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TOTAL EXCITATION CROSS SECTIONS OF METASTABLE LEVELS OF INERT-GAS ATOMS IN ELECTRON IMPACT

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The total excitation cross section of a specific level (or levels) contains important information on the probability of the given process. Especially important information of this kind for practical purposes is that used in designing various plasma devices, laser media, etc.

In the present work, the results of determining the total absolute excitation cross sections of metastable levels of the atoms He($2^{3,1}S$), Ne($3^3P_{2,0}$), and Ar($4^3P_{2,0}$) in electron energies are given for the first time.

The total cross sections of inelastic electron—atom (molecular) collisions are usually measured by calculating the total number of electrons undergoing inleastic collision or by determining the integral flux of spectral radiation emitted by the excited atoms. In the case where the final state is long-lived (metastable), however, the possibility of direct recording of the excitation product appears. The problem then reduces to ensuring complete collection of the excited particles and determining their absolute number.

The method here proposed is based on measuring the differential (with respect to the drift angle excitation cross sections of metastable levels [1] and subsequently integrating them over all possible scattering angles of the excited particles. This method is, as it were, an analog of the traditional method of integrating differential electron-scattering cross sections; however, as shown below, it has whole series of advantages.

The experimental procedure consists in initial measurement of the differential (with respect to the drift angle) cross sections at different incident-electron energies. Beams of inert-gas atoms are formed by a gasdynamic source. Metastable atoms excited by the electron beam formed by a 127° cylindrical electrostatic monochromator are recorded by a channel electron multiplier (CEM) rotating in the beam-intersection plane. The angular resolution of the metastable-atom detector in this plane is $\Delta\theta_e = 0.1°$; in the perpendicular plane, it is $\Delta\Phi_e = 2°$. The electron energy is measured in limits from the excitation threshold to 500 eV; the halfwidth of their energy spread is 0.08-0.1 eV. The experimental scheme and its basic features were outlined in detail in [1].

The differential excitation cross sections of the given levels are measured as the dependence of the number of metastable atoms scattered at different angles (drift angles) at a fixed electron energy on the angular position of the detector. The electron energy E is varied with a step of 5-10 eV at small energies ($e < 100$ eV) and a step of 100 eV in the range E = 100-500 eV. The angular step of detector rotation is 0.1° in the vicinity of the singularities in the differential cross sections and 1° on the smooth sections of the curves.

Since there is no selection of metastable atoms in terms of the states, all the differential and total cross sections measured correspond to excitation of the atoms to two states: 2^3S and 2^1S in He, 3^3P_2, 3^3P_0 in Ne, and 4^3P_2, 4^3P_0 in Ar.*

The differential excitation cross sections of these levels measured in this way $\sigma(\theta, \Phi, E)$ are then subjected to the integration procedure

*Note that the population of these levels in the experiment is not only by direct excitation but also by cascade transitions.

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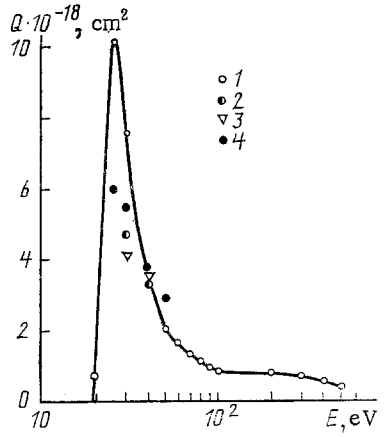

Fig. 1. Total excitation cross sections of the metastable $2^{3,1}S$ levels of the He atom according to the present work (1) and [6] (2), [7] (3), and [8] (4).

$$Q(E) = \int_{\theta_{min}}^{\theta_{max}} \int_{\Phi_{min}}^{\Phi_{max}} \sigma(\theta, \Phi, E) \sin\theta d\theta d\Phi. \quad (1)$$

Here Q(E) is the total (integral) excitation cross section; θ, Φ are the polar (drift angle) and azimuthal scattering angles of the metastable atom in the spherical coordinate system.

Since it is observed that, in the plane perpendicular to that of beam intersection, the metal atoms are enclosed within a narrow range of angles ($\sim 2°$) and are practically completely captured by the angular dimensions of the detector $\Delta\Phi_e$, the integral in Eq. (1) may be simplified, with sufficient accuracy

$$Q(E) = \Delta\Phi \int_{\theta_{min}}^{\theta_{max}} \sigma(\theta, E)\, d\theta, \quad (2)$$

since

$$\Delta\Phi_e = \Delta\Phi \cdot \sin\theta.$$

Integrals of the type in Eq. (2) are calculated by the Simpson (trapezium) method [2] using a specially written program on an EMG-666B microcomputer. The integration step is 0.1°; the accuracy in determining the integral in Eq. (2) is no worse than 5%. The set of integrals in Eq. (2) with different electron-energy values E allows the energy dependences of the relative excitation cross sections of the levels to be determined.

Since the problem of absolute calibration of secondary electron multipliers (and in particular CEM) remains unresolved as yet, because of the indeterminacy in finding absolute recording efficiencies of the neutral particles, indirect methods of calibrating the resulting cross sections are used.

To this end, the dependences Q(E) obtained are normalized to the theoretical cross sections obtained in [3-5]. The latter exist practically only for the helium atom; for other inert-gas atoms, theoretical information of this kind is very sparse. Thus, for the neon atom, there is only a calculation by the distorted-wave method [3] and for the argon atom, apart from the calculation of [3], there is only a calculation by many-body theory [4].

The absolute total excitation cross sections of the metastable levels $He(2^{3,1}S)$, $Ne(3^3P_{2,0})$, and $Ar(4^3P_{2,0})$ are shown in Figs. 1 and 2, in comparison with the data of other investigations by the direct-calibration method.

For the helium atom (Fig. 1), the dependence Q(E) is normalized to the theoretical cross section obtained in [5] by the distorted-wave method at E = 200 eV, i.e., in the region of best agreement of the theoretical and experimental data of [5]. Also in Fig. 1, the results in [6, 7] obtained by integrating the differential scattering cross sections of the electrons and the method of recording metastable atoms [8] are shown. As is evident from Fig. 1, the most satisfactory agreement with the data of direct measurements is observed in the electron-

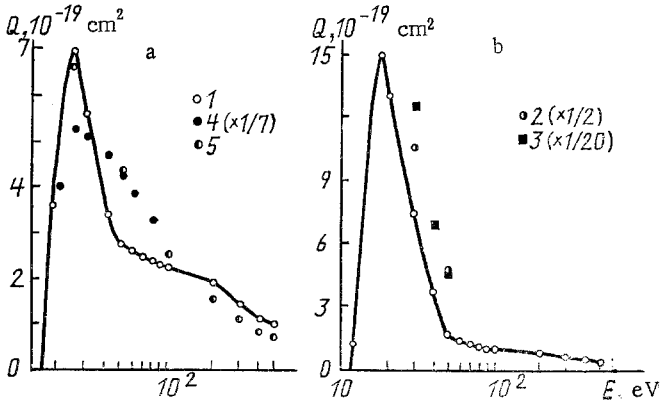

Fig. 2. Total excitation cross sections of metastable levels of the atoms Ne ($3^3P_{2,0}$) (a) and Ar ($4^3P_{2,0}$) (b). Data of the present work (1) and of [4] (2), [8] (3), [9, 10] (4), and [11] (5).

TABLE 1. Rate Constants of the Electronic Excitation of the Metastable States of Atoms (in units of cm^3/sec)

Temp., eV	Atom (level)		
	He ($2^{3,1}S$)	Ne ($3^3P_{2,0}$)	Ar ($4^3P_{2,0}$)
0,5	$9{,}80\cdot10^{-20}$	$1{,}37\cdot10^{-24}$	$1{,}29\cdot10^{-20}$
1,0	$3{,}6\cdot10^{-18}$	$2{,}45\cdot10^{-17}$	$2{,}57\cdot10^{-15}$
1,5	$3{,}92\cdot10^{-15}$	$6{,}32\cdot10^{-15}$	$1{,}63\cdot10^{-13}$
2,0	$1{,}39\cdot10^{-13}$	$1{,}00\cdot10^{-13}$	$1{,}39\cdot10^{-12}$
2,5	$1{,}19\cdot10^{-12}$	$5{,}23\cdot10^{-13}$	$4{,}50\cdot10^{-12}$
3,0	$4{,}89\cdot10^{-12}$	$1{,}57\cdot10^{-12}$	$1{,}02\cdot10^{-11}$
3,5	$1{,}33\cdot10^{-11}$	$3{,}41\cdot10^{-12}$	$1{,}82\cdot10^{-11}$
4,0	$2{,}79\cdot10^{-11}$	$6{,}08\cdot10^{-12}$	$2{,}78\cdot10^{-11}$
5,0	$7{,}67\cdot10^{-11}$	$1{,}35\cdot10^{-11}$	$4{,}96\cdot10^{-11}$
6,0	$1{,}47\cdot10^{-10}$	$2{,}26\cdot10^{-11}$	$7{,}15\cdot10^{-11}$
8,0	$3{,}15\cdot10^{-10}$	$4{,}20\cdot10^{-11}$	$1{,}09\cdot10^{-10}$
10	$4{,}78\cdot10^{-10}$	$5{,}94\cdot10^{-11}$	$1{,}35\cdot10^{-10}$
15	$7{,}55\cdot10^{-10}$	$8{,}97\cdot10^{-11}$	$1{,}67\cdot10^{-10}$
20	$8{,}81\cdot10^{-10}$	$1{,}07\cdot10^{-10}$	$1{,}72\cdot10^{-10}$
25	$9{,}26\cdot10^{-10}$	$1{,}18\cdot10^{-10}$	$1{,}69\cdot10^{-10}$

energy range E = 40-50 eV. In the region of the maximum of the energy dependence, the discrepancy increases by a factor of 1.7 in comparison with the data of [8] and by a factor of 2-2.5 in comparison with those of [6, 7]. This may evidently be explained by the normalization error, associated both with the approximation of the theoretical calculation and with inaccuracy in calculating the integrals in Eq. (2). In addition, errors are possible in determining the absolute magnitudes of the cross sections in [6-8] due to incomplete collection of the metastable atoms and the error in determining the absolute recording efficiency [8], as well as the unavoidable inaccuracy in integrating the differential cross sections at electron-scattering angles close to 0° and 180° [6, 7].

Note, in passing, that the method proposed here is free from many of these deficiencies, since the drift angles of the metastable atoms are enclosed in a relatively narrow range, bounded by the drift angles at which the differential cross section takes a zero value [1], which eliminates the need for interpolating the experimental data as in the case of electron recording [6, 7].

Agreement with the absolute values of the total excitation cross sections of the metastable levels of Ne and Ar atoms (Fig. 2) with the data of direct measurements [4, 8-10] is considerably worse than in the case of He atoms. Several possible reasons for this may be

cited. First, the experimental curves are normalized to the theoretical curves* at low energies E (60 and 80 eV for Ne and Ar, respectively), which is associated with the lack of theoretical data at high energies. This leads to decrease in calibration accuracy [5]. Second, the range of drift angles of the Ne and Ar atoms is considerably narrower than for the He atom, which reduces the accuracy of calculation of the integrals in Eq. (2) because of the lower relative angular resolution of the detector. Third, the data of [4, 8-11] is not free from the deficiencies of the direct methods discussed above for the case of the He atom. The set of these factors evidently leads to the considerable discrepancy between the cross-section values obtained in the present work and in other (except [11], perhaps). The unsatisfactory agreement of the values and general trend of the cross sections measured in [8-11] is also noteworthy.

The lack of theoretical data for Kr and Xe atoms does not permit the normalization procedure to be performed on the experimental excitation cross sections of metastable $5^3P_{2,0}$ and $6^3P_{2,0}$ levels; however, the general trend of the energy dependences overall is similar to that observed in the case of Ne and Ar atoms.

The total excitation cross sections of the metastable levels of inert-gas atoms determined here are not only of intrinsic interest but are also important from the viewpoint of determining the rates of the reactions occurring. In fact, according to the definition, the rate constant of the reaction is expressed as follows [12]

$$k = \langle Q \cdot v \rangle = \left(\frac{2}{m}\right)^{1/2} \int_{E_1}^{E_2} Q(E) \cdot E^{1/2} \cdot f(E)\, dE, \tag{3}$$

where Q(E) is the total reaction cross section; m is the electron mass; f(E) is the energy distribution function of the electrons.

Table 1 gives the temperature dependence of the rate constants of the reaction of electron excitation of metastable levels of He, Ne, and Ar atoms. The dependences are calculated by a specially developed program on a microcomputer.

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*Note that the calculation of [3] was for the transition $1^1S_0 \rightarrow 3^3P_{2,1,0}$. Therefore, a factor of 2/3 is introduced in the theoretical cross-section values for the neon atom here, so as to take account only of the excitation of metastable $^3P_{2,0}$ levels.