Composition of the slow ions produced upon ionization of gases by high energy protons

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A systematic investigation is carried out of the charge distributions of slow ions produced in single collisions of 0.2–0.8 MeV protons in He, Ne, Ar, Kr, H_2 and N_2 gases. It is shown that for all singly-charged slow positive ions the energy dependence of the cross sections is in accordance with the Bethe-Born theory. Deviations from the theory are observed for the partial cross sections of multicharged ions. Some suggestions regarding the nature of the deviations are made.

1. INTRODUCTION

The production of slow ions with different charges when gas atoms and molecules are bombarded with protons has been the subject of many studies, mainly the researches by Fedorenko and co-workers in the proton energy range from several keV to 180 keV[1,2]. At high energies (0.8–3.75 MeV), investigations of this kind were carried out by Wexler.

The targets used in these studies were the gases He, Ne, Ar, Kr, H_2, and N_2. Recently Puckett and Martin[4,5] measured the partial cross sections for the production of slow He^+ and He^{2+} ions when helium is bombarded with protons of energy 0.15 – 1.0 MeV. The data obtained by them agree well, for He^+ as well as for He^{2+}, both with the data of[2] at energies up to 0.18 MeV, and with the data of[3] at 0.8 – 1.0 MeV. For the other investigated targets, there are no data in the intermediate energy region. Attempts to compare the data of[1,2] and of[3] by extrapolation have shown that for high-charge components of slow ions there are observed discrepancies that greatly exceed the limits of the possible measurement errors. In a number of cases these discrepancies reach a factor of 8 (see[5]). At the same time, it is of great interest to obtain reliable data on the partial ionization cross section in the region of high proton energies, at least from the point of view of comparison with the theoretical calculations.

We report here systematic investigations of the charge distributions of the slow ions produced by single collisions of protons of energy 0.2 – 1.8 MeV in the gases He, Ne, Ar, Kr, H_2, and N_2.

2. APPARATUS AND MEASUREMENT PROCEDURE

The composition of the slow ions produced in the gases by passage of high-energy protons was investigated with an installation described in detail earlier[6] and supplemented with an ion analyzer shown schematically in Fig. 1.

On the basis of methodical measurements similar to those developed and described in detail, e.g., in[7,8], we established the electric fields needed to shape the slow-ion beams, as well as the dimensions of the slits used both in the system of the shaping electrodes and in the analyzing part of the installations. The working potentials of the drawing-system electrodes are indicated in Fig. 1.

The slow positive ions were registered with an ion counter[9]. The measurements were performed in a regime in which individual particles were counted. The counted pulses were normalized to a definite number of particles of the primary beam, as determined with a current integrator. The working parameters of the beam, which are indicated in Fig. 1, were chosen such as to make the counting characteristic, when plotted as a function of each parameter, ultimately flatten out. This ensured good reproducibility of the results, and the counter noise level was always less than 1 count/sec.

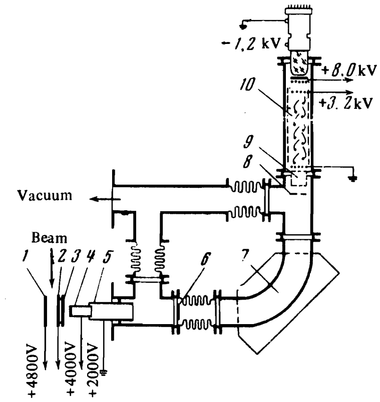

FIG. 1. Diagram of slow-ion analyzer. 1, 2–plates of capacitor producing the repelling electric field, 3–guard plate, 4, 5–electrode system to accelerate and focus the slow ions; 6–8–magnetic mass analyzer with slits, 9–Faraday cylinder, 10–ion counter.

The factors tending to reduce the counter efficiency were minimized, and the missed counts were due mainly to the small average coefficient of secondary ion-electron emission when the first copper-beryllium dynode of the secondary-electron multiplier was bombarded with low-energy ions. For all the ions registered by us, we determined the counter efficiency and introduced suitable corrections. Thus, for example, for krypton ions, having an energy 4.4 i keV (i is the ion charge multiplicity), the counting efficiencies for singly-, doubly-, triply-, quadruply-, and quintuply-charged ions were 60, 70, 77, 94, and about 100 per cent, respectively.

The mass spectrograms were obtained with the pressure in the collision chamber equal to $(1-5) \times 10^{-5}$ Torr, the pressure in the analysis and detection space being $(1-3) \times 10^{-6}$ Torr. Admission of enough gas into the collision chamber to produce the indicated pressure exerted no noticeable influence on the relative composition of the slow ions.

We determined the relative intensities of the slow positive ions, $\alpha_i = \sigma_i/\Sigma\sigma_i$, where σ_i are the partial cross

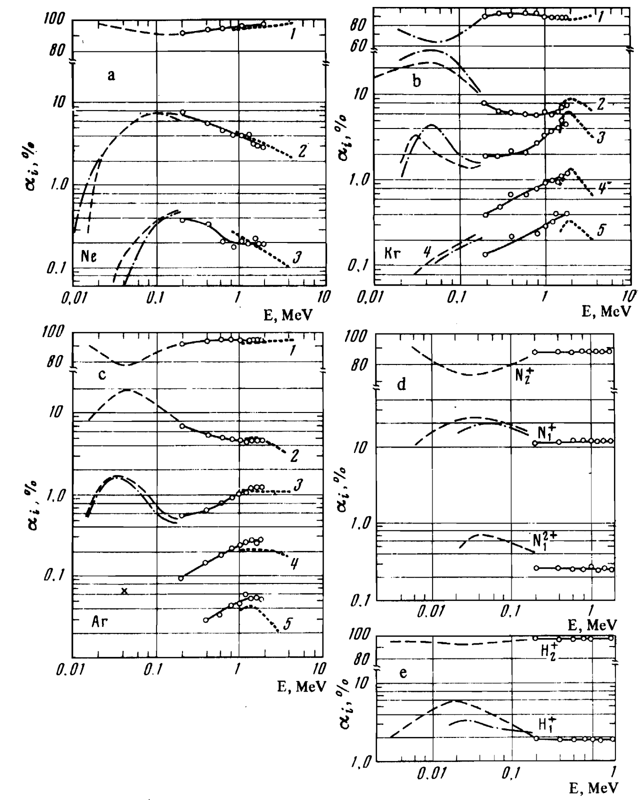

FIG. 2. Dependence of the relative intensities α_1 of the slow ions on the proton energy: a—in Ne, b—in Kr, c—in Ar, d—in N_2, e—in H_2. The numbers on the curves are the charge multiples of the slow positive ions. O—present data, dash-dot curves—data of [1], dashed curves—data of [2], dotted curves—data of [3].

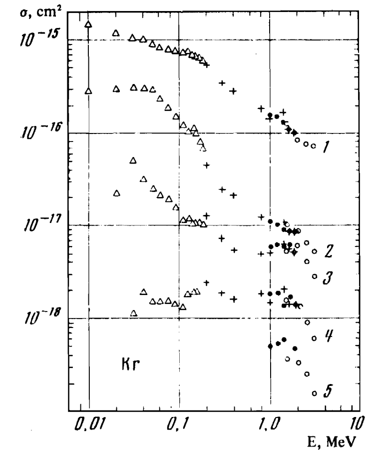

FIG. 3. Dependence of the partial cross sections σ_i for the production of slow positive ions on the proton energy in Kr. The numbers at the curves show the charge multiples of the slow positive ions: Δ—data of [2], +—data of present paper, ●—combination of the data on α_i from the present paper and on σ_+ from [13], O—α_i from [3] and σ_+ from [13].

sections for the production of slow ions with charge i. The random errors in the measurement of α_i were estimated from the reproducibility of the results and amounted to approximately ± 5% for ions with charge multiplicity 1 – 3, and from ± 10 to ± 15% for ions with larger charges.

3. MEASUREMENT RESULTS AND DISCUSSION

The main task of the present study was to obtain systematic data for α_i in the uninvestigated region of energy of the incident protons. The results have made it possible to explain the nature of the discrepancies pointed out by Puckett and Martin[5]. To explain these discrepancies it is more convenient to compare the quantities α_i rather than σ_i, for the following reasons: 1) the α_i are determined directly in the experiment from an analysis of the slow particles, with relatively small errors; 2) when the values of σ_i are compared, apre-ciable errors can result from the large systematic errors in the measurement of the total apparent cross sections on the basis of which the partial cross sections are obtained; 3) the data for the high energy region, cited by Wexler,[3] were obtained by extrapolating the curves of Hooper et al.[10,11] to the region of high energies, and in the case of the ionization of krypton Wexler used an even less justified extrapolation of the curve from the paper of Solov'ev, Il'in, Oparin, and Fedorenko[2].

The measured charged fraction of slow positive ions produced in single collisions of protons with targets Ne, Ar, Kr, H_2, and N_2 are shown in Fig. 2.1) The figure shows also the curves obtained on the basis of the data of[1-3].

Using the presented values of α_i, it is easy to obtain, in turn, the values of the corresponding partial ionization cross sections, by combining α_i with the published[1,2,10-13] values of the total apparent cross sections for the production of positive ions in the gases indicated above.

Figure 3 shows by way of example the energy dependence of the partial cross sections for the ionization of krypton by protons.

The present data, in conjunction with the available data obtained earlier by others, enable us to examine the composition and singularities of the appearance of slow positive ions in a wide range of velocities ((1.5 – 30) $\times 10^8$ cm/sec). The good agreement between our results both at low and at high velocities in all the considered cases eliminate the contradictions that appear in a number of $\alpha_i(E)$ curves, and is due to the irregularities in the course of these curves. Thus, in Fig. 2c we see that the relative contribution of the doubly charged argon ions is maximal at a bombarding-proton velocity $\sim v_0$ ($\alpha_2^{max} \approx 20\%$), then decreases, the rate of decrease slows down at high energies, the curve flattens out ($\alpha_2 \approx 5\%$) at a velocity $\sim 6v_0$, and the relative contribution of the doubly-charged argon ion again decreases. There is also a clearly seen irregularity of the energy dependence of the relative contribution of the triply-charged argon ions.

Even more obvious is the irregularity of the α_i curves in the case of Kr, which are shown in Fig. 2b. Such an energy dependence of α_i indicates that each of these curves is a superposition of at least two curves, one of which has a maximum in the low-energy region, and the other in the high-energy region. Each of the component curves reflects different interaction mechanisms leading to identical final products. The maxima of the curves at high energies are observed at proton velocities $\sim 6 - 8\ v_0$.

According to the theoretical representations, the energy dependence of the partial ionization cross sections in the region investigated by us can be described in general form by a formula obtained in the Bethe-Born approximation:

$$\sigma_i = \frac{A_i \ln E}{E} + \frac{B_i}{E},$$

where E is the proton energy, and A_i and B_i are constant quantities for the given type of target.

Our analysis of the energy dependence of the partial cross sections has shown that there is agreement with the predictions of the theory for all the singly-charged slow positive ions. This relation is also satisfied by the energy dependence of the partial cross sections for the production of the ions Ne^{2+} and N^{2+}. For other partial cross sections for the production of multiply charged ions, deviations are observed from the energy dependence in the Bethe-Born approximation. To explain the nature of these deviations it is necessary to carry out special experiments.

At present one can advance the hypothesis that the irregularities of the plots of the relative intensities of slow ions of a given sort, as well as the deviation from the energy dependence of the corresponding partial cross sections σ_i from the theoretical prediction, are due to the mechanism of direct knock-out of electrons from the inner atomic shells by the high-energy protons, followed by Auger-transition cascades. An appreciable contribution can be made also by processes that lead to a simultaneous knock-out of several electrons from the outer shell as a result of one collision act. The maximal probabilities of such processes, which lead in final analysis to the formation of the corresponding slow multiply-charged ions, probably lie in the proton-energy range investigated by us (1 – 1.5 MeV).

[1)]The values of α_i, obtained by us for the H^+ + He pair are not shown. These values of α_i agree well, both in absolute magnitude and in their energy dependence, with the data of Puckett and Martin [5].

[1]N. V. Fedorenko, V. V. Afrosimov, R. N. Iljin, E. S. Solovyov, Proc. of the IV Conf. of Ioniz. Phenomena in Gases, Uppsala, 1959, North-Holland Amsterdam, 1960, p. 47.

[2]E. S. Solov'ev, R. N. Il'in, V. A. Oparin, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. 42, 659 (1962) [Sov. Phys.-JETP 15, 459 (1962)].

[3]S. Wexler, J. Chem. Phys. 41, 1714 (1964).

[4]D. W. Martin, L. J. Puckett, G. O. Taylor, Proc. of the V Intern. Conf. of the Phys. of Electr. and Atomic Collision, Leningrad, USSR, 1967, p. 207.

[5]L. J. Puckett, D. W. Martin, Phys. Rev. A1, 1432 (1970).

[6]L. I. Pivovar, Yu. Z. Levchenko, and Z. N. Grigor'ev, Zh. Eksp. Teor. Fiz. 54, 1310 (1968) [Sov. Phys.-JETP 27, 699 (1968)].

[7]N. V. Fedorenko and V. V. Afrosimov, Zh. Tekh. Fiz. 26, 1941 (1956) [Sov. Phys.-Tech Phys. 1, 1872 (1957)].

[8]Ya. M. Fogel', A. G. Koval', Yu. Z. Levchenko, and A. F. Khodyachikh, Zh. Eksp. Teor. Fiz. 39, 548 (1960) [Sov. Phys.-JETP 12, 384 (1961)].

[9]V. F. Kozlov, V. Ya. Kolot, and A. N. Dovbnya, Prib. Tekh. Éksp. No. 6, 81 (1965).

[10]J. W. Hooper, D. S. Harmer, D. W. Martin, E. W. McDaniel, Phys. Rev. 125, 2000 (1962).

[11]J. W. Hooper, E. W. McDaniel, D. W. Martin, D. S. Harmer, Proc. of the II Intern. Conf. on the Phys. of Electr. and Atomic Collisions, N. Y., 1962, p. 67.

[12]J. W. Hooper, E. W. McDaniel, D. W. Martin, D. S. Harmer, Phys. Rev. 121, 1123 (1961).

[13]L. I. Pivovar and Yu. Z. Levchenko, Zh. Eksp. Teor. Fiz. 52, 42 (1967) [Sov. Phys.-JETP 25, 27 (1967)].

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