

# Radiative decay of NaI autoionization states excited in electron-atom collisions

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The radiative decay of NaI autoionization states has been observed for the first time. The absolute cross sections for the electronic excitation of  $(2p^6 3p)^2P$ - $(2p^5 3p 3s)^4L$  transitions have been determined. Resonances are found in the threshold region on the measured excitation functions for the initial levels of the radiative transitions.

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The literature reveals no information of any sort on the radiative decay of autoionization states of sodium atoms. In this letter we are reporting a study of the excitation of autoionization states of NaI, whose decay is accompanied by the emission of ultrasoft x rays.

The experiments were carried out with a spectrometric apparatus with electron and atomic beams intersecting at right angles and with a grazing-incidence vacuum monochromator.<sup>1</sup> In an effort to detect faint lines, we recorded the sodium emission spectrum in the ultrasoft-x-ray region in a point-by-point manner, scanning the wavelength at a certain step and integrating the signal for 300 s for each point. The spectra were measured at

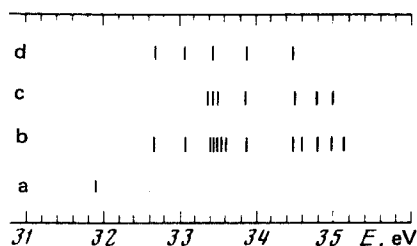


FIG. 1. Energy positions of the levels of the configuration NaI  $2p^5 3p 3s$  (measured from the ground state of the atom), observed in Ref. 3 (a), Ref. 4 (b), Ref. 5 (c), and the present experiments (d).

various energies of the bombarding electrons over the range from 30 to 500 eV in the interval 30–45 nm. In addition to the known<sup>2</sup> lines of NaII in this region, we observed lines at 38.3, 39.0, 39.6, 40.0, and 40.5 nm. These lines are observed at energies below the excitation threshold for the deepest level of the sodium ion, so they must be regarded as corresponding to spectral transitions in the system of the atom, from highly excited states of the  $(2p^5 3s nl)^k L$  type. Working from data obtained in these experiments on the energy of the detected x rays and on the threshold excitation energy for the lines, we found that the  $(2p^6 3s)^2 P$  state is the final state for all the observed transitions, while the initial states correspond to the  $2p^5 3p 3s$  configuration and to various values of the orbital angular momentum and the spin. Figure 1 is a level diagram for the  $2p^5 3p 3s$  configuration. Shown here are the level positions corresponding to the following states: the lowest-lying metastable quartet state, observed in Ref. 3; states which have been observed in the electron emission spectra at various energies of the exciting electron beams<sup>4,5</sup>; and states from which radiative transitions are observed in the present experiments. It can be seen from this diagram that the levels from which the radiative transitions are observed have energies which agree quite well with certain levels observed in the electron emission spectra. The fact that both radiative and radiationless transitions are observed in the decay of many levels indicates a pronounced breaking of  $L$ - $S$  coupling for the sodium-atom states  $(2p^5 3p 3s)^k L$ .

We also determined the absolute values of the electronic-excitation cross sections for the observed spectral lines of NaI. For this purpose, the intensities of these lines were compared with that of the resonance line NaII 37.2 nm (the  $2p^6 - 3s'[3/2]_1^0$  transition), for which the absolute excitation cross section was determined by normalizing its excitation function to a theoretical cross section<sup>6</sup> for excitation of the  $3s'[3/2]_1^0$  NaII level at a bombarding-electron energy of 1000 eV, with allowance for cascade contributions.<sup>7</sup> The

TABLE I.

$\lambda$ , nm	$E_{thr}$ , eV	$E_M$ , eV	$\sigma$ , $10^{-20}$ cm <sup>2</sup>	$\sigma_M$ , $10^{-20}$ cm <sup>2</sup>	Initial state for the transition
40.5	32.7	34	2	6	$2p^5 3p 3s^4 S$
40.0	33.1	—	1	—	$2p^5 3p 3s^4 D$
39.6	33.5	33.7	1.2	5	$2p^5 3p(^3 P) 3s^2 D$
39.0	33.9	—	0.8	—	$2p^5 3p(^3 P) 3s^2 S$
38.3	34.5	—	0.4	—	$2p^5 3p(^1 P) 3s^2 P$

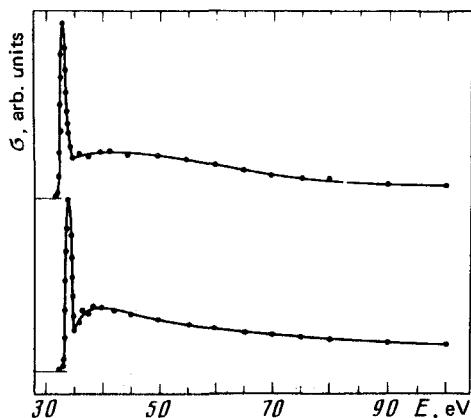


FIG. 2. Excitation functions for the spectral lines NaI 39.6 nm (lower curve) and 40.5 nm.

cross sections for the excitation of radiative transitions determined in this manner for an electron energy of 40 eV ( $\sigma$ ) and for the energy corresponding to the maxima of the excitation function ( $\sigma_M$ ) are listed in Table I. Also shown here are the wavelengths  $\lambda$ , the threshold line excitation energies  $E_{thr}$  (which we determined within 0.05 eV), the energies corresponding to the maxima of the line excitation functions,  $E_M$ , and the initial states for the observed spectral transitions, identified in accordance with the data of Ref. 5.

Figure 2 shows the excitation functions for the two most intense NaI lines. These functions are basically alike, having a narrow peak immediately after the excitation threshold, along with a broader peak near 40 eV. At high energies, the excitation functions for the lines at 39.6 and 40.5 nm fall off in proportion to  $E^{-1}$  and  $E^{-3}$ , respectively. The width of the narrow peaks in the excitation functions at the half-maximum level is  $\sim 1$  eV, approximately the same as the energy spread of the bombarding electrons. It may thus be assumed that the excitation of the initial states for these transitions near the threshold is of a clearly expressed resonance nature.

The excitation function for the lowest-energy quartet state<sup>3</sup> is quite similar to the excitation functions measured by us for the lines at 39.6 and 40.5 nm. With regard to the radiative transitions from autoionization states of K, Rb, and Cs atoms, which have been observed previously,<sup>7-10</sup> we note that only in the case of cesium do the excitation functions for the transitions from the autoionization states have a narrow peak beyond the excitation threshold.

The resonances in the excitation functions for the NaI lines may result from a further population of the initial states for the observed spectral transitions through the decay of short-lived  $\text{Na}^-$  autodetachment states formed during capture of the electrons by the atoms. These autodetachment states may be states of the  $(2p^5 3p 3s)^2 L n l^{1,3} L$  type. The occurrence of a single narrow peak immediately beyond the excitation threshold for a level, however, is more characteristic of the resonances which stem from the particular shape of the atomic potential for electronic excitation, i.e., so-called shape resonances.<sup>11</sup>

For a definitive interpretation of the resonances observed in the excitation functions for the NaI lines it would be extremely useful to have a theoretical study of the energy

dependence of the electronic-excitation cross sections for the  $(2p^5 3p 3s)^k L_J$  levels with allowance for the open and closed excitation channels.

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