# Investigation of short-wave radiation emitted in slow collisions between $Na^+$ ions and Ne atoms

V. P. Belik, S. V. Bobashev, and S. P. Dmitriev

*A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences*
(Submitted May 23, 1974)
Zh. Eksp. Teor. Fiz. 67, 1674–1681 (November 1974)

Radiation emitted in the 200–1000 Å region in collisions between 0.2–10 keV $Na^+$ ions and Ne atoms is investigated. Exictation functions are obtained for the most intense spectral lines and the absolute values of the line excitation cross sections are estimated. The λ 407.1 Å Ne II line is found to be the most intensely excited. Various processes that may lead to excitation of the line are discussed. It is demonstrated that a certain isolated group of quasimolecular states of the system takes part in the phase interference of the excited states of the ($Na^+Ne$) quasimolecule.

## INTRODUCTION

The investigation of inelastic collisions of $Na^+$ ions with Ne atoms has led to the observation of a number of interesting effects. Earlier studies[1] have revealed regular oscillations of the total cross sections for the excitation of resonant lines of the neon atom; these oscillations were attributed to interference of two states of the quasimolecule ($Ne^+Ne$)[2]. This was followed by discovery of regular oscillations of the total cross sections for the charge exchange of $Na^+$ ions with neon atoms[3], and also a structure in the excitation functions of the spectral lines of the neon atoms in the visible region of the spectrum[4]. Recently[5,6] there was observed an appreciable polarization of the radiation in the spectral lines of the neon atoms excited by a number of ions, and the degree of polarization turned out to be largest for excitation of Ne by $Na^+$ ions. For the $Na^+$ + Ne pair, a study was also made of the spectra of the electrons[7] and of the spectra of the differential inelastic energy losses[8]. All these measurements were performed at $Na^+$ ion energies $E < 10$ keV, when the energy loss in inelastic collision is comparable with the energy W of the relative motion of the colliding particles ($W < 5$ keV).

We have studied the excitation functions of certain resonant vacuum-ultraviolet lines emitted in collisions between $Na^+$ ions ($E < 10$ keV) and Ne atoms. Our purpose was to study other possible processes whereby both collision partners lose energy, and to ascertain which of the states of the quasimolecule ($Na^+Ne$) take part in the phase interference that leads to the appearance of regular oscillations in the total cross sections of the inelastic processes.

## EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The experimental setup is shown in Fig. 1. To obtain a beam of singly-charged $Na^+$ ions in the ground state, we used the source 1 with surface ionization. The source, a system of quadrupole lenses, and the capacitor 3 were placed in a vacuum chamber connected to the collision chamber 4. In the collision chamber we mounted the ion receiver 5 and the entrance slit 8 of the vacuum monochromator 6. For the spectral analysis of the emission, we used a vacuum monochromator with concave diffraction grating, similar to the instrument described by Sorokin, Rozov, and Blank in[9]. The diffraction grating 7 (R = 1 m, 600 lines/mm) was coated with a layer of gold. The monochromator was designed for the spectral region 200—1000 Å. The reciprocal linear dispersion of the instrument in first order was

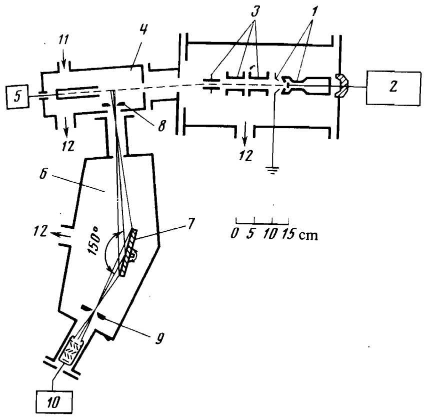


FIG. 1. Experimental setup: 1—ion source, 2—high voltage supply of ion source, 3—system for focusing the ion beam (quadrupole lens and clearing capacitor), 4—collision chamber, 5—ion receiver and ion-current recorder, 6—vacuum monochromator, 7—concave diffraction grating, 8, 9—entrance (stationary) and exit (movable) slits of the vacuum monochromator, 10—open electron multiplier and recording apparatus, 1—gas inlet, 12—to vacuum pump.

3 Å/mm. The radiation was registered with an open VÉU-1A electron multiplier 10.

Typical values of the measured quantities are the following: the current of the $Na^+$ ions in the collision chamber at E = 4 keV was 10 μA; the residual pressure in the collision chamber, in the ion-source chamber, and in the monochromator chamber was $1 \times 10^{-6}$ mm Hg, the pressure of the neon in the collision chamber was $(8—10) \times 10^{-4}$ mm Hg, and the output current of the VÉU-1A multiplier, registered at the maximum of the λ 407.1 Å line of NeII was $\sim 10^{-11}$ A at E = 4 keV.

## MEASUREMENT RESULTS AND DISCUSSION

We investigated the spectrum of the radiation produced by collision of $Na^+$ ions with Ne atoms in the wavelength interval 200--1000 A. Figure 2 (solid line) shows the part of the spectrum obtained at the $Na^+$ ion energy, E = 4 keV (W = 2.13 keV); it contains all the intense NaII, NeI, and NeII lines. A characteristic feature of the spectrum is the appreciable intensity of the λ407.1 Å line of the $Ne^+$ ion; the intensity of this line was approximately double the combined intensity of the remaining $Ne^+$ lines.

The table lists the observed spectral lines, their wavelengths, classification[10], relative intensity, and estimated absolute values of their excitation cross sections. Owing to the insufficient resolution of the monochromator, many of the observed lines could not be identified exactly, so that the table lists wavelengths of groups of neighboring lines, which were not resolved by our instrument.

The contour of the NeII λ 407.1 Å line was additionally investigated with a setup containing a monochromator of the Seiya-Namioka type[11]. The contour of this line, taken in fifth order (the reciprocal linear dispersion of the monochromator was 1 Å/mm) at E = 4 keV indicates that of the two closely locating lines NeII λ 407.1 Å ($3s'^2D_{3/2} \to 2p^5\ ^2P^0_{1/2}$ and NeII λ 405.9 Å ($3s'^2D_{5/2,\ 3/2} \to 2p^5\ ^2P^0_{3/2}$ it is the first that makes the overwhelming contribution to the intensity.

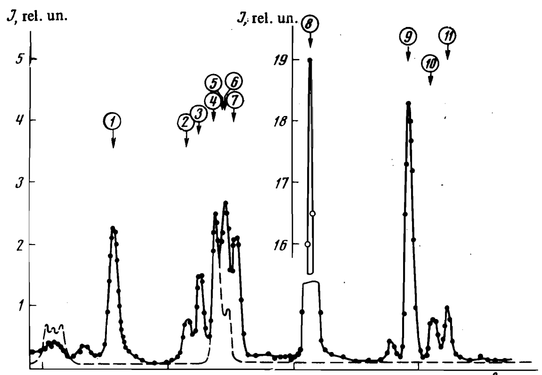


FIG. 2. Part of the vacuum-ultraviolet emission spectrum obtained in the $Na^+$ + Ne collision (solid line) and $K^+$ + Ne collision (dashed line). W = 2.13 keV. 1) NeII (λ326.1 Å); 2) NeII (λ356.6 Å); 3) NeII (λ361.8 Å); 4) NeI λ735.9 Å; 5) NeI λ743.7 Å; 6) NaII λ372.1 Å; 7) NaII λ376.4 Å; 8) NeII λ407.1 Å; 9) NeII (λ447.0 Å), 10) NeII (λ456.3 Å); 11) NeII λ462.1 Å. The wavelengths indicated in the parentheses pertains to a group of lines, since the insufficient resolution of the monochromator made it impossible to identify the lines exactly (see the table). All the lines were taken in second order, with the exception of the NeI λ735.9 Å and λ743.7 Å lines and the three KII lines (600.8 Å, 607.9 Å, 612.6 Å), which were obtained in first order. J is the relative intensity and λ is the wavelength.

Intensities of the observed NeII and NaII lines at E = 4 keV.

| | Line Number | λ, Å, experiment | Classification of lines: λ, Å | Levels: lower | Levels: higher | Relative intensity | Excitation cross section, $10^{-18}$ cm$^{-2}$ |
|---|---|---|---|---|---|---|---|
| Ne II | 1 | 326.1 | 325.4 | $2p^5\ ^2P^0_{1/2}$ | $4s\ ^2D_{3/2}$ | 2.2 | 3 |
| | | | 326.1 | $^2P^0_{3/2}$ | $3d'\ ^2F_{5/2}$ | | |
| | | | 326.5 | $^2P^0_{3/2}$ | $^2D_{3/2,\ 5/2}$ | | |
| | | | 326.8 | $^2P^0_{3/2}$ | $^2S_{1/2}$ | | |
| | 2 | 356.6 | 356.4 | $^2P^0_{1/2}$ | $3d^2P_{1/2}$ | 0.8 | 1.5 |
| | | | 356.5 | $^2P^0_{3/2}$ | $^2D_{3/2}$ | | |
| | | | 356.8 | $^2P^0_{3/2}$ | $^2D_{5/2}$ | | |
| | 3 | 361.8 | 361.4 | $^2P^0_{3/2}$ | $3s''\ ^2S_{1/2}$ | 1.5 | 2.5 |
| | | | 362.6 | $^2P^0_{1/2}$ | $^2S_{1/2}$ | | |
| | 8 | 406.9 | 407.1 | $^2P^0_{1/2}$ | $3s'\ ^2D_{3/2}$ | 19 | 30 |
| | 9 | 447.0 | 446.2 | $^2P^0_{3/2}$ | $3s^2P_{3/2}$ | 4.3 | 7 |
| | | | 446.6 | $^2P^0_{1/2}$ | $^2P_{1/2}$ | | |
| | | | 447.8 | $^2P^0_{1/2}$ | $^2P_{3/2}$ | | |
| | 10 | 456.5 | 455.3 | $^2P^0_{3/2}$ | $^4P_{3/2}$ | 0.8 | 1.5 |
| | | | 456.3 | $^2P^0_{1/2,\ 3/2}$ | $^4P_{1/2,\ 3/2}$ | | |
| | | | 457.0 | $^2P^0_{1/2}$ | $^4P_{3/2}$ | | |
| | 11 | 462.1 | 460.7 | $^2P^0_{3/2}$ | $2p^6\ ^2S_{1/2}$ | 1.0 | 2 |
| | | | 462.4 | $^2P^0_{1/2}$ | $^2S_{1/2}$ | | |
| Na II | 6 | 372.1 | 372.1 | $2p^6\ ^1S_0$ | $3s\ [^1/_2]^0$ | 2.7 | 4.5 |
| | 7 | 376.2 | 376.4 | $^1S_0$ | $3s\ [^3/_2]^0$ | 2.1 | 3 |
| Ne I | 4 | 736.0 | 735.9 | $2p^6\ ^1S_0$ | $3s\ [^1/_2]^0$ | — | — |
| | 5 | 743.3 | 743.7 | $^1S_0$ | $3s\ [^3/_2]^0$ | — | — |

*See Fig. 2.

The considerable excitation of the spectral lines of the neon ion in collisions of the $Na^+$ ions with the Ne atoms is apparently connected with the individual properties of the investigated pair. To illustrate this assumption, Fig. 2 (dashed line) shows part of the emission spectrum produced in slow collisions of $K^+$ ions with neon atoms. This spectrum was obtained at an energy W = 2.13 keV under the same experimental conditions as the emission spectrum in collisions of $Ne^+$ with Ne (solid line). From a comparison of the spectra that in the case $K^+$ + Ne the resonant lines of the Ne atoms are excited with practically the same probability as in the $Ne^+$ + Ne case, whereas the lines of the $Ne^+$ ions are intensely excited only in $Na^+$ + Ne collisions.

We measured the excitation functions of the most intense spectral lines registered in the emission spectrum, with the exception of the resonance lines of the neon atom, which were investigated earlier[1]. Figure 3 shows the excitation cross section of the NeII λ 407.1 Å line, while Fig. 4 shows the cross section for the excitation of the line NeII λ 326.1 Å and of the resonance line NaII λ 376.4 Å. The cross section for the excitation of NeII λ 407.1 Å increases rapidly from the threshold $E_{th}$ = 230 eV (W = 122 eV) and reaches a maximum value at E ≥ 1.2 keV (W = 0.6 keV). The cross sections exhibit negligible oscillations in the region 1–4 keV, but the maxima of these oscillations (Fig. 3) reveal no regularity as functions of the reciprocal velocity, and it is namely such a regularity which is typical of the interference of quasimolecular states[1].

The absolute excitation cross sections of the spectral lines shown in Figs. 3 and 4 were determined in the following manner. A specially designed photoionization chamber was used to determine the absolute flux of the radiation for all the spectral lines whose wavelengths were shorter than the red boundary $\lambda_b$ = 575 Å of the neon photoionization, in the $Na^+$ + Ne process in the energy range from the experimental threshold $E_{th}$ = 230 eV of appearance of the radiation up to E = 1000 eV. At E = 600 eV, the flux corresponds to the total cross section $\sigma_c = 2.1 \times 10^{-17}$ cm$^2$ for the excitation of all the lines with wavelength $\lambda < \lambda_b$ (the accuracy of the absolute measurements is 20%).

An investigation of the threshold behavior of the most intense lines of the spectrum (Fig. 2) has shown that at E = 600 eV the largest contribution to the intensity is made by the NeII λ 407.1 A line, and the contribution of the remaining lines of NeII and NeII does not exceed

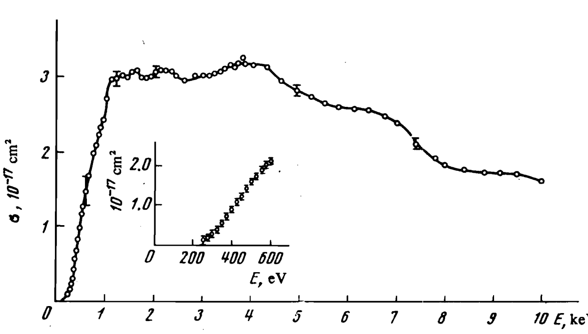


FIG. 3. Cross section for the excitation of the NeII λ407.1 Å line vs. the energy of the $Na^+$ ion. The insert shows the absolute radiation flux of all the lines whose wavelengths are shorter than $\lambda_b$ = 575 Å.

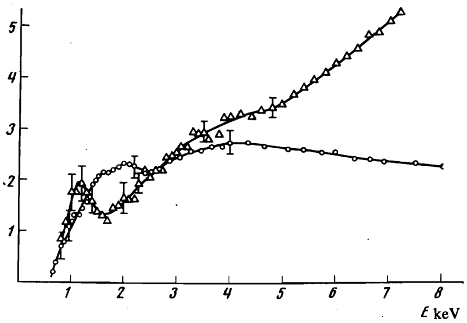


FIG. 4. Dependence of the excitation cross section of the NeII λ326.1 Å line and of the resonance line NaII λ 376.4 Å on the energy of the $Na^+$ ions. Δ—excitation cross section of NaII λ 376.4 Å line, ○—excitation cross section of the NeII λ 326.1 Å line.

30%. The neon photoionization cross section is practically independent of the wavelength in the region 320—460 Å [13], and therefore the absolute value of the excitation cross section of the λ 407.1 Å spectral line (Fig. 3) can be assumed to be equal to the total cross section for the excitation of all the spectral lines with $\lambda < \lambda_b$, decreased by 30%, i.e., $\sigma = 1.4 \times 10^{-17}$ cm² at E = 600 eV. The insert of Fig. 3 shows the cross section for the excitation of the emission of all the lines with $\lambda < \lambda_b$, measured with the aid of a photoionization chamber[12].

The absolute cross sections over the excitation of the remaining lines, given in the table and in Fig. 4, were obtained by normalizing the relative excitation functions to the cross section $\sigma = 3.2 \times 10^{-17}$ cm² for the excitation of the NeII λ 407.1 Å line at E = 4 keV; it was assumed here that the lattice reflection coefficient in second order of the spectral decomposition does not change significantly in the wavelength band 320—460 Å. On the basis of these assumptions and of the accuracy (assumed to be 30%) with which the absolute cross section for the excitation of the NeII λ 407.1 Å is determined we can obtain the absolute values of the cross sections shown in Fig. 4 and in the table with accuracy not higher than 50%.

Returning to the discussion of the curve of the excitation of the NeII λ 407.1 Å line (Fig. 3), we note that the excitation-energy is $E_{th} = 730$ eV ($W_{th} = 122$ eV). What is important, in our opinion, is that the excitation thresholds of the spectral line of the $Ne^+$ ion, of the resonance lines of the neon atom[1], and of the discrete groups of electrons investigated in[7], have energies $W \approx 100—130$ eV, even though the excitation potentials are significantly different in these three cases. The energy deficits are $\Delta E_r = 16.85—16.67$ eV for the excitation of the resonance lines of the neon atoms, $\Delta E_a = 43.41—43.60$ eV for the auto-ionization state $2s2p^6(^2S)3s$[7], and $\Delta E = 52.1$ for the excitation of the NeII λ 407.1 Å line. This means that in the latter case the deficit is approximately equal to half the kinetic energy $W_{th}$.

The excitation of the NeII λ 407.1 Å line can be caused by the following processes:

1. Charge exchange of the sodium ions with the neon atom, to the ground or excited states of Na with simultaneous excitation of the ion $Ne^+$:

$$Na^+(2p^6\,{}^1S_0) + Ne(2p^6\,{}^1S_0) \begin{cases} \nearrow Na^0(3s\,{}^2S_{1/2}) + Ne^+(3s'\,{}^2D_{3/2}), & \Delta E_1 = 47.6 \text{ eV} \\ \searrow Na^0(3p\,{}^2P_{3/2,\,1/2}) + Ne^+(3s'\,{}^2D_{3/2}), & \Delta E_2 = 49.1 \text{ eV}. \end{cases} \quad (1)$$

$\Delta E_{1,2}$ are the resonance deficits at large internuclear distances.

2. The ionization of the neon by the $Na^+$ ions with excitation

$$Na^+(2p^6\,{}^1S_0) + Ne(2p^6\,{}^1S_0) \to Na^+(2p^6\,{}^1S_0) + Ne^+(3s'\,{}^2D_{3/2}) + e, \quad \Delta E = 52.1 \text{ eV}. \quad (2)$$

3. A possible mechanism whereby the $3s'^2D_{3/2}$ level of $Ne^+$ is excited is the excitation of auto-ionization states of neon ($Ne^{**}$)

$$Na^+(2p^6\,{}^1S_0) + Ne(2p^6\,{}^1S_0) \to Na^+(2p^6\,{}^1S_0) + Ne^{**} \to Na^+(2p^6\,{}^1S_0) + Ne^+(3s'\,{}^2D_{3/2}) + e. \quad (3)$$

According to the studies of Ogurtsov, Flaks, and Avakyan[14] and of Edwards and Rudd[15], the possible auto-ionization states are

a) $Ne^{**}2s2p^5(^1P)3s(^2P)3p(^1P)$ and b) $2s2p^5(^1P)3s^2(^1P)$.

A discrete group of electrons of energy 30 eV should be observed in case (a), and of energy 24—25 eV in case (b).

In the investigated reaction $Na^+ + Ne$, as follows from[7], only groups of fast electrons with energies 21 eV and 22—28 eV are observed. Bydin, Vol'pas, and Ogurtsov[7] connect the appearance of the second group of electrons with the excitation of the states $2s2p^6(^2S)np(^{1,3}P)$, $2s2p^6(^2S)ns(^{1,3}S)$, $2p^4(^3P)3s(^2P)\cdot np(^1P)$ and $2p^4(^3P)3p(^4D)np(^3P)$, which have an excitation potential smaller than the $3s'^2D_{3/2}$ level of the $Ne^+$ ion. Whether the second group of electrons is connected with the excitation of the state $2s2p^6(^1P)3s^2(^1P)$ or not can be determined from the form of the excitation function of this group and from the absolute value of the excitation cross section.

Another possible cause of the anomalous excitation of the state $3s'^2D_{3/2}$ may be cascade transitions from the higher-lying states of the $Ne^+$ ion. On the basis of the published probabilities of transitions from the states 3d′ and 3s′[16,17], we have estimated that the contribution of the cascade transitions to the cross section for the excitation of the $3s'^2D_{3/2}$ state does not exceed 2%. To be sure, allowance for only a limited number of high-lying levels does not exclude the possibility of population of the state $3s'^2D_{3/2}$ via cascade transitions, but nevertheless this mechanism of two-step effective population of the state seems little likely.

It follows from the foregoing that the most probable process of excitation of the NeII λ 407.1 Å line is ionization with excitation (2). The cross section for the charge exchange (process 1), according to Latypov and Shaporenko[3], is $\sigma \approx 1 \times 10^{-17}$ cm² (accuracy ±40%), for E = 2 keV, i.e., much less than the cross section for the excitation of the $3s'^2D_{3/2}$ state of NeII at the same energy (Fig. 3).

Attention is called to the course of the excitation of the resonant state $3s'[1\tfrac{1}{2}]_1^0$ of the sodium ion NaII (Fig. 4), which differs qualitatively from the course of the cross section for the excitation of the resonant states of fast $K^+$, $Rb^+$, and $Cs^+$ ions in slow collisions with inert gases[11,18,19]. The minimum in the cross section of NaII $3s'[1\tfrac{1}{2}]_1^0$, which correlates with the maximum of the excitation cross section of NeII λ 407.1 Å (Fig. 3), allows us to assume that we are encountering here the influence of one inelastic process on another. The possibility of this influence, which is connected with the decrease of the probability of one inelastic process with a sharp growth of the probability of the other, was analyzed in detail earlier[18]. Within the framework of the Landau-Zener model, however, we cannot expect the appearance of singularities in the course of the total cross sections, due to this influence, as a consequence of integration over a large set of impact parameters[20]. Nonetheless, we can return to a discussion of this possibility.

It follows from recent studies[5,6] that an important role is played in collisions of $Na^+$ with Ne, by rotational transitions, which have not been considered in the Landau-Zener theory; for rotational transitions, the region of impact parameters that play a major role in the integration on going from the probability to the total cross section is quite narrow[21], so that it can be assumed that in the considered $Na^+$ + Ne collision process the influence of one inelastic channel on the other can lead to singularities in the energy dependence of the total cross sections of the inelastic processes.

The results of the investigation of the excitation functions of the most intense spectral lines excited in $Na^+$ + Ne collisions, which were obtained in the present study and also elsewhere[1,6], show that only an isolated group of quasimolecular states of the (Na + Ne) system takes part in the phase interference phenomenon. These are those quasimolecule states which lead at large internuclear distances to population of the $2p^5 3p$ levels of the Na atom and $2p^5 3p$ levels of the Ne atom. Their interaction causes a regular structure of the excitation functions of the Ne atoms lines lying in the physical region of the spectrum, and in counterphase with them, to oscillation of the excitation functions of the Na atom[6]. In our opinion, the resonance states $2p^5 3s$ ($1s_2$ and $1s_4$ in Paschen's notation) of the neon atom are populated in $Na^+$ + Ne collisions via cascade transitions $2p^5 3p \to 2p^5 3s$ ($2p_1$—$2p_{10}$) in such a way that the population of the state $1s_4$ is determined completely by the cascade transitions $2p_2, 2p_3, 2p_4, 2p_7, 2p_8 \to 1s_4$, which bring about the oscillatory structure of the excitation functions of the NeI λ 743.8 Å resonance line as a function of the energy of the $Ne^+$ ions[1].

The authors are grateful to V. M. Dukel'skiĭ for constant interest in the work and to G. N. Ogurtsov and Z. Z. Latypov for useful discussions.

1 S. V. Bobashev, ZhETF Pis. Red. 11, 389 (1970) [JETP Lett. 11, 260 (1970)].
2 V. A. Ankudinov, S. V. Bobashev, and V. I. Perel', Zh. Eksp. Teor. Fiz. 60, 906 (1971) [Sov. Phys.-JETP 33, 490 (1971)].
3 Z. Z. Latypov and A. A. Shaporenko, ZhETF Pis. Red. 12, 177 (1970) [JETP Lett. 12, 123 (1970)].
4 N. H. Tolk, C. W. White, S. H. Dworetsky, and D. L. Simmes, Abstracts VII ICPEAC, Amsterdam, 1971, p. 584.
5 T. Andersen, A. Kirkegard, Nielsen K.J. Olson, Phys. Rev. Lett., 31, 12, 139, 1973.
6 N. H. Tolk, C. W. White, S. H. Neff, and W. Lichten, Phys. Rev. Lett., 31, 11, 671 (1973).
7 Yu. F. Bydin, V. A. Vol'pyas, and V. I. Ogurtsov, ZhETF Pis. Red. 18, 547 (1973) [JETP Lett. 18, 322 (1973)].
8 V. V. Afrosimov, Yu. S. Gordeev, V. M. Lavrov, and V. K. Nikulin, Abstracts VII ICPEAC, Amsterdam, 1971, p. 143.
9 O. M. Sorokin, S. P. Rozov, and V. A. Blank, Optikomekh. promyshlennost', No. 2, 29 (1968).
10 A. R. Striganov and N. S. Sventitskiĭ, Tablitsy spektral'nykh linii (Tables of Spectral Lines), Atomizdat (1966).
11 V. B. Matveev, S. V. Bobashev, and V. M. Dukel'skiĭ, Zh. Eksp. Teor. Fiz. 55, 781 (1968) [Sov. Phys.-JETP 28, 404 (1969)].
12 S. V. Bobashev, Phys. Lett., 31A, 4, 204 (1970).
13 A. N. Zaĭdel' and E. Ya. Shreĭder, Spektroskopiya vakuumnogo ul'trafioleta (Spectroscopy of Vacuum Ultraviolet), Nauka (1967), p. 326.
14 G. N. Ogurtsov, I. P. Flaks, and S. V. Avakyan, Zh. Tekh. Fiz. 40, 2124 (1970) [Sov. Phys.-Tech. Phys. 15, 1656 (1971).
15 A. K. Edwards and M. E. Rudd, Phys. Rev., 170, 140 (1968).
16 B. F. J. Luyken, Physika, 51, 445 (1971).
17 D. Hodges, H. Marants, and C. L. Tang, J. Opt. Soc. Am., 60, 192 (1970).
18 V. B. Matveev, S. V. Bobashev, and V. M. Dukel'skiĭ, Zh. Eksp. Teor. Fiz. 57, 1534 (1969) [Sov. Phys.-JETP 30, 829 (1970)].
19 S. Bobashev and I. Shmaenok, Abstracts VIII ICPEAC, Beograd, 1973, p. 221.
20 I. Yu. Krivskiĭ, M. V. Baletskaya, S. S. Pop, and I. P. Zapesochnyĭ, Ukr. Fiz. Zh. 17, 536 (1972).
21 A. Russek, Phys. Rev., 4A, 1918 (1971).

Translated by J. G. Adashko
181