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# *PRODUCTION OF HIGHLY EXCITED 30–180 keV HELIUM ATOMS DURING CHARGE EXCHANGE AND THEIR IONIZATION IN A STRONG ELECTRIC FIELD*

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The production of highly excited helium atoms ($n = 9-17$) during charge exchange involving $He^+$ ions with energies of 30–180 keV on neon, sodium, and magnesium atoms has been investigated. It was found that the population of the highly excited states and the cross section for the production of highly excited atoms during charge exchange of helium ions and of protons of the same velocity are nearly equal. The ionization of highly excited helium atoms by a strong electric field is discussed.

## INTRODUCTION

THE production of highly excited hydrogen atoms during atomic collisions and the ionization of such atoms by electric fields have been investigated in recent years. Proton charge exchange in different targets, leading to the formation of highly excited atoms, was investigated experimentally in[1-3] and theoretically in[4,5]. Hiskes et al have also reported some calculations on the ionization of excited hydrogen atoms by electric fields[6]. A detailed review of the literature on the ionization of highly excited atoms by electric fields has been given by Riviere[7].

Although the above experimental papers are concerned with highly excited hydrogen atoms with principal quantum number $n > 8$, the results can be used to estimate the number of excited atoms with lower values of n that are produced during the exchange charge process. Berkner et al.[8] have shown that, in the case of charge exchange involving protons in magnesium, the population of the excited states of the atoms is proportional to $n^{-3}$ right up to $n = 6$. In the case of charge exchange on gaseous atoms, comparison of the results reported in[1] with those given by Andreev et al.[9] shows that this law is valid up to $n = 3$. It follows that, by investigating the production of highly excited atoms, we can obtain an overall estimate of the degree of excitation of atoms during charge exchange.

The present work was initiated with a view to obtaining data on the dependence of the degree of excitation of helium atoms, produced as a result of charge exchange, on the structure of the electron shells of the target atoms. We have investigated the production of highly excited atoms ($g \leq n \leq 17$) during charge exchange involving $He^+$ ions with energies of $30 \leq T \leq 180$ keV on neon, sodium, and magnesium atoms, all of which have similar nuclear charges but different structure of the outer electron shell.

## EXPERIMENTAL METHOD

We have used the apparatus described in detail in our previous papers[1,2]. A beam of fast $He^+$ ions was allowed to pass through a chamber filled with the target gas or vapor. The pressure in the chamber was varied in the range $10^{-5}-10^{-3}$ Torr. In the case of metal vapor, the pressure was determined from the temperature of the chamber. The beam of atoms which appeared as a result of the charge exchange processes was cleared from ions by a weak transverse electric field and then entered a region of longitudinal electric field with $E \leq 170$ kV/cm. Ions produced during the ionization of the atoms by the high electric field were recorded by a Faraday cylinder or a scintillation counter. We measured the relative number 1 of excited atoms, which were ionized by the electric field, as a function of the field strength E.

To obtain data on the population of states with different principal quantum numbers n, we measured the quantity dI/dE which provides a kind of "electrical spectrum." This function was obtained by imposing a sequence of rectangular pulses of amplitude $\Delta E$ on the constant field E, and then recording the corresponding variable signal $\Delta I$ by the method of synchronous detection. The signal $\Delta I$ was recorded by counting the individual ions. Depending on the magnitude of E, the pulse amplitude $\Delta E$ was chosen between 0.8 and 2 kV/cm.

## RESULTS AND DISCUSSION

Figure 1 shows the electrical spectrum of highly excited helium atoms produced as a result of charge exchange involving $He^+$ ions with energies of 120 keV on magnesium atoms (the shape of the spectrum in the case of neon atoms was the same). For comparison, the figure also shows the electrical spectrum of hydrogen atoms produced by charge exchange of $H^+$ ions with energies of 120 kV in magnesium.

The shape of the hydrogen spectrum and the position of the lines are in good agreement with previous work[1,10,11]. The helium lines, on the other hand, are narrower and taller (in comparison with the values dI/dE between the lines) and are shifted relative to the hydrogen lines. The line width in this spectrum is connected with the sub-barrier origin of the ionization phenomenon and was determined for each Stark component by the time spent in the field and the field distribution along the beam axis. The hydrogen line widths under experimental conditions similar to our own have

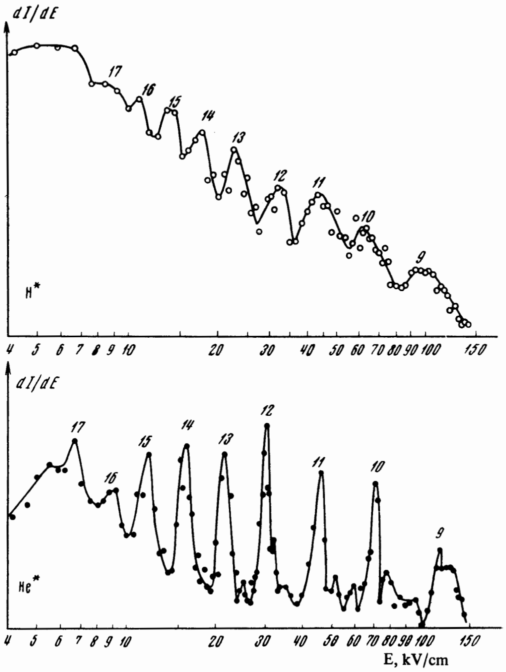

FIG. 1. Electrical spectra of highly excited helium and hydrogen atoms at 120 keV. Magnesium vapor target. The figure shows the principal quantum numbers corresponding to the spectral lines.

been calculated by Rivere and Sweetman[10]. It follows from these calculations that the line width of a single Stark component (determined by the principal quantum number n, the difference between the parabolic quantum numbers $n_1 - n_2$, and the magnetic quantum number m) is much greater than the separation between neighboring components. Therefore, the hydrogen Stark levels which are characterized by quantum numbers n and $n_1 - n_2$, and are produced during the splitting of a given level with quantum numbers n and $l$ in the absence of the field, cannot be resolved in the spectrum and form a single broad line for the given n. The shape of this line will vary depending on the $l$ population, but the accuracy of the experiment is insufficient to enable us to determine the initial population from the line shape.

In the case of helium, in which there is no degeneracy in $l$, the Stark effect has a somewhat different character. If the field is allowed to increase slowly (which was the case in our experiment) we have at first the quandratic Stark effect. This is followed by the linear Stark effect in higher fields. The transition from the quadratic to the linear Stark effect has been considered by Foster[12] who showed that, in sufficiently strong fields, the splitting of the helium levels is the same in magnitude as the splitting of hydrogen levels in the case of the linear Stark effect, and the ns level of helium corresponds to the deepest ("red") hydrogen component for which the parabolic quantum numbers are $n_1 = 0$ and $n_3 = n - 1$, and the "violet" hydrogen component with $n_1 = n - 1$ and $n_2 = 0$ corresponds to the singlet sublevel of the excited helium atom with $l = 1$, $m = 0$ for the excited electron, or the triplet sublevel with $l = n - 1$, $m = 0$ and the lowest binding energy.

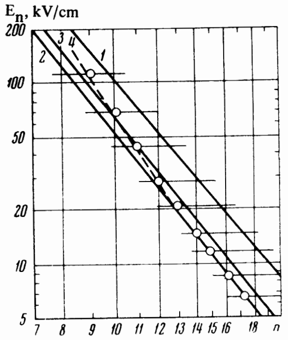

FIG. 2. Electric field $E_n$ corresponding to the ionization of highly excited atoms with different n. The horizontal lines represent fields corresponding to the line maxima in the spectrum of helium. The inclined lines show the function $E_n(n)$ for: 1–the "violet" component of hydrogen, 2–the "red" component of hydrogen, 3–line maxima in the spectrum of hydrogen, 4–line maxima in the spectrum of helium.

Comparison of the line width in the helium spectrum with the calculated width for hydrogen[10] shows that in the case of helium a very small number of neighboring Stark components appear to be populated within each n level. The calculations by Hiskes[5] show that the s, p, and d levels are preferentially populated in the case of proton charge exchange. It is probable that this is also valid for the highly excited helium atoms. If this is so, then the above properties of helium levels would suggest that the main contribution to the helium lines in the electric field is due to components analogous to the "red" components of hydrogen.

Exact calculations on the ionization of helium atoms by electric fields have not as yet been performed. We have therefore assumed that, for sufficiently high n, the ionizing fields for the corresponding hydrogen and helium components are the same, although as n decreases there may be differences connected with the deeper position of the helium levels in comparison with the hydrogen levels[13]. Figure 2 shows the positions of the lines in the helium spectrum of Fig. 1, and the dependence of the ionizing field on n in the case of the "red" and "violet" components of the hydrogen atoms calculated in[6]. It follows from Fig. 2 that for $12 \le n \le 17$ there is good agreement between the measured positions of the helium lines and the calculations. In this range of values of n, the field $E_n$ corresponding to the maximum of the n-th line of the spectrum is given by (in kV/cm)

$$E_n = 5.8\cdot 10^5 / n^4 \text{ [kV/cm]}. \qquad (1)$$

We note that the validity of this result is restricted, firstly, by the fact that $E_n$ is a function (although a slowly varying function) of the time spent by the atom in the field (in our case about $10^{-10}$ sec) and, secondly, by the fact that the quantum-mechanical calculations for hydrogen[6] taking into account sub-barrier transtions yield $E_n \sim n^{-q}$ where $q = 3.7 - 3.8$.

As indicated above, during proton charge exchange leading to the formation of highly excited hydrogen atoms, the population of the states with different n is defined by

$$\frac{\sigma_c^n}{\sigma_0} = \frac{a}{n^3}, \quad \sigma_0 \equiv \sum_{n=1}^{\infty} \sigma_c^n, \qquad (2)$$

where $\sigma_c^n$ is the cross section for the formation of an atom with principal quantum number n during the charge exchange process, $\sigma_0$ is the total charge-exchange cross section, and a is a parameter characterizing the population of the highly excited states. The population of the helium states with different n (Fig. 1) is also in agreement with Eq. (2). Equations (1) and (2)

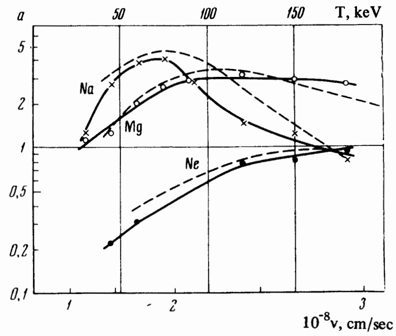

FIG. 3. Dependence of a on the velocity of highly excited helium (solid curves) and hydrogen atoms (broken curve). T is the energy of the helium atoms.

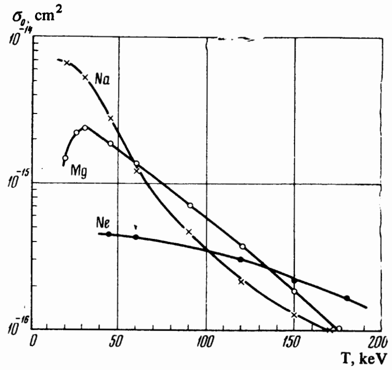

FIG. 4. Total charge-exchange cross section $\sigma_0$ of He$^+$ ions as a function of their energy T for different targets.

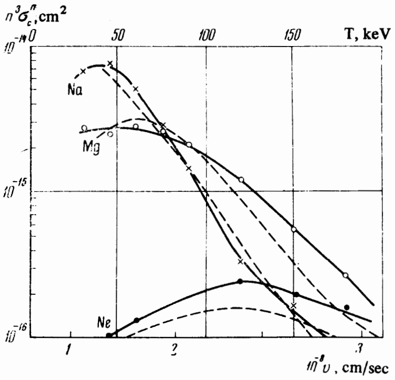

FIG. 5. Cross section for electron capture by He$^+$ and H$^+$ into highly excited states as a function of the ion velocity v for different targets.

can then be used as in[1] in the case of hydrogen to show that[1]

$$I(E) = 6.6\cdot10^{-4}a\sqrt{E}, \tag{3}$$

where E is in kV/cm. From the measured function I(E) we can calculate a. The dependence of this quantity on the velocity during charge exchange of He$^+$ ions on neon, sodium, and magnesium atoms is shown in Fig. 3. For comparison, the figure also shows the analogous functions for protons. It is clear that the values of a for hydrogen and helium are quite close to one another.

The cross section $\sigma_c^n$ for the formation of highly excited helium atoms can be obtained from Eq. (2) by using the value of a and the total charge-exchange cross section $\sigma_0$ measured in an individual experiment. The values of $\sigma_0$ for He$^+$ on neon, sodium, and magnesium atoms are shown in Fig. 4.

The cross sections for the production of highly excited hydrogen and helium atoms during charge exchange are shown in Fig. 5. It is clear from this figure that the cross sections are close both in magnitude and in the velocity dependence. It may therefore be concluded that the qualitative features of the production of highly excited helium atoms during charge exchange are similar to those in the case of hydrogen atoms and molecules[3,15]. In particular, for ion velocities in the range $10^8 - 2\times10^8$ cm/sec, the outer shell electron from the target atom is preferentially captured into the highly excited state. The cross section for this capture process is a maximum when the relative velocity of the colliding atomic particles and the velocity of the outer electron in the target atom are equal, and the magnitude of this cross section at maximum, $\sigma_{c\,max}^n$, is related to the ionization potential V (in electron volts) of the target atoms by the formula

$$n^3\sigma_{c\,max}^n \approx 5.4\cdot10^{-13}V^{-5/2}\ [\mathrm{cm}^2]. \tag{4}$$

As noted in the Introduction, the relatively large value of $n^3\sigma_c^n$ indicates strong excitation during charge exchange. It follows that the high charge-exchange cross sections of He$^+$ on metal atoms are due to the formation of a large number of excited atoms. This is in agreement with the results reported in the[16] where it was shown that, in the case of charge exchange of 3-25 keV He$^+$ ions on cesium atoms, the most likely result is the production of highly excited helium atoms in the triplet state.

The cross section $\sigma_c^n$ for charge exchange with the production of highly excited helium atoms is somewhat higher than the analogous cross section for hydrogen on neon and, at higher energies, on metal atoms as well. As noted in our previous paper[3], these cases involve capture from a filled shell of the target atom. It would appear that the capture proceeds at lower impact parameters, and the screening of the nucleus by the electron in the He$^+$ ion is weakened, so that the larger effective charge increases the capture probability.

The most important difference between highly excited helium and hydrogen atoms is connected with the fact that the helium levels are not degenerate with respect to *l*, and this can be seen in the shape of the electrical spectrum.

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[1] In our preliminary publication [14] we advanced a less justified assumption in numbering the lines, and obtained as a result a different coefficient in (1) and overestimated the population and the capture cross section by approximately 30%.

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13