INVESTIGATION OF THE TIME CORRELATION OF PHOTONS EMITTED IN Ne II *SPECTRAL LINES OF SEPARATE NEON ATOMS EXCITED BY ELECTRON IMPACT*

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Submitted to JETP editor September 7, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **46**, 1188-1196 (April, 1964)

It is shown that neon atoms excited by electron impact emit "simultaneously" on the average 2 ± 0.2 photons in the ~ 3000—4000 Å spectral range in the Ne II lines. A calculation based on the intensity of the spectral lines in Ne II cascade transitions shows that on the average an atom can emit "simultaneously" no more than 1.6—1.7 photons.

THE time correlation of the photons emitted when neon atoms are excited by electron impact was studied in many theoretical and experimental investigations[1-8].

In the present paper we report an investigation of the time correlation of photons emitted by neon atoms excited by electron impact. The neon was at a pressure 10^{-3}—10^{-4} mm Hg, at which the time between atomic collisions ($\sim 5 \times 10^{-4} - 5 \times 10^{-5}$ sec) greatly exceeds the lifetime of the atoms in the excited states ($\sim 10^{-8}$ sec for allowed transitions).

A schematic diagram of the apparatus is shown in Fig. 1. The electron beam E, measured by a Faraday cylinder F, excited the neon atoms[9]. The light emitted by the atoms was gathered by means of conical mirrors M with ~4π geometry onto two photomultipliers I and II, cooled with liquid nitrogen (FÉU-13, the spectral characteristics when cooled are shown in Fig. 2). To separate a definite spectral region, optical filters O were placed in front of the photomultipliers. The sensitivity of the recording system was sufficient to record individual photons. The pulses from the photomultipliers were fed to scaler circuits and to a coincidence circuit. The resolution time of the coincidence circuit could be varied by changing the duration of the pulses shaped by the multipliers.

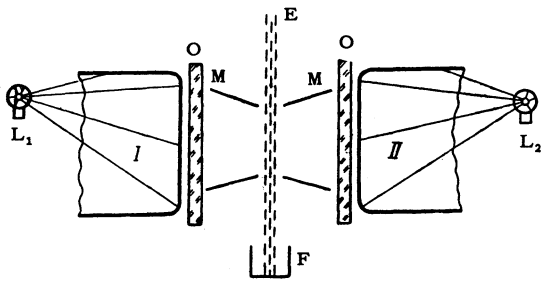

FIG. 1. Schematic diagram of installation (symbols defined in the text).

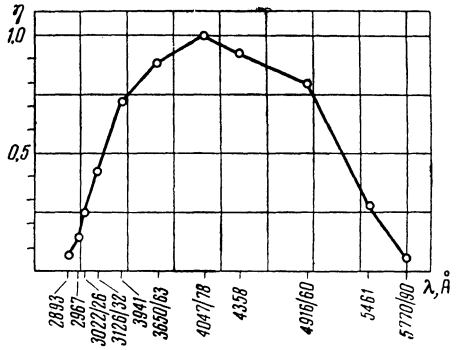

FIG. 2. Spectral sensitivity of photomultipliers.

To determine the resolution time of the coincidence circuit, each multiplier was additionally illuminated by a separate light source (monitor lamps L_1 and L_2).

If N_C is the number of random coincidences for a channel count N, then the resolution time of the coincidence circuit is determined from the formula

$$\tau_0 = N_c/2N^2, \quad N_1 = N_2 = N. \tag{1}$$

If the atoms excited by the electron impact radiate "simultaneously" more than one photon, then the number of coincidences (at the same count N) may turn out to be larger than the number of random coincidences N_C. If in this case we substitute in (1) this number of coincidences, the resultant value of τ will exceed the value τ_0 calculated from the random coincidences N_C. The time correlation of the photons was characterized by the difference $\Delta\tau(N) = \tau(N) - \tau_0(N)$. The resolution time of the coincidence circuit τ_0, measured from the number of true coincidences, was ~5 × 10^{-7} sec, which is several dozen times larger than the average lifetime of the atoms in the excited states for allowed transitions.

Table I

No. of line	Wavelength, Å	Degree of neon excitation	Transition	ΔJ	Intensity, relative units
1	3229.50	II	$3p'\,^2F^0 - 3d'\,^2G$	7/2—9/2	
2	3230.16	II	$3s'\,^2D - 3p'\,^2D^0$	5/2—5/2	3.12
3	3232.38	II	$3s'\,^2D - 3p'\,^2D^0$	3/2—3/2	
4	3297.74	II	$3s\,^4P - 3p\,^4D^0$	5/2—5/2	0.24
5	3309.78	II	$3s\,^2P - 3p\,^2P^0$	3/2—1/2	0.84
6	3319.75	II	$3s'\,^2D - 3p'\,^2P^0$	3/2—1/2	7.9
7	3320.29	II	$3p\,^4D^0 - 3d\,^4D$	7/2—5/2	
8	3323.75	II	$3s\,^2P - 3p\,^2P^0$	3/2—3/2	17.24
9	3334.87	II	$3s\,^4P - 3p\,^4D^0$	5/2—7/2	0.96
10	3344.43	II	$3s\,^4P - 3p\,^4D^0$	1/2—1/2	13.9
11	3345.49	II	$3s'\,^2D - 3p'\,^2P^0$	5/2—3/2	
12	3377.23	II	$3p\,^2P^0 - 4s\,^2P$	1/2—1/2	11.72
13	3378.28	II	$3s\,^2P - 3p\,^2P^0$	1/2—1/2	
14	3390.56	II	$3p\,^4D^0 - 3d\,^4D$	1/2—3/2	3.6
15	3392.78	II	$3s\,^2P - 3p\,^2P^0$	1/2—3/2	
16	3416.87	II	$3p\,^2D^0 - 3d\,^2D$	5/2—5/2	0.84
17	3417.71	II	$3p\,^2D^0 - 3d\,^2F$	5/2—7/2	
18	3418.007	I	$3s\,[1^1/_2] - 4p'\,[^1/_2]$	1—1	
19	3447.703	I	$3s\,[1^1/_2]^0 - 4p\,[1^1/_2]$	2—2	1.2
20	3453.10	II	$3p\,^2D^0 - 3d\,^2D$	3/2—3/2	1.56
21	3454.195	I	$3s\,[1^1/_2]^0 - 4p\,[^1/_2]$	1—0	
22	3464.339	I	$3s\,[1^1/_2]^0 - 4p\,[2^1/_2]$	2—2	0.48
23	3466.579	I	$3s'\,[^1/_2]^0 - 4p'\,[1^1/_2]$	0—1	
24	3472.571	I	$3s\,[1^1/_2]^0 - 4p\,[2^1/_2]$	2—3	0.12
25	3480.75	II	$3s''\,^2S - 3p''\,^2P^0$	1/2—3/2	4.31
26	3481.96	II	$3s\,^2P - 3p\,^2S^0$	3/2—1/2	
27	3501.215	I	$3s\,[1^1/_2]^0 - 4p\,[1^1/_2]$	1—1	0.12
28	3503.61	II	$3p\,^2S^0 - 3d\,^2P$	1/2—1/2	
29	3520.472	I	$3s'\,[^1/_2]^0 - 4p'\,[^1/_2]$	1—0	14.12
30	3542.28	II	$3p'\,^2D^0 - 3d'\,^2P$	5/2—3/2	0.12
31	3542.90	II	$3p\,^4S^0 - 3d\,^4P$	3/2—5/2	
32	3565.84	II	$3p\,^4S^0 - 3d\,^4P$	3/2—3/2	4.8
33	3568.53	II	$3s'\,^2D - 3p'\,^2F^0$	5/2—7/2	
34	3571.26	II	$3p\,^4S^0 - 3d\,^4F$	3/2—5/2	
35	3574.64	II	$3s'\,^2D - 3p'\,^2F^0$	3/2—5/2	3.35
36	3593.526	I	$3s'\,[^1/_2]^0 - 4p'\,[1^1/_2]$	1—2	0.96
37	3593.640	I	$3s'\,[^1/_2] - 4p'\,[^1/_2]$	1—1	
38	3594.18	II	$3p\,^4S^0 - 3d\,^4P$	3/2—1/2	
39	3632.75	II	$3p\,^4S^0 - 3d\,^2D$	3/2—3/2	0.36
40	3633.665	I	$3s'\,[^1/_2]^0 - 4p\,[^1/_2]$	1—0	
41	3643.89	II	$3s\,^2P - 3\,p\,^2D^0$	3/2—3/2	1.2
42	3644.86	II	$3p\,^2P^0 - 3d\,^2P$	1/2—3/2	
43	3664.112	II	$3s\,^4P - 3p\,^4P^0$	5/2—3/2	0.48
44	3694.197	II	$3s\,^4P - 3p\,^4P^0$	5/2—5/2	1.08
45	3709.64	II	$3s\,^4P - 3p\,^4P^0$	3/2—1/2	3.6
46	3713.084	II	$3s\,^2P - 3p\,^2D^0$	3/2—5/2	
47	3727.08	II	$3s\,^2P - 3p\,^2D^0$	1/2—3/2	1.2
48	3766.29	II	$3s\,^4P - 3p\,^4P^0$	3/2—5/2	0.36
49	3769.449	I	$3s'\,[^1/_2] - 3d'\,[2^1/_2]^0$	1—3	
50	3777.16	II	$3s\,^4P - 3p\,^4P^0$	1/2—3/2	0.24
51	5852.4878	I	$3s'\,[^1/_2]^0 - 3p'\,[^1/_2]$	1—0	21.8
52	5944.8342	I	$3s\,[1^1/_2]^0 - 3p'\,[1^1/_2]$	2—2	
53	6074.3377	I	$3s\,[1^1/_2]^0 - 3p\,[^1/_2]$	1—0	
54	6096.163	I	$3s\,[1^1/_2]^0 - 3p'\,[1^1/_2]$	1—2	
55	6143.062	I	$3s\,[1^1/_2]^0 - 3p\,[1^1/_2]$	2—2	
56	6163.5939	I	$3s'\,[^1/_2]^0 - 3p'\,[^1/_2]$	0—1	
57	6266.495	I	$3s'\,[^1/_2]^0 - 3p'\,[1^1/_2]$	0—1	
58	6334.4279	I	$3s\,[1^1/_2] - 3p\,[2^1/_2]$	2—2	
59	6382.9914	I	$3s\,[1^1/_2] - 3p\,[1^1/_2]$	1—1	
60	6402.246	I	$3s\,[1^1/_2] - 3p\,[2^1/_2]$	2—3	
61	6506.5279	I	$3s\,[1^1/_2]^0 - 3p\,[2^1/_2]$	1—2	
62	6532.8824	I	$3s'\,[^1/_2]^0 - 3p'\,[1^1/_2]$	0—1	

The excitation of neon by electron impact was investigated by Hanle[10] and Hermann[11]. The excitation of neon atoms at a gas pressure 10^{-3}—10^{-4} mm Hg by a beam of 150-eV electrons causes emission of a considerable number of spectral lines. The main contribution to the registered correlation could be made by those spectral lines which entered the region of the spectral sensitivity of the multipliers (2900—6000 Å, Fig. 2).

Table I summarizes the results of the measurements of the relative intensities of the spectral lines in the spectral region 3000—6500 Å, excited by electron impact under these conditions. In column 2 are given the wavelengths taken from the tables of the spectral lines of earlier investigations[12,13] (in the present experiment the wavelength could be measured accurate to $\gtrsim 1$ Å). In column 3 are given the corresponding transitions

from the work by Moore[14]. The neon spectrum in this region consists of two groups of the most intense lines. The first group of lines in the yellow-red part of the spectrum (5820—6600 Å) is the result of the transitions $3^m s - 3^n p$ (m, n—multiplicities of the terms) when neutral neon atoms (Ne I) are excited. The second group of lines is located in the ultraviolet part of the spectrum (3200—3700 Å) and consists, with the exception of one intense and several very weak lines of Ne I (transitions $4^f s - 4^k p$) of the lines due to the excitation of singly ionized neon atoms (Ne II).

Time correlation between the radiation of the lines of Ne I and Ne II has low probability. However, to verify the time correlation of these two groups of spectral lines, filters UFS-1 and BS-8 (Colored-glass Catalog) were placed in front of the photomultipliers to separate these two sections of the spectrum. The UFS-1 filter passed the ultraviolet group of spectral lines, and the BS-8 filter the yellow-red group.

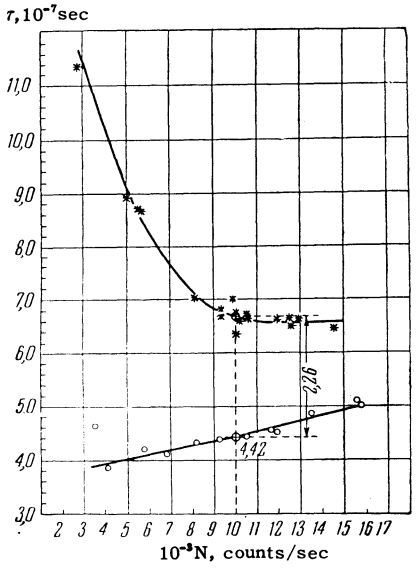

FIG. 3. Measurements of the correlation $\Delta\tau$ in neon: *—beam, o—monitor; UFS-1 filters in front of the photomultipliers.

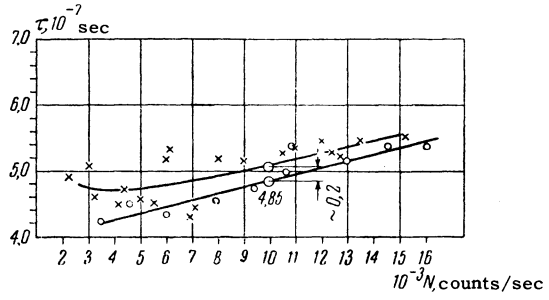

FIG. 4. Measurements of correlation $\Delta\tau$ in neon: x—beam, o—monitor; BS-8 filters in front of the photomultipliers.

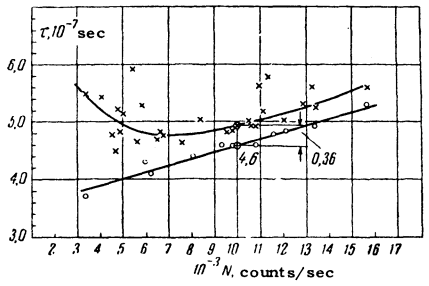

FIG. 5. Measurements of correlation $\Delta\tau$ in neon: x—beam, o—monitor; UFS-1 and BS-8 filters in front of the photomultipliers.

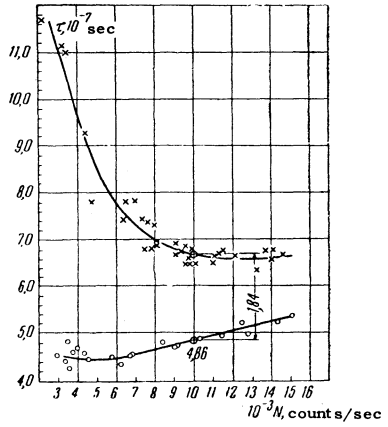

FIG. 6. Measurements of correlation $\Delta\tau$ in neon: x—beam, o—monitors; measurements without filters.

The results of the measurements of $\tau(N)$ and $\tau_0(N)$ with different combinations of these filters are shown in Figs. 3, 4, and 5. The geometry in these measurements did not differ from the geometry used during measurements of the correlation without the filters (Fig. 6). At a counting rate $N = 10^4$ pulses/sec, the values of $\Delta\tau$ obtained from the results shown in Figs. 3—6 ($p = 10^{-3}$ mm Hg; $W_e = 150$ eV) are listed in Table II.

The results show that the main contribution to the time correlation of the photons is made by the ultraviolet group of spectral lines (3200—3700 Å). As was already indicated, this group of spectral lines, excited by electrons with energy 150 eV, contains a considerable number of Ne II lines. The energy threshold of excitation of the ultraviolet group of spectral lines of Ne II is ~50 eV. By varying the energy of the exciting electrons it

Table II

Photomultiplier I	Photomultiplier II	$\Delta\tau$, 10^{-7} sec
No filter	No filter	1.8±0.2
UFS-1 filter	UFS-1 filter	2.3±0.2
BS-8 filter	BS-8 filter	0.2±0.2
UFS-1 filter	BS-8 filter	0.4±0.2

Table III

Line wave length, Å	Electron energy, eV						
	25	37,5	50	75	100	125	150
5852	7.2	3.88	4,92	3.47	5.15	4,48	4.2
3709/3713	0.28	0,785	0,9	2,56	7.12	7.74	9.35
3565/3568/3571/3574	0.58	1.115	2,75	2,83	9.52	11.16	13,7
3520,47	15.0	16.63	22.96	17.46	24.3	21.26	21.74
3390/3392	0,00	1.4	1.705	1.42	2.86	2.88	3.32
3377/3378	0.00	0.66	0.12	3.34	10.76	9.74	16.71
3344/3345	0.00	0.02	0.03	2,77	10.1	14.67	18.52
3319/3320/3323	0.58	0.00	0.00	6.54	20.34	27.3	35.13
3229/3230/3232	0.1	0,00	0,008	1.35	4.0	4.77	6.01

was possible to vary the ratio of the intensity of the Ne I and Ne II lines, and investigate the correlation as a function of this ratio. In Table III and on Fig. 7 are shown the ratios of the intensities of the strongest spectral lines at electron energies 25, 37.5, 50, 75, 100, 125, and 150 eV. The relative intensities of these spectral lines were obtained with the aid of a cooled photomultiplier installed in the output beam of an ISP-28 quartz spectrograph. The conditions for the excitation of the neon were identical with the conditions for the correlation measurements, and the geometry did not change the spectral composition of the radiation. The results of these measurements show that at electron energies 25, 37.5, and 50 eV there is excited in this part of the spectrum essentially

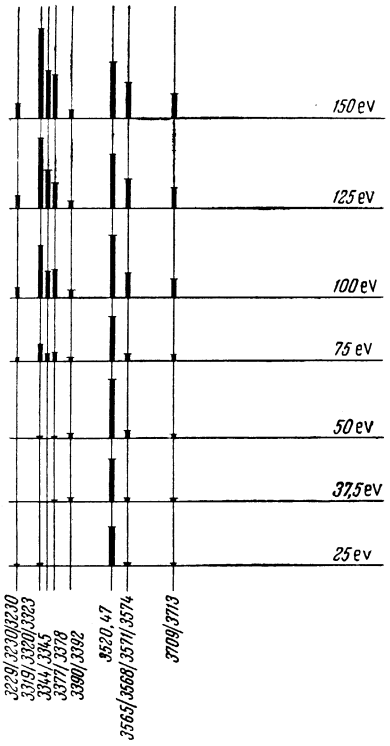

FIG. 7. Relative intensities of strongest spectral lines for different exciting-electron energies. The height of each line is proportional to the intensity.

one Ne I line—3520.472 Å (the transition $3s'[\frac{1}{2}]^0 - 4p'[\frac{1}{2}]$), and starting with an electron energy 50—75 eV, the Ne II lines appear.

Figures 8 and 9 ($p = 10^{-4}$ mm Hg) show the results of an investigation of the correlation [$\tau(N)$, $\tau_0(N)$, and $\Delta\tau(N)$] with UFS-1 filters at electron energies 25, 37.5, 50, 75, 100, 125, and 150 eV. The time correlation of the photons occurs at electron energies 50—75 eV, when the Ne II lines appear, and reaches "saturation" at electron energies 100, 125, and 150 eV.

Figure 10 ($p = 10^{-4}$ mm Hg) shows the dependence of $\Delta\tau$ on the ratio of some of the intensities of the Ne II lines to the sum of the intensities of the Ne I lines in this part of the spectrum, which shows additionally the absence of a temporal connection between these spectral transitions. Assuming spatially-isotropic radiation of the correlating photons, we can easily show that

$$\Delta\tau = (n-1)(\eta/4N)(\Omega/4\pi), \qquad (2)$$

where n—number of the photons isotropically emitted by the atom, η—efficiency of photon registration, N—number of pulse counts in the channel, and $\Omega/4\pi$—geometry of light gathering. The efficiency of registration of the photons from the ultraviolet group of spectral lines was ~1%. The obtained experimental value $\Delta\tau = 2 \times 10^{-7}$ sec (at $N = 10^4$ pulses/sec and a gathering geometry $\Omega/4\pi \sim 0.8$) yields in formula (2) a value $n_{exp} = 2$, which corresponds to the emission of two photons in each electron-atom collision.

Figure 11 shows the diagram of the energy levels and transitions of Ne II in the ultraviolet region of the spectrum, taken from Table I. The line thickness is proportional to the intensity of the corresponding transition. Wherever in Table I the intensity was determined for an aggregate of several transitions, this intensity is distributed in Fig. 11 between these transitions equally (owing to the lack of more complete data). It is seen from Fig. 11 that a certain number of transitions are realized in cascade form (for example, tran-

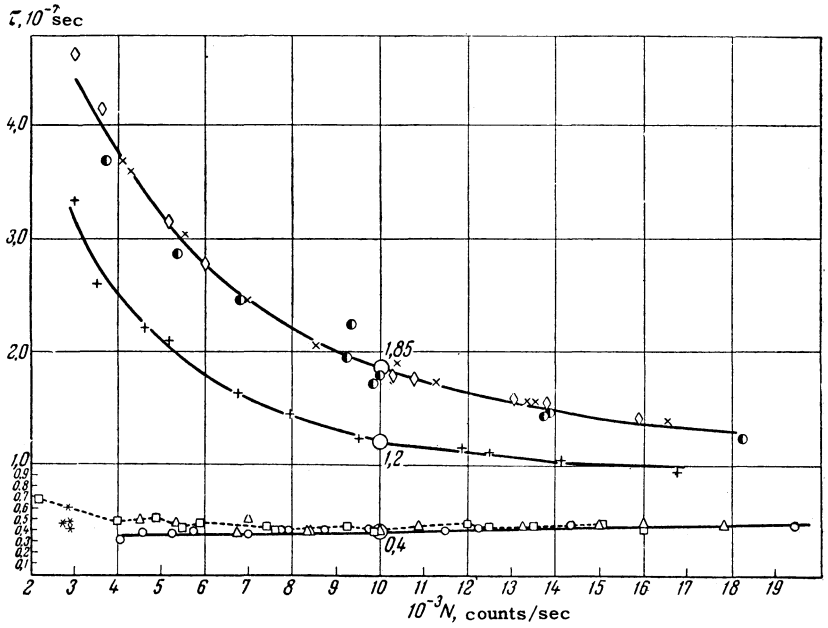

FIG. 8. Measurements of correlation $\Delta\tau$ in neon: o—monitors; *—beam, W_e = 25; △—beam, W_e = 37.5; □—beam, W_e = 50; +—beam, W_e = 75; ●—beam, W_e = 100; ◇—beam, W_e = 125; ×—beam, W_e = 150 (W_e in electron volts).

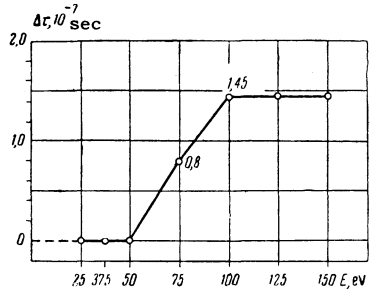

FIG. 9. Measurements of correlation $\Delta\tau$ in neon as a function of the electron beam energy.

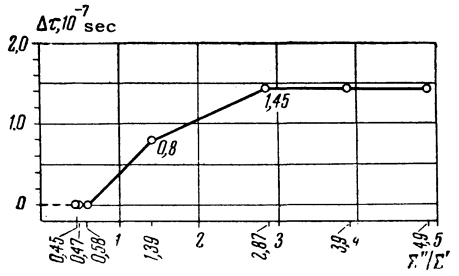

FIG. 10. Measurements of the correlation $\Delta\tau$ in neon; Σ''/Σ' – ratio of sum of intensities of the lines of Ne II to the sum of intensities of the Ne I lines in the ultraviolet part of the spectrum.

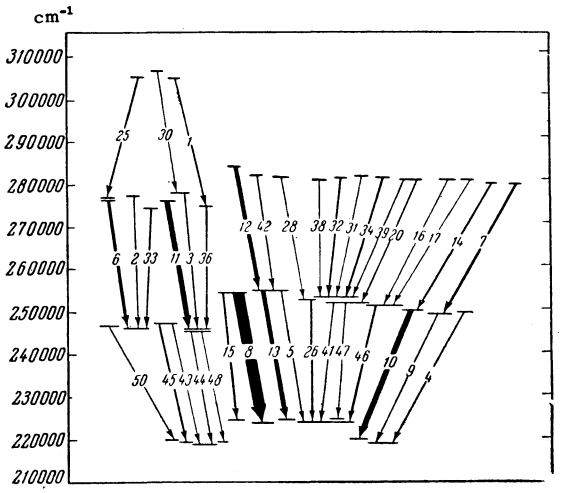

FIG. 11. Ne II terms and transitions. The figures correspond to the number of the spectral line in Table I. The thickness of the arrow is proportional to the line intensity.

sition 12 → transition 13; 16 + 17 → 47; 14 → 10; 7 → 9, etc.).

These cascade transitions can give "simultaneous" radiation of several photons (in a time $\sim 10^{-8}$ sec, "inside" the resolution time of the coincidence circuit). In addition to such a direct cascade transition, cascade transitions can be realized via radiation of intermediate transitions (not in the ultraviolet region) whenever the latter are not forbidden by the selection rules $\Delta J = 0$ and ± 1 (for example, the lower level of transition 25 → upper level of transition 26; lower level of transitions 38, 32, 31, 34, 39 → upper level of transition 10, etc.).

As already mentioned, the absence of data on the intensity of each individual transition for some closely lying transitions (for example, transitions 1, 2, 3; 6, 7; 10, 11; 14, 15, etc.) does not make it possible to calculate exactly the intensity of the cascade transitions. However, from the available data we can estimate the upper limit of the intensity of the cascade transitions by assuming such an intensity distribution among the closely-lying transitions which would be most favorable for the formation of the "cascade." Thus, for example,

in calculating the intensity of the 14 → 10 cascade it was assumed that the entire intensity of the transitions 14 + 15, which is equal to 3.6% of the total intensity of the ultraviolet group of lines (taken to be 100%), is concentrated in the transition 14, in order to obtain the largest intensity of the cascade transition, equal to 3.6% (double photons) of the total intensity of the ultraviolet group of lines. The remaining part of the intensity of the transitions 10 + 11 (equal to 13.9 − 3.6 = 10.3%) can participate in a "cascade" with other transitions. Thus, the lower level of the group of transitions 38; 32; 31; 34 and 39 (summary intensity 0.96% + 4.8% + 0.12% + 0.36% = 6.24%) can go over by means of an intermediate transition to the upper level of transition 10 and transition 4, which are not forbidden by the selection rules. With transition 4, this group of transitions gives cascade transitions with intensity 0.24% of the total intensity, while with transition 10—6%.

Thus, by successively taking into account all the possible cascade combinations in the transitions, we were able to obtain for transitions in double "cascades," an upper intensity limit equal to 16.9% (double photons), and with allowance for the possibility of intermediate transitions—equal to 16.9 + 15.4 = 32.3% (double photons). Consequently, only 60—70% (32.3% × 2) of the total number of photons can give a two-photon time correlation. Such a fraction of the correlating photons can yield for the number n in formula (2) a value 1.6—1.7, in contrast with the obtained experimental value $n_{exp} = 2 \pm 0.2$. Such an estimate of the intensity of the cascade transitions which make contributions to the time correlation of the photons, indicates a certain contradiction with experiment and necessitates more detailed investigations.

The author considers it his duty to thank A. R. Striganov for help in interpretation of the spectral lines, and also R. A. Vanetsian for useful advice and valuable remarks.

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