Excitation Processes in Helium Induced by Impact of Deuterons and Protons

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(Received June 27, 1961)

The excitation of helium atoms by impact of protons and deuterons is examined in the energy range from 40–200 kev. The cross sections of some ${}^1S$, ${}^1D$ and the $3\,{}^1P$ state are determined. The excitation of the $2\,{}^1P-4\,{}^1S$ line attains a broad maximum at 65 kev for protons, and at 115 kev for deuteron excitation. The $3\,{}^3D$ state appears to be weakly populated by direct D^+ excitation; at 130 kev D^+ energy, $Q(3\,{}^3D)\leq 2\times 10^{-20}$ cm^2. Inelastic collisions between excited helium and foreign atoms bringing about the transition from singlet to triplet states are discussed.

I. INTRODUCTION

IN the past years considerable work has been done on the excitation of helium by electron impact. At the same time comparatively little information has been obtained on the excitation of helium by protons or deuterons. Such data are of interest for a better understanding of excitation processes and for plasma physics.

The early experimental approach to the problem of excitation by protons and hydrogen atoms was undertaken under not sufficiently defined conditions.[1,2] Recently the techniques used in excitation experiments by ions have considerably been improved. It has been found that an appreciable excitation of helium does not appear until the proton beam energy reaches 2 kev,[1,3] whereas the excitation of the $4\,{}^1S$ and $5\,{}^1S$ states appears to be strong at 200-kev proton energy.[4]

The purpose of the present experiment is to extend the energy range of helium excitation measurements using a well-defined ion beam, and also to examine the excitation transfer reactions.

II. EXPERIMENTAL

The Institute "Ruđer Bošković" accelerator giving a magnetically analyzed beam of protons or deuterons in the energy range from 40–200 kev was used in the present experiment[5]; good focusing properties were obtained at higher energies. Some details of the collision chamber are shown in Fig. 1. The ion beam cross-sectional area is defined by the inlet hole drilled in an 1-mm thick steel plate. The Faraday cup and the collision chamber are insulated. Secondary electrons from the Faraday cage are reflected by the grid 2, maintained 120 v negative to the cage. Secondaries are also removed from the ion beam by the repeller plate. The electrons ejected from the brass wall by helium metastables, soft x rays, and resonant photons are reflected by the grid 1. In that way the chance of collisions with electrons is considerably reduced in the collision space. The ion beam was imaged by a spherical glass lens on the slit of a Hilger glass spectrograph. Large slit widths were used throughout the experiment. The spectral sensitivity of the photographic emulsion was determined by use of a five-step rotating disk and a helium glow discharge lamp, calibrated by a Philips standard tungsten lamp of known light emission. The fast Kodak Panchro-Royal film was used, nevertheless very long exposures were necessary.

The absolute intensity of the 5875-A helium line was measured by an EMI 6256 B photomultiplier. The signal from the multiplier tube was measured by a sensitive galvanometer; the dark current was $\approx 10^{-8}$ amp. The line was isolated using a narrow band interference filter. The quantum efficiency k of the photomultiplier in connection with the interference filter and the glass lenses was checked by the calibrated helium lamp: $k=ih\nu/\epsilon s\omega$, where i is the photomultiplier current output; ϵ is the light emissivity of the helium lamp; s is the radiation area, and ω is the solid angle.

From the relative intensities obtained from photometric data and the 5875-A line absolute intensity, the absolute intensities of other helium lines were derived.

Spectroscopically pure helium was admitted into the chamber via a needle valve, and the chamber was continuously pumped through the inlet hole. With the needle valve closed and 20-μa proton beam current, the residual pressure in the chamber increased to about 3×10^{-5} mm Hg. The total pressure including vapors was probably higher owing to the sputtering of metal surfaces under ion bombardment. The pressure was measured absolutely by means of a McLeod gauge and monitored by a calibrated Pirani gauge.

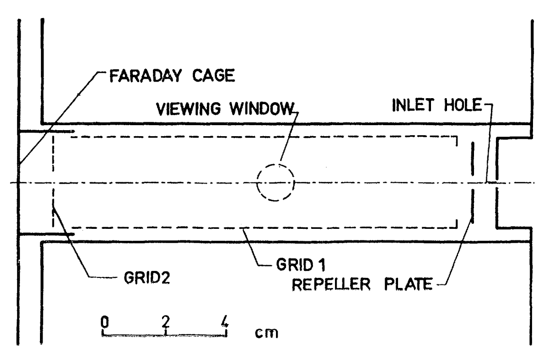

FIG. 1. Collision chamber.

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TABLE I. Excitation cross sections in 10^{-20} cm² units for 130-kev deuteron impact.

Transition	Q_{jk}	Level	Q_j
$2\,{}^1S-3\,{}^1P$	37	$3\,{}^1P$	86
$2\,{}^1P-4\,{}^1S$	34	$4\,{}^1S$	57
$2\,{}^1P-5\,{}^1S$	11	$5\,{}^1S$	23
$2\,{}^1P-4\,{}^1D$	16	$4\,{}^1D$	22
$2\,{}^1P-5\,{}^1D$	7.6	$5\,{}^1D$	12

A considerable noise was detected in the 5000-A region using an interference filter and the multiplier tube as detector; in the 5875-A region the noise was found to be smaller. It is supposed that the noise originates mainly from D_2-bands. Thus, in separating spectral lines by interference filters it was necessary to measure the spectral emission before and after the admission of the gas into the chamber, and subtract the noise i_0 from each emission reading i_p. The photon flux per unit time and unit length of the ion beam, E_{jk}, corresponding to the transition $j\rightarrow k$ is then given by $E_{jk}=4\pi(i_p-i_0)/\omega k$.

The partial pressure of deuterium and thus probably the spectral background depend on the pressure drop at the inlet hole. The actual pumping speed ensures a practically constant flow of deuterium from the collision space, up to 10-μ Hg pressure in the chamber, and i_0 may be considered constant in the observed pressure range.

Considerable uncertainty is due to the variation of the ion beam intensity, the error in the pressure measurement, and the photometric evaluation of the data. The relative values of the cross sections are estimated to be accurate within $\pm 20\%$. The absolute values depend also on the stability of the helium lamp and its calibration, and are accurate within $\pm 30\%$. The relative variation of E_{jk} with ion energy and with pressure is more accurate and is correct to better than $\pm 8\%$.

III. TREATMENT OF DATA

At low pressure, neglecting the cascade population of the j state and transfer reactions, the collision cross section for the excitation of the jth level is given by

$$Q_j=E_{jk}(\gamma g+A_j)/nA_{jk}i/e, \tag{1}$$

where γ is the radiative transition probability from the state j to the ground state; A_j is the sum of all other radiative transition probabilities from the state j; A_{jk} is the radiative transition probability from the state j to the state k; g is the coefficient of imprisonment of the resonance radiation; n is the target gas density. In the present analysis the calculated values of transition probabilities[6,7] were used.

The $2\,{}^1S-n\,{}^1P$ lines are enhanced owing to the imprisonment of resonance quanta. The coefficient of imprisonment has been calculated for cylindrical geometry[8]; for the present case it is assumed that the effective imprisonment radius is approximately equal to the radius of the chamber.

γ is zero for all except ${}^1P$ states and Eq. (1) is thus reduced to

$$Q_j=E_{jk}A_j/nA_{jk}i/e. \tag{2}$$

Q_j as given by Eqs. (1) and (2) is sometimes defined as the apparent cross section Q_j'.[9]

IV. RESULTS

The values of the excitation cross sections Q_{jk} and Q_j for 130-kev deuterons at 6-μ helium pressure are given in Table I.

An interesting feature in the above results, as compared with electron cross sections,[7,10] is the comparatively strong excitation of the $n\,{}^1S$ states and the small cross section of the $3\,{}^1P$ state as observed also for 200-kev proton excitation.[4]

The excitation function of the 5015-A and 5047-A lines was measured by the photomultiplier and an interference filter; the two lines were not resolved by the filter. Figure 2 shows the variation of light intensity as a function of proton and deuteron energies. For the D^+ excitation two maxima are visible, at 80 kev and 115 kev, respectively. At higher pressures the 80-kev peak was not detected. From the cross sections given in Table I, and taking into account the imprisonment coefficient g for the 5015-A line as well as the observed approximately linear variation of the 5047-A line intensity with pressure, the line intensity ratio $E_{5047\text{ A}}/E_{5015\text{ A}}$ is found to be about 6. Consequently the maxima in Fig. 2 correspond predominantly to the 5047-A line excitation. With increasing pressure the 65-kev and 115-kev peaks are

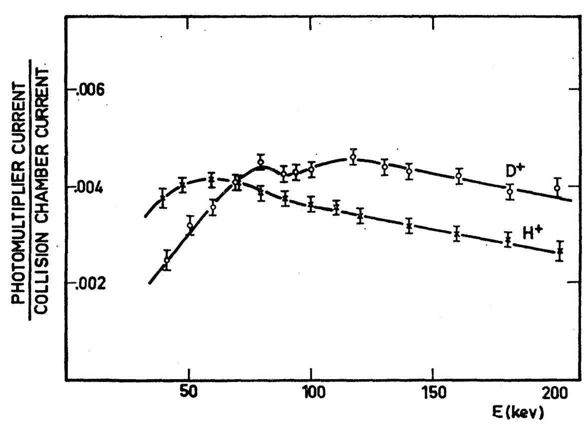

FIG. 2. Excitation of the $2\,{}^1P-4\,{}^1S$ line by deuterons and protons with 10 μa ion beam current and 0.5 μ helium pressure.

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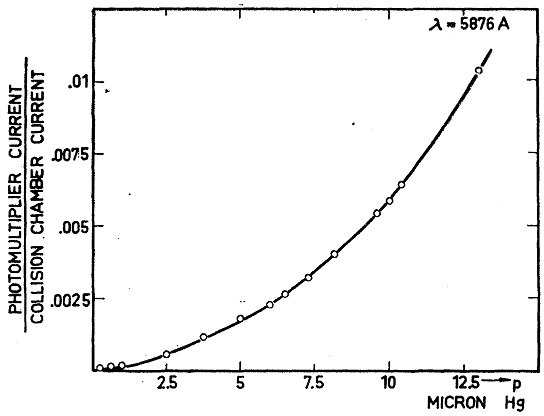

FIG. 3. 5875A line intensity as a function of He pressure with a beam current of 20 μa and 130 kev deuteron energy.

slightly displaced toward higher energies, due probably to the steep increase of the 5015-A intensity.

Considering that the excitation function of any state of the same series can be expressed by the product of a characteristic shape function with a constant,[11] the maximum of the proton excitation curve at 65 kev is in a fairly good agreement with the maximum of the ionization curve calculated by Mapleton[12] and measured by Fedorenko, *et al.*[13]

The values of Q_j for the $3\,^3D$ and $4\,^3D$ states are found to be 4×10^{-20} cm^2 and 1.6×10^{-20} cm^2, respectively; it shows that the 130-kev deuterons are very ineffective in exciting triplet states. In fact, since the spin-orbit coupling in helium is very weak, the change of the total electron spin by impact of D^+ seems to be very improbable.

With constant energy of incident ions and constant target gas pressure the $2\,^3P-3\,^3D$ line intensity is proportional to the ion beam current. Further, it is found that with constant beam current and ion energy the intensity of the $2\,^3P-3\,^3D$ line increases quadratically with pressure. Figure 3 shows the 5875-A line intensity plotted against the pressure at 130 kev and 20 μa D^+ beam current. At low pressure there exists an approximately linear relationship between line intensity and helium pressure. From the departure from linearity at higher pressures the true value of $Q(3\,^3D)$ can be estimated. The intensity in the observed pressure range can be represented by

$$E=(i/e)(Qn+Cn^2). \qquad (3)$$

The first term represents the direct excitation of the $2\,^3P-3\,^3D$ line. Hence the true excitation cross section for the $3\,^3D$ state is found to be $\approx 2\times10^{-20}$ cm^2. Assuming that the quadratic component can be attributed only to excitation transfer according to

$$\mathrm{He}(3\,^1P)+\mathrm{He}(1\,^1S)\rightarrow\mathrm{He}(1\,^1S)+\mathrm{He}(3\,^3D),$$

the constant C [Eq. (3)] is given by $C=Q'\sigma v\tau$, where Q' is the cross section for the excitation of the $3\,^1P$ state, σ the cross section of the transfer reaction, τ the mean life time of the $3\,^1P$ state, and v is the mean velocity of helium atoms. With the value of Q' (Table I) and the mean lifetime[14] corrected for the imprisonment of resonance radiation, and assuming that v is equal to the mean thermal velocity, one finds $\sigma=8\times10^{-14}$ cm^2.

Figure 4 shows the excitation function for the 5875-A line. As seen, the line intensity decreases with increasing ion energy but also two overlapping small maxima are visible. The hump at about 115 kev coincides with the excitation maximum in Fig. 2, and it is consequently attributed to the transfer processes. With increasing beam current the 115-kev peak is more pronounced. The small peak at 180 kev is tentatively related to the excitation resulting from sputtered atoms. The trend of the excitation curve indicates that the direct excitation processes reach their maximum in the region of 70 kev or lower. The uncertainty of the present measurements below 70 kev is considerable.

Owing to the small value of $Q(3\,^3D)$ the relative importance of some processes other than deuteron excitation, which might also cause the direct excitation of triplet states, will be considered. The increase of the 5875-A line intensity at lower deuteron energies suggests that such processes might be effective.

The concentration of neutrals in the beam originating from charge exchange processes[15,16] is certainly lower than 2% under the actual experimental conditions. Assuming that the cross section for the excitation of the $3\,^3D$ level by fast hydrogen atoms is approximately equal to the excitation by impact of electrons of the same relative velocity, the hydrogen atoms from charge exchange can account for at most 0.4×10^{-20} cm^2. However, not well known is the content of D atoms in the beam resulting from neutralization at the inlet hole. According to some authors it may not be negligible,[16] but the available data do not allow a quantitative estimation of the above effect.

Furthermore, the excitation by metallic atoms sputtered by the ion beam at the inlet orifice and in the Faraday cage could also contribute to the $3\,^3D$ level population. Recently Moe and Petsch[17] have observed the excitation of neon by slow potassium ions. A similar process cannot be completely excluded in the described experimental arrangement. The true value of $Q(3\,^3D)$

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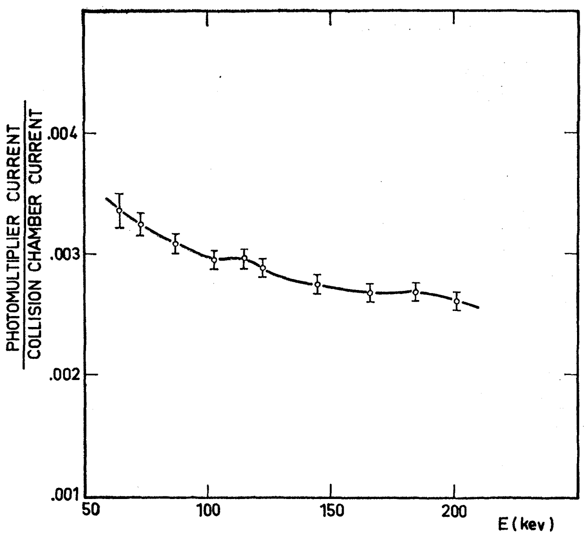

FIG. 4. Excitation function of the $2\,^3P-3\,^3D$ line with 20 μa beam current and at 6.7 μ helium pressure.

for deuteron excitation derived from Eq. (3) is thus probably too high, and $Q(3\,^3D)\leqslant 2\times 10^{-20}$ cm^2.

V. DISCUSSION

The ion velocities at which the excitation maxima occur (Fig. 2) are about (3 to 3.5)$\times 10^8$ cm sec^{-1}, as expected by the near adiabatic condition $a/v\approx h/(\Delta E)$.[18]

As seen, the excitation by 130-kev deuterons is about 1.7 times more intense than that by 200-kev protons. Accordingly we would expect for $Q(4\,^1S)$ and $Q(5\,^1S)$ larger values than those recently reported for 200-kev proton excitation.[4]

Contrary to the large apparent transfer cross section $(3\,^1P-3\,^3D)$ obtained from the ion excitation experiments, the conclusions of the recent electron excitation experiments are unanimous in finding that the Wigner spin conservation rule is partially obeyed,[7,10] and that the $3D$ levels are populated to only a small degree, by collisional transfer from the $3\,^1P$ state.

The concentrations of foreign gases were obviously higher in the ion-excitation experiments, and proportional to the ion beam current. The possibility of a perturbing influence of foreign atoms was recently discussed by Hughes, *et al.*[4] However the observed proportionality of the 5875-A line intensity to the deuteron beam current seems to exclude an appreciable population of the $3\,^3D$ level by collisions of He $(3\,^1P)$ with foreign atoms or molecules.

The analysis of the population of triplet levels requires further experimental data. We would like to point out that the target gas in the ion excitation experiments is heated by scattered deuterium atoms and the assumption that the velocity of helium atoms in the collision space is thermal may also contribute to an overestimation of the transfer cross sections.

ACKNOWLEDGMENTS

The authors are indebted to Professor M. Paić and Professor Z. Janković for discussing the manuscript, and to Mr. Ž. Pavlović for technical assistance.

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