An experimental study of single electron loss cross sections for hydrogen atoms and negative hydrogen ions in various media

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Cross sections $\sigma_{i,i+1}$ for the loss of an electron by fast hydrogen atoms and negative ions in H_2, He, N_2, Ne, Ar, and Xe are measured at energies $E = 0.3$ and 0.7 MeV. We have analyzed the experimental and theoretical data on these cross sections in the range $E = 0.03$–5 MeV. It is found that in media with atomic numbers $Z_t > v/2$, where v is the ion velocity in atomic units, the $\sigma_{i,i+1}$ increase with Z_t on the average as $Z_t^{0.5-0.8}$, and that on changing from inert gases to alkali metal vapors they increase abruptly by a factor of 1.5. To fit this dependence, a semiempirical formula is suggested, based on the classical treatment of ionization in the screened field of the target atomic nuclei. For light media, $Z_t \lesssim v/2$, the cross sections $\sigma_{i,i+1}$ increase with Z_t monotonically as $Z_t^{1.5}$ and are consistent with Born approximation calculations.

1. INTRODUCTION

Previous[1,2] experimental studies of the cross sections $\sigma_{i,i+1}$ for the loss of an electron by fast helium, nitrogen, and neon ions have shown that for ion velocities of $v \approx 4$–5 au, the variation of the cross section with the target atomic number Z_t is markedly nonmonotonic. In neon, where the screening of the Coulomb field of the target atomic nucleus is the greatest, the $\sigma_{i,i+1}$'s are less than in nitrogen and argon. A nonmonotonic variation of $\sigma_{i,i+1}$ with Z_t is also seen in experimental data for hydrogen atoms and negative hydrogen ions[3,4] and for metastable helium atoms.[5,6] To examine more closely the $\sigma_{i,i+1}(Z_t)$ dependence, the present authors have measured these cross sections for 0.3 and 0.7 MeV hydrogen particles in He, Ne, Ar, and Xe, and in molecular gases H_2 and N_2. The $\sigma_{-1,0}$ on Ne and Xe at $E = 0.3$ MeV were obtained for the first time here. These data, complemented by an analysis of available experimental data in the range $E = 0.03$–5 MeV (Refs. 3–5, 7–11), and combined with the Born (PWBA)[12–16] and the free-collision (FCA)[17–19] results, enabled a simple semi-empirical formula to be proposed for the nonmonotonic $\sigma_{i,i+1}(Z_t)$ dependence by applying the Bohr picture[20] to the ionization in the screened field of target nuclei. The values of ion and electron velocities will be given below in atomic units of $v_0 = 2.19 \cdot 10^8$ cm/s.

2. EXPERIMENTAL PROCEDURE

Cross sections for the loss and capture of an electron by hydrogen ions and atoms were determined with the experimental setup which has been described more than once in our papers.[21,22] After acceleration in a 72-cm cyclotron, molecular H_2^+ ions, with energies $E = 0.30 \pm 0.01$ and 0.70 ± 0.02 MeV/nucleon, passed through a thin, flowing, nitrogen target 10^{15} atoms/cm^2 thick. The H^+ and H^- ion beams resulting from charge exchange in the target were separated out by a magnetic analyzer and directed into a collision chamber, a cylinder 24 cm long provided with entrance and exit channels 0.5 cm high, 0.1–0.2 cm wide, and 2.6 cm long. The thickness of the (flowing) target in the chamber was determined to within $\sim 10\%$ by ionization manometers, calibrated with a compression manometer for different gases. In working with atomic H^0 beams, the charged components H^+ and H^- were deflected by an electrostatic analyzer 12 cm long, placed 80 cm from the collision chamber entrance.

The particle charge composition after passage through the collision chamber was determined by a measuring system consisting of an analyzing magnet and a set of proportional counters ~ 40 cm from the exit channel. The strength of the analyzing magnet field was taken such that particles of only one particular charge, $i = -1, 0$, or 1, reached the middle of each counter. From the particle charge composition obtained, the electron loss and capture cross sections for hydrogen particles were found by the method described in Ref. 21. The measured cross sections σ_{10} for electron capture by protons were presented in Ref. 23.

The measured cross sections are those for the electron loss events with particles scattered through angles $\theta < \theta_m = \Delta/L \simeq 0.005$ radian (where Δ is the exit channel width and L the collision chamber length). The portion of the cross section corresponding to greater ion scattering angles does not exceed σ_p, where $\sigma_p = \pi p^2(\theta_m)$ is the total scattering cross section through angles $\theta > \theta_m$ ($p(\theta)$ being the impact parameter for ion scattering through an angle θ). The value of σ_p increases with Z_t as Z_t^2 for $E = 0.3$ MeV, $\sigma_p \sim 10^{-20}$ cm^2 for $Z_t = 2$ and $\sigma_p \sim 10^{-17}$ cm^2 for $Z_t = 54$.[21] In all cases considered, the ratio $\sigma_p/\sigma_{i,i+1}$ does not exceed $2 \cdot 10^{-3}$, which is by no means beyond the error band. Control experiments with a 2-mm-wide moving slit in front of the counter entrance have shown that the limits of the spatial–angular distribution due to particles scattered in the last third of the chamber path before hitting the edges of the counter are accounted for by at most 1–2% of all particles.

The error in the $\sigma_{i,i+1}$'s thus obtained is largely composed of the collision-chamber gas-layer thickness error ($\sim 10\%$) plus the run-to-run spread, and is on the average 10–15% of $\sigma_{0,1}$ for electron loss by hydrogen atoms, and 20% of $\sigma_{-1,0}$ for electron detachment in negative hydrogen

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TABLE I. Present electron-loss cross sections $\sigma_{0,1}$ and $\sigma_{-1,0}$ for H^0 atoms and negative H^- ions (in 10^{-16} cm²/atom).

Target	$E=0.30\pm0.01$ MeV		$E=0.70\pm0.02$ MeV
	$\sigma_{0,1}$	$\sigma_{-1,0}$	$\sigma_{0,1}$
H_2	0.30±0.10	1.0 ± 0.2	-
He	0.40±0.06	-	0.20 ± 0.02
N_2	1.6±0.2	3.9 ± 0.6	0.9 ± 0.1
Ne	1.1±0.2	2.4 ± 0.5	0.8 ± 0.1
Ar	2.7±0.3	1.9 ± 0.3	1.9 ± 0.2
Xe	4.2±0.4	12.5 ± 2.0	-

ions. The cross sections $\sigma_{-1,0}$ on neon and xenon at $E=0.3$ MeV were obtained for the first time in the present work. The $\sigma_{i,i+1}$'s in other media agree to within 10–20% with the results of Refs. 3–5 and 8–10.

3. DISCUSSION

The present $\sigma_{i,i+1}$ values for hydrogen particle energies of $E=0.3$ and 0.7 MeV are given in Table I and Figs. 1 and 2 as functions of Z_t. Also shown in the figures are the corresponding values for $E=0.03$ MeV and $E=5$ MeV taken from Refs. 3–5 and 7–11. By and large, it can be seen from the figures that with increasing Z_t the $\sigma_{i,i+1}$'s increase as Z_t^α. As the energy E is increased from 0.03 to 0.7 MeV, the exponent α increases from 0.5 to 0.8 and is constant throughout the entire range of Z_t. For $E=5$ MeV, the variation of $\sigma_{i,i+1}$ with Z_t was found to differ in light and heavy media: while $\alpha\approx1.5$ for $Z_t\lesssim7$, in the range $Z_t>7$ the exponent is $\alpha\simeq0.8$, i.e., about the same as that for the lower energy value.

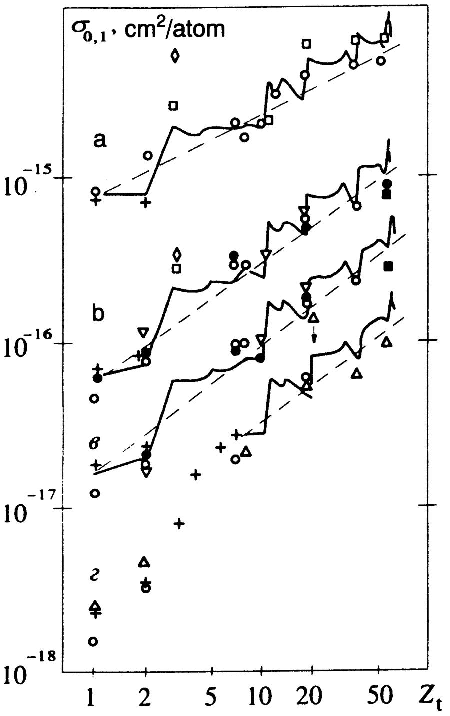

FIG. 1. Variation of cross sections $\sigma_{0,1}$ with Z_t: a) $E=0.03$ MeV (magnified 10 times), b) $E=0.3$ MeV (magnified 2 times), c) $E=0.7$, and d) $E=5$ MeV. Experiment: (●), the present work; (◇), Ref. 7; (○), Ref. 3; (□), Ref. 4; (■), Ref. 5; (▽), Ref. 10; and (△), Ref. 11. Calculations: (+), PWBA for $Z_t=1$ and 2 (Ref. 12), $Z_t=3,4$, and 6 (Ref. 14), and $Z_t=7$ (Ref. 13); dashed straight line, Eq. (1); solid line, Eq. (2). In Eqs. (1) and (2) $\alpha=1/2$ for $E=0.03$ MeV, $\alpha=2/3$ for $E=0.3$ MeV, and $\alpha=3/4$ for $E=0.7$ and 5 MeV.

However, systematic deviations are observed against the general background of cross section values that increase with Z_t. On going from inert gases to alkali metal vapors (i.e., on changing Z_t by unity, from 2 to 3, from 10 to 11, etc.), the cross sections $\sigma_{i,i+1}$ increase on the average by a factor of 1.5. In the range of intermediate Z_t (Z_t=3–10 and 11–18), the $\sigma_{i,i+1}$'s change much more gradually. Thus, the dependence $\sigma_{i,i+1}(Z_t)$ becomes step-like.

In accordance with the well-known Bohr criterion,[20] in cross section calculations for inelastic ion–atomic nuclei collisions the Born approximation is valid for light ions with atomic number $Z\lesssim Z_t$ provided $\kappa_t\leqslant1$ (where $\kappa_t=2Z_t/v$, v being the ion velocity in atomic units), that is, in the region of fast collisions for particle velocities $v\gtrsim2Z_t$. The analysis in Ref. 12 shows that the range of applicability of the Born approximation in the case of ions colliding with neutral atoms is about the same as for the ionization of particles colliding with atomic nuclei.

Thus, the Born approximation may be used for targets with $Z_t\lesssim v/2$, i.e., in the range $E=0.3$–0.7 MeV ($v\approx4$–5) for hydrogen particles in hydrogen and helium, and at $E=5$ MeV ($v\approx14$), for a wider range of target media, Z_t=1–7. The cross sections $\sigma_{0,1}$, in the nonrelativistic Born approximation (PWBA), have been calculated for hydrogen atoms on hydrogen and helium atoms,[12] lithium, beryllium, and carbon atoms[14] and on nitrogen atoms.[13] The cross sections $\sigma_{0,1}$ computed for the helium target in the range $E=0.3$–5 MeV agree to within 10–15% with the experimental values. At the same time, the $\sigma_{0,1}$ predicted for the hydrogen target at $E=0.3$–5 MeV (Ref. 12) and for the nitrogen target at $E=5$ MeV (Ref. 13) are on the average 30% higher than the experimental ones (Fig. 1). Such a discrepancy between the computed cross sections and the target-atom-related measured ones is presumably due to the fact that first, the calculations are for monatomic H and N gases, whereas the experiment was performed on molecular H_2 and N_2 targets; and, second, that using a coefficient 1/2 for changing from molecular to monatomic targets is a rather crude approximation.[19,24] According to Ref. 19, the value of this coefficient becomes 1/2 only for $E\geqslant10$ MeV. PWBA $\sigma_{-1,0}$'s for the detachment of an electron were calculated for H^- ions incident upon hydrogen and helium atoms[15,16] and upon lithium, beryllium, and carbon[14] atoms. The predictions for hydrogen and helium targets agree well with the measured values of $\sigma_{-1,0}$ (Fig. 2).

Depending on the medium, for $E=5$ MeV, because of the strong screening of the Coulomb field of low-Z_t atomic nuclei, in changing from $Z_t=1$ to $Z_t=2$ the $\sigma_{0,1}$ increases by a factor 1.5, and $\sigma_{-1,0}$, by a factor of only 1.1. As Z_t is further increased, the variation of $\sigma_{i,i+1}$ with Z_t becomes stronger and is close to $Z_t^{1.5}$. From the calculations, in the range $v>5$ the cross sections $\sigma_{i,i+1}$ in light media decrease

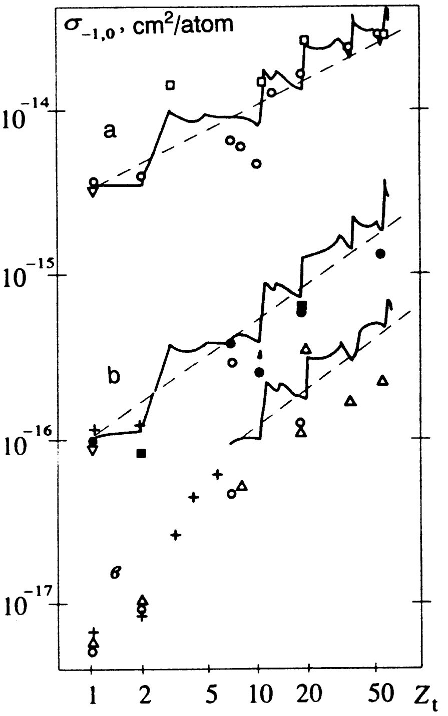

FIG. 2. Variation of cross sections $\sigma_{-1,0}$ with Z_t: a) $E=0.03$ MeV (magnified 10 times), b) $E=0.3$ MeV, and c) $E=5$ MeV. Experiment: (●), the present work; (○), Ref. 3; (□), Ref. 4; (■), Ref. 8; (▽), Ref. 9; and (△), Ref. 11. Calculations: (+) PWBA for $Z_t=1$ and 2 (Refs. 14 and 15), $Z_t=3,4$, and 6 (Ref. 14); dashed line, Eq. (1), solid line, Eq. (2). In Eqs. (1) and (2), $\alpha=1/2$ for $E=0.03$ MeV, $\alpha=2/3$ for $E=0.3$ MeV, and $\alpha=3/4$ for $E=5$ MeV.

rapidly with v as v^{-2} (Ref. 12). In the heavier media, where the PWBA overestimates the cross section, the experimental variation of $\sigma_{i,i+1}$ with v and Z_t is weaker.

Because the PWBA holds only for light targets with $Z_t \lesssim v/2$, and because ionization cross-sections for ion–atom collisions in heavy targets are extremely tedious to calculate quantum mechanically, FCA (free collision approximation) calculations were carried out in Refs. 17–19. The existing FCA models are variations of the semiclassical ionization model due to Bohr[23] and can be used to describe the loss of a weakly bound electron in targets with $Z_t > v/2$ (Ref. 12).

FCA electron-loss $\sigma_{0,1}$ calculations have been carried out for hydrogen atoms in hydrogen and helium[17] and in all inert gases.[18,19] Moreover, similar $\sigma_{i,i+1}$ calculations have been carried out for molecular H_2, N_2, and O_2 targets.[19] The results agree with the experimental $\sigma_{0,1}$'s to within 30% for molecular targets and to within 20% for the inert gases. Cross sections $\sigma_{-1,0}$ for electron detachment from H^- ions in hydrogen and helium targets[17] agree with measurements to within 30%. Similar $\sigma_{-1,0}$ calculations of Ref. 18 employ two models of the H^- ion electron shell. According to one, both electrons are equivalent and weakly bound to the nucleus; in the second, only one electron, with binding energy $I_{-1} \approx 0.8$ eV, is weakly bound, whereas the binding energy of the other is close to that in the hydrogen atom. The second model is in better agreement with experiment. The predicted $\sigma_{-1,0}$ are, on the average, 20–30% higher than those measured.[18]

To fit the target-to-target variation of the experimental electron-loss cross sections $\sigma_{i,i+1}$ for hydrogen atoms and negative hydrogen ions on molecular and inert gases, the following modification of the familiar Bohr formula[20] is suggested:

$$\sigma_{i,i+1}=N_i\ \pi a_0^2\,\frac{Z_t^\alpha}{v u_i}, \qquad (1)$$

where $u_i=\sqrt{I_i/I_0}$ is the average orbital velocity of the detached electrons, N_i and I_i are the number and binding energy of the equivalent ion-shell electrons, $I_0=13.6$ eV, and $a_0=5.29\cdot 10^{-9}$ cm. For the hydrogen atom, $N_i=1$. The known experimental values of $\sigma_{0,1}$, setting $\alpha=1/2$ for E = 0.03 MeV, $\alpha=2/3$ for $E=0.3$ MeV, and $\alpha=3/4$ for $E=0.7$ MeV, are fitted by Eq. (1) to within 20%. For the calculation of the cross sections $\sigma_{-1,0}$ for the detachment of an electron from negative H^- ions, it was assumed, according to Ref. 18, that $N_i=1$ and $I_i=0.8$ eV (Ref. 25). The discrepancy between the $\sigma_{-1,0}$ found from Eq. (1) and the measured values is in the 30–40% range (Fig. 2).

The abrupt increase in hydrogen particle $\sigma_{i,i+1}$'s for alkali vapors over those for inert gases is due to the smaller screening effect of the outer electrons on the Coulomb field of alkali atomic nuclei. In order to establish a quantitative relationship between the increase in $\sigma_{i,i+1}$ and the corresponding decrease in the orbital velocities of the outer target-atom electrons, consider the ratio

$$\eta(Z_t,Z_t^{+1})+\frac{\sigma(Z_t+1)}{\sigma(Z_t)}\Big/\frac{u(Z_t)}{u(Z_t+1)},$$

where $\sigma(Z_t)$ is the electron-loss cross section for a target atomic number Z_t, and $u(Z_t)=\sqrt{I(Z_t)/I_0}$ is the average orbital velocity of an outer electron in the same target. Target-atom ionization potentials $I(Z_t)$ are taken from Ref. 26. Analysis of the results shows that the cross section ratios $\sigma(Z_t+1)/\sigma(Z_t)$ are within 30–40% of the $u(Z_t)/u(Z_t+1)$ ratios. On the whole, at $E=0.03$ MeV, for which most of the experimental data have been obtained, for $\sigma_{0,1}$'s in five target pairs (He/Li, Ne/Na, Ar/K, Kr/Cs and Xe/Rb) we obtain $\eta=0.9\pm0.3$, and for $\sigma_{-1,0}$'s in four pairs (He/Li, Ne/Na, Ar/K, and Xe/Rb), $\eta=1.1\pm0.4$. In determining the ratio $\eta(2,3)$ at $E=0.03$ MeV for the He/Li pair, the $\sigma_{0,1}$ values of Ref. 4 were assumed. The value of this cross section for Li as given in Ref. 7 is 2.5 times that of Ref. 4 and is probably an overestimate. At the same time, at $E=0.3$ MeV the $\sigma_{0,1}$'s obtained in Refs. 7 and 4 agree to within 20%.

For the maximum hydrogen particle energy, $E=5$ MeV, data on $\sigma_{i,i+1}$ are only available for the Ar/K pair[11] (for potassium, the cross sections were actually measured at a somewhat higher energy, $E=5.14$ MeV). Upon changing from argon to potassium, $\sigma_{0,1}$ and $\sigma_{-1,0}$ increase by a factor of 2.5 and 3.0, respectively, which is 1.5 times the corresponding orbital-velocity increase, $u(\mathrm{Ar})/u(\mathrm{K}) \approx 1.9$. In the 0.03–0.7 MeV range, the decrease in $\sigma_{i,i+1}$ in neon, as compared to nitrogen, averages 1.3 ± 0.2, which agrees with the corresponding increase by a factor of 1.2 in the outer orbital velocities in nitrogen compared to neon atoms.

Based on the electron-loss cross section data for hydrogen particles in alkali vapors, Eq. (1) was multiplied by a factor $1/u(Z_t)$, to become symmetric with respect to the fast particles and the target atoms,

$$\sigma_{i,i+1}=N_i \pi a_0^2 \frac{Z_t^{\alpha}}{v u_i u(Z_t)} . \tag{2}$$

Equations (1) and (2) are valid for fast particle velocities $v \gtrsim (1-2)u_i$ in targets with $Z_t > v/2$, where the cross sections $\sigma_{i,i+1}$ slowly decrease with increasing v as v^{-1}.

In the energy range considered ($E=0.03$–5 MeV), the departure of the measured $\sigma_{0,1}$'s from those calculated with Eq. (2) does not generally exceed 20%. For $E=5$ MeV, consistent with the applicability of Eq. (2), calculations yield $\sigma_{0,1}$ values close to those measured for $Z_t>7$. In the lighter targets, with $Z_t \lesssim 7$, the correct $\sigma_{0,1}(Z_t)$ dependence is given by PWBA calculations (Fig. 1). For the $\sigma_{-1,0}$ in the energy range $E=$ 0.03–0.3 MeV, Eq. (2) agrees with experiment to within 30–40%. However, for $E=5$ MeV, the computed $\sigma_{-1,0}$ (for $Z_t>7$) are about twice as large as those measured in Ref. 11 (Fig. 2). Analysis of the experimental $\sigma_{i,i+1}$ values of Refs. 1–6 shows that Eq. (2) also fits, to within 30–40%, the $\sigma_{i,i+1}(Z_t)$ dependences for various light-element ions heavier than hydrogen.

4. CONCLUSION

As a result of this study of the experimental and theoretical electron-loss cross section data for hydrogen particles, it has been shown that for targets with $Z_t > v/2$, the $\sigma_{i,i+1}$ vary slowly with v and Z_t (approximately as $v^{-1}Z_t^{0.5-0.8}$). On going from inert gases to alkali metal vapors, the $\sigma_{i,i+1}$ increase abruptly by a factor of 1.5. The reason for the cross section increasing this sharply with unit change in Z_t is presumably the relatively weaker screening of the Coulomb field of alkali nuclei as compared with inert gases. Based on a classical approach to ionization in a strongly screened atomic field, a simple semi-empirical formula has been developed, yielding the correct variation of $\sigma_{i,i+1}$ with Z_t for various ions of light elements.

For lighter targets with $Z_t \lesssim v/2$, where the experimental $\sigma_{i,i+1}$'s are in agreement with PWBA calculations, the cross sections $\sigma_{i,i+1}$ decrease much more rapidly with particle velocity v (v^{-2} in the high-velocity limit), and increase with Z_t monotonically as $Z_t^{1.5}$.

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[1] I. S. Dmitriev, Yu. A. Tashaev, V. S. Nikolaev *et al.*, Zh. Eksp. Teor. Fiz. **73**, 1684 (1977) [Sov. Phys. JETP **46**, 884 (1977)].

[2] I. S. Dmitriev, N. F. Vorob'ev, Zh. M. Konovalova et al., Zh. Eksp. Teor. Fiz. **84**, 1987 (1983) [Sov. Phys. JETP **57**, 1157 (1983)].

[3] H. Tawara and A. Russek, Rev. Mod. Phys. **45**, 178 (1973).

[4] C. J. Anderson, R. J. Girnius, A. M. Howald, and L. W. Anderson, Phys. Rev. **A22**, 822 (1980).

[5] E. Horsdal-Pedersen, L. Lassen, and J. V. Mikkelsen, J. Phys. **B10**, 669 (1977).

[6] E. Horsdal-Pedersen, J. Heinemeier, L. Lassen, and J. V. Mikkelsen, J. Phys. **B13**, 1167 (1980).

[7] B. A. Djachkov, Sov. At. Energy **27**, 958 (1969).

[8] J. Heinemeier, P. Hvelplund, and F. R. Simpson, J. Phys. **B9**, 2669 (1976).

[9] J. Geddes, J. Hill, M. Shah *et al.*, J. Phys. **B13**, 319 (1980).

[10] D. P. Almeida, N. V. de Castro-Faria, F. L. Freie Jr. *et al.*, Phys. Rev. **A36**, 16 (1987).

[11] V. I. Radchenko, Zh. Eksp. Teor. Fiz. **105**, 834 (1994) [Sov. Phys. JETP **78**, 445 (1994)].

[12] I. S. Dmitriev, Ya. M. Zhileıkin, V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **49**, 500 (1965) [Sov. Phys. JETP **22**, 352 (1966)].

[13] V. S. Senashenko, V. S. Nikolaev, V. Yu. Shafer, and I. S. Dmitriev, Vestnik MGU, Ser. Phys. Astron. No. 2, 136 (1970).

[14] A. K. Kaminskiĭ, R. A. Meshcherov, and V. S. Nikolaev, Trudy Radiotekhn. Inst., No. 10, 330 (1973).

[15] G. H. Gillespie, Phys. Rev. **A15**, 563 (1977).

[16] Y. T. Lee and J. C. Y. Chen, Phys. Rev. **A19**, 526 (1979).

[17] I. S. Dmitriev and V. C. Nikolaev, Zh. Eksp. Teor. Fiz. **44**, 660 (1963) [Sov. Phys. JETP **17**, 447 (1963)].

[18] D. P. Dewangan and H. R. J. Walters, J. Phys. **B11**, 3984 (1978).

[19] K. Riesselmann, L. M. Anderson, L. Durand, and C. J. Anderson, Phys. Rev. **A43**, 5934 (1991).

[20] N. Bohr, *The Penetration of Atomic Particles through Matter*, Kgl. Danske Videnskab. Selskab. Mat.-Fys. Medd. **18**, 8 (1948).

[21] V. C. Nikolaev, I. S. Dmitriev, L. N. Fateeva, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. **40**, 989 (1961) [Sov. Phys. JETP **13**, 695 (1961)].

[22] Ya. A. Teplova and I. S. Dmitriev, in *The Development of Nuclear and Atomic Studies in the Institute of Nuclear Physics at Moscow State University* [in Russian], MGU, Moscow (1994), p. 132.

[23] V. C. Nikolaev, I. S. Dmitriev, Ya. A. Teplova, and Yu. A. Faınberg, Vestnik MGU, Ser. Phys. Astron. **35**, 84 (1994).

[24] A. B. Wittkower, G. Levy, and H. B. Gilbody, Proc. Phys. Soc. London **91**, 306 (1967).

[25] H. Massey, *Negative Ions*, Cambridge University Press, Cambridge (1976).

[26] W. Lotz, J. Opt. Soc. Am. **60**, 206 (1970).

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