Formation of excited states of zinc, cadmium, and mercury atoms and ions in collisions with low-energy protons

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Excitation functions have been found (for the first time) for the spectral lines of zinc, cadmium, and mercury atoms and ions excited by proton impact near the threshold. Anomalously large ion cross sections have been found. An oscillatory structure found in the excitation functions of several lines indicates that the interaction of the particles is of a quasimolecule nature.

Many experimental studies on inelastic collisions of ions and atoms have now been published. The overwhelming majority have been carried out at high energies and deal with the collisions of many-electron systems. Electron-electron correlation effects in the cores of the colliding particles are known to play a significant role in the dynamics of these processes,[1] particularly for systems with a large number of electrons. To take these correlations into account correctly is an independent theoretical problem, which simplifies substantially if the field of the projectile ion (in particular, a proton) is a purely Coulomb field. Nevertheless, the experimental study of the excitation of atoms and molecules by such ions remains an open question. The difficulties seem to lie in the production and shaping of intense beams of protons of controllable energy and small energy spread. In this sense, there is particular interest in studying inelastic processes involving a "structureless" heavy particle: a proton. The results of such studies are crucial to an understanding of the elementary processes that occur in plasmas containing hydrogen and in atmospheric and astrophysical phenomena. Such studies may also be helpful in producing population inversions in gas lasers.

In this letter we report the first observation of anomalously large cross sections for ion spectral lines in the collisions of low-energy protons with zinc, cadmium, and mercury atoms. We have also found a regular oscillatory structure in the excitation functions of lines, indicating that the interaction of the particles is of a quasimolecule nature.

The experimental apparatus is described in Ref. 2. This apparatus makes it possible to study excitation processes by an optical method in the visible and ultraviolet parts of the spectrum (220–800 nm). The excitation functions are found by taking the average of many curves (8–10 measurements). The error of the relative measurements of the excitation functions is no worse than 3–4%, while the error in the measurement of the absolute excitation cross sections is 45–50%. The absolute cross sections are found by comparing the intensities of spectral lines excited by proton impact with the intensities of lines excited by electron impact with a known excitation cross section.

We turn now to the results. Analysis of the excitation spectra reveals lines associated with the following processes:

$$H^+ + A \rightarrow H^+ + A^* + \Delta E_1 \quad (1)$$
$$H^+ + A \rightarrow H^+ + A^{**} + e + \Delta E_2 \quad (2)$$
$$H^+ + A \rightarrow H^0 + A^{+*} + \Delta E_3 \quad (3)$$
$$H^+ + A \rightarrow H^* + A^+ + \Delta E_4 \quad (4)$$

where A is the target atom, and ΔE_i is the energy defect of the reaction. For each pair of colliding particles, the spectra reveal roughly the same number of spectral lines belonging to atoms and ions of the given elements. Since many of the excited states of these particles emit in the wavelength range which we were able to study in these experiments, we were able to compare the efficiencies of these two processes. This comparison showed that the effective cross sections for the ion spectral lines are significantly larger than those for the atomic lines (by about two orders of magnitude). This anomaly is observed regardless of how many electrons are involved in the collision event (regardless of whether it is a one- or two-electron process). For example, the effective spectral lines emitted from shifted levels ($\lambda = 5894$ Å, $\lambda = 7479$ Å for ZnII and $\lambda = 3250$ Å, $\lambda = 4416$ Å for CdII) exceed the cross sections for the single-electron processes that lead to the formation of atomic states. Exceptional cases are the resonant lines of ZnI and CdI, whose cross sections are given without allowance for self-absorption and which reach values on the order of 10^{-17} cm^2. This result is at odds with the data of Ref. 3, where inelastic collisions of He^+ and H^+ with Na and K atoms were studied. Bearman *et al.*[3] concluded that the efficiency of the single-electron processes is greater than that of the two-electron processes and that this rule is more important than the energetics of the reaction in determining the preferred inelastic channels.

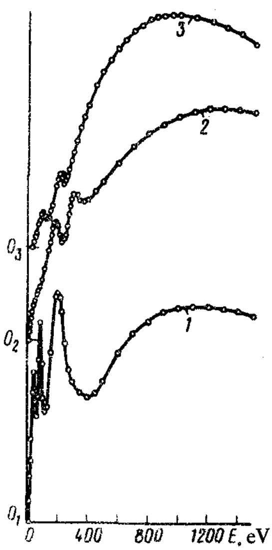

FIG. 1. Excitation functions of the spectral lines of zinc, cadmium, and mercury atoms. 1—ZnI, $\lambda = 6362$ Å ($4^1D_2 \rightarrow 4^1P_1$); 2—CdI, $\lambda = 3610/12/14$ Å ($6^2D_j \rightarrow 5^3P_j$); 3—HgI, $\lambda = 4358$ Å ($7^3S_1 \rightarrow 6^3P_1$).

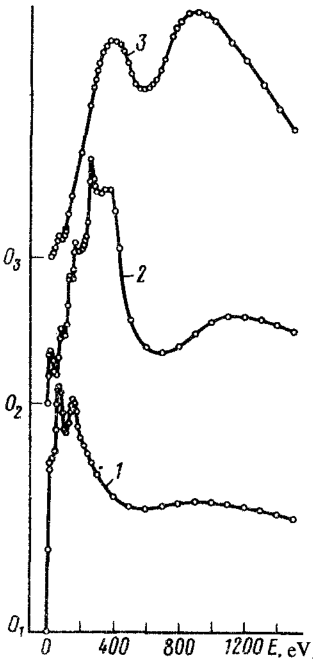

FIG. 2. Excitation functions of spectral lines of zinc, cadmium, and mercury ions. 1—ZnII, $\lambda = 5894$ Å ($4s' - {}^2D_{3/2} \rightarrow 4^2P_{1/2}$); 2—CdII, $\lambda = 2749$ Å ($6^2S_{1/2} \rightarrow 5^2P_j$); 3—HgII, $\lambda = 2847$ Å ($7^2S_{1/2} \rightarrow 6^2P_{3/2}$).

Another distinctive feature of our results is a well-defined oscillatory structure in the measured excitation functions. Figures 1 and 2 illustrate the situation with the excitation functions of several spectral lines. The cross section increases rapidly near the threshold; the experimental excitation thresholds for the functions that we measured agree within the experimental errors with the kinematic thresholds. Interestingly, in no case did we detect that shift of the thresholds in the excitation functions toward increasing energy of the projectile ions which is characteristic of the collisions of heavy particles.

Finally, we note that the peaks of the excitation function for the spectral line $\lambda = 6362$ Å ZnI are spaced uniformly along the reciprocal-velocity scale. This result is apparently the first observation of a regular oscillatory structure in the interaction of a "structureless" particle (the proton) with atoms and is evidence of a quasimolecule mechanism for the interaction of the particles, as discussed in Refs. 4 and 5.

A detailed analysis of the results will be offered in future papers.

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