from a capillary heated to 2700 K. A jet of atoms was used as a target in order to keep hot surfaces away from the region where the emission was detected. The degree of dissociation of H_2 in the collision chamber, averaged over the region from which the emission was observed, was determined by a mass-spectroscopic method and found to be $m = n_H/(n_H + n_{H_2}) = 0.53 \pm 0.02$, where n_H and n_{H_2}

are the densities of hydrogen atoms and molecules, respectively. The density of hydrogen atoms in the collision region was $n_H = 1.5 \times 10^{12}$ cm^{-3}. The emission resulting from the decay of the excited states of the multiply charged ions produced upon the capture of an electron from a hydrogen atom was singled out with absorbing filters and detected by a secondary-emission detector with a CsI photocathode. The total x-ray emission cross section $\sigma_\Sigma = \Sigma_n \sigma(np\text{–}1s)$ was measured with the help of an alumi-

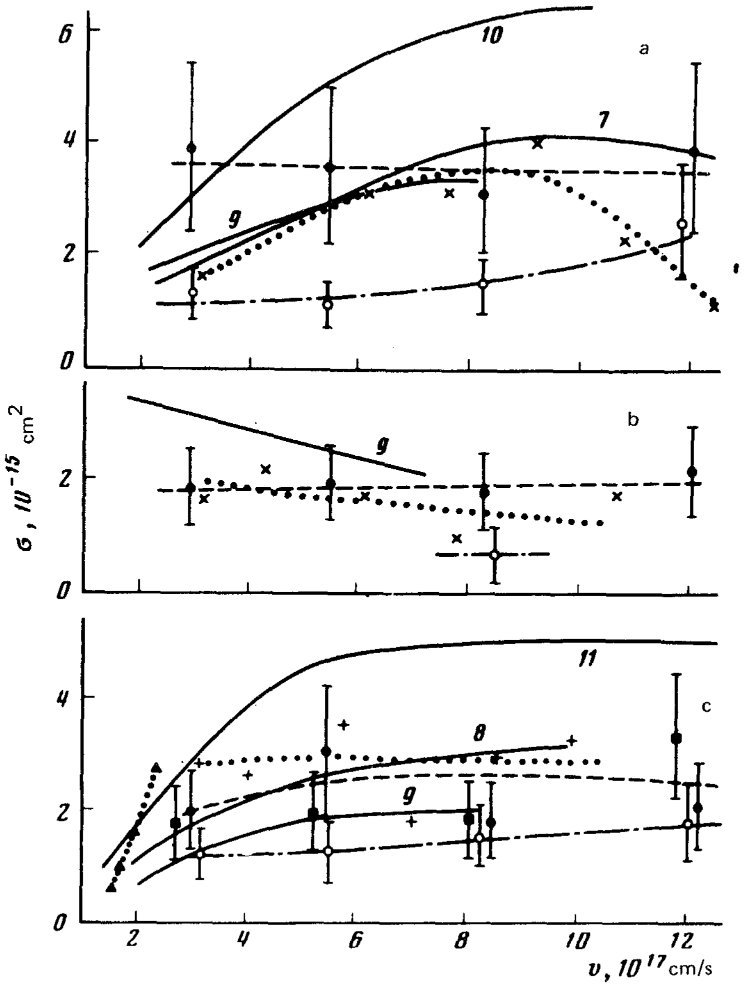

FIG. 1 Total cross sections for x-ray emission, σ_Σ, and cross sections for the emission in the $2p$–$1s$ line, $\sigma(2p\text{–}1s)$, in the capture of an electron from a hydrogen atom by a multiply charged ion. Here v is the collision velocity. The labels on the solid curves are the references to the theoretical papers with the corresponding calculations. Data from the present experiments: ● and ○ —the cross sections σ_Σ and $\sigma(2p\text{–}1s)$ for (a) O^{8+}–H, (b) N^{7+}–H, and (c) C^{6+}–H; ■ —the cross section σ_Σ for N^{6+}–H collisions (c). Dashed and dot-dashed curves — average cross sections σ_Σ and $\sigma(2p\text{–}1s)$, respectively. Data on electron capture cross sections from Ref. 5: x — for (a) O^{8+}–H and (b) N^{7+}–H; + — N^{6+}–H (c). From Ref. 6: ▲ — C^{6+}–H (c).

num filter. The emission cross section for the transition $2p$–$1s$, $\sigma(2p-1s)$, in the C^{5+} and O^{7+} ions was determined with the help of scandium and fluoroplastic filters, respectively. An absolute calibration of the cross sections was carried out with the help of our earlier measurements of the x-ray emission cross sections in collisions of nuclei with hydrogen molecules.[4] The absolute errors of the present measurements are 40%, and the relative errors 25%.

The total cross sections for the x-ray emission in these collisions (Fig. 1) are extremely large and essentially independent of the collision velocity. Figure 1 also shows the total cross sections for electron capture according to measurements[5,6] involving the analysis of the charge composition of a beam transmitted through a gaseous target. Some theoretical predictions are also shown.[7–11] There is a satisfactory agreement with the experimental data of Refs. 5 and 6; among the various theoretical papers, the predictions generated by the strong-coupling method[7,8] show the best agreement. The approximate agreement of the experimental electron-capture cross sections[5] and the cross sections for x-ray emission confirm that the electron is captured primarily to excited states. In collisions of ions with identical charge, C^{6+} and N^{6+}, the cross sections σ_{Σ} turn out to be approximately the same, suggesting that the presence of the K electron has only a slight effect on the capture to excited states. In the C^{6+}–H collisions we measured the cross sections for emission in the ultraviolet region (the sum of the cross sections for the transitions $4l$–$3l'$, 4–$2l'$, and $3l$–$2l'$) in addition to the cross sections $\sigma(2p-1s)$ and σ_{Σ}. From these measurements we drew the conclusion that states with principal quantum numbers $n = 3$ and $n = 4$ are populated in this case; the relative population of these levels is essentially independent of the collision velocity at $\sigma(4)/[\sigma(3) + \sigma(4)] = 0.7 \pm 0.15$.

Comparison of the cross sections $\sigma(2p-1s)$ with the total cross section in the case of C^{6+}–H suggests that states with large orbital angular momenta l are populated more effectively than in the capture of an electron from the H_2 molecule.[4] There is a tendency toward an increase in the population of the large-l states with increasing collision velocity (see the cases C^{6+}–H and O^{8+}–H).

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