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Spectra Induced by 200-kev Proton Impact on Helium*

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Spectra induced by 200-kev proton impact on helium have been observed in the spectral region of λ3500 A to λ6000 A. ^1S states appear to be strongly excited. Absolute cross-sections for the direct excitation of the $4\,^1S$ and $5\,^1S$ states of neutral helium were determined as well as the simultaneous ionization and excitation cross-section for helium into the $n=4$ state of He$^+$. Of the more intense lines, only the $2\,^1P-n\,^1S$ lines and the He II λ4686 line behaved linearly with pressure within experimental error. Triplet spectra were observed in which the dominant feature was the $2\,^3P-n\,^3D$ lines. The populations of the $4\,^3D$ and $4\,^1D$ states, in particular, were analyzed as a function of a direct mechanism and collision of the second kind which seem to fit the data fairly well. A very weak Doppler-shifted H_β line was detected. If this is interpreted to be produced by charge exchange, then the cross section for electron capture into the $n=4$ state of hydrogen is estimated to be of the order of 8×10^{-21} cm^2.

I. APPARATUS

PROTONS from the University of Arkansas Cockroft-Walton accelerator were allowed to enter a differentially pumped collision chamber (Fig. 1) where proton-helium collisions were observed spectroscopically. The optical axis of a JA-82000 scanning spectrometer used in recording the spectra made an angle of 25° with the proton beam (Fig. 2), thus enabling the observation of Doppler-shifted hydrogen lines produced by charge exchange. The photomultiplier used was an EMI-6256B whose spectral sensitivity is unfortunately limited in the H_α region.

The collision chamber was insulated so that the chamber itself served as a Faraday cup. The beam was collimated by allowing it to pass through two $\frac{1}{16}$-in. holes. An electron repeller was positioned after the collimator. Three sets of parallel plates were installed at the entrance of the collision chamber. The original intent of these plates was to provide a means to measure ionization currents. By charging the center plates we were able to throw a transverse field across the beam in the observation region. A Pirani gauge which had been previously calibrated against a McLeod gauge was situated near the observation region. Helium was leaked in through a liquid-air-cooled charcoal trap.

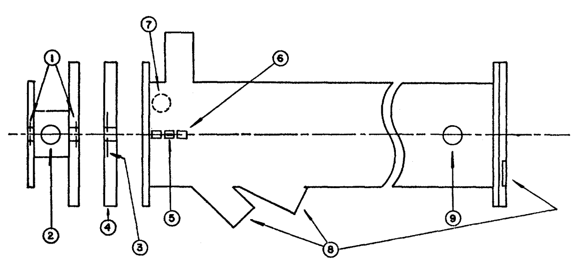

Fig. 1. Details of collision chamber. (1) beam collimating holes ($\frac{1}{16}$ in.), (2) differential pumping outlet, (3) electron repeller, (4) Lucite spacer, (5) observation region, (6) plates to apply an electric field across the observation region, (7) Pirani gauge, (8) observation ports, (9) target gas inlet.

A more suitable accelerator and collision chamber are being built. Thus, this paper can be considered as a report of preliminary results from such spectral studies.

II. OPTICAL CALIBRATION

A 25-w frosted incandescent lamp that had been absolutely calibrated at six points from 3800 A to 6500 A by the Yerkes Observatory was used as a standard source. The calibration curve gave the intensity P in photons rad^{-2} sec^{-1} (50 A)$^{-1}$, at a particular wavelength. The lamp was placed a considerable distance away along the optical axis of the spectrometer (see Fig. 3). A fused-quartz condensing lens was placed a distance (20 cm) equal to twice its focal length in front of the entrance slit of the spectrometer. The fused quartz window used on the chamber was inserted in the light path. With this arrangement the entrance window of the system is at a distance twice the focal length measured from the lens on the side toward the standard source. The area of the entrance window is the slit width a times the length of the slit l that the photomultiplier sees. The solid angle accepted by the system

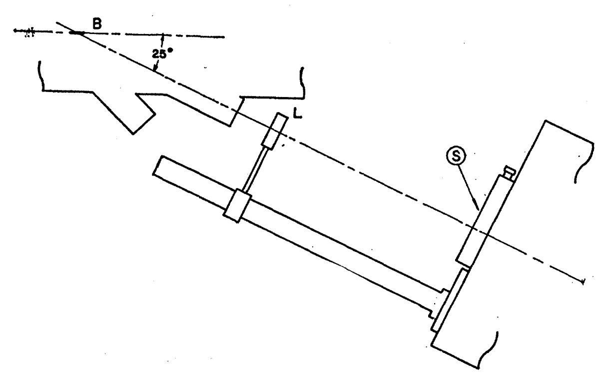

Fig. 2. Spectrometer position. The proton beam B is imaged by lens L on the spectrometer slit S.

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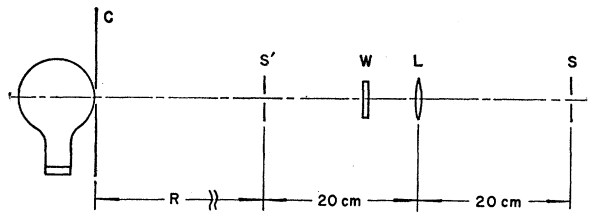

FIG. 3. Calibration of spectrometer. The standard lamp with associated diaphragm C is placed a distance R from the entrance window S' (image of the spectrometer entrance slit S formed by the fused-quartz lens L). W is the fused-quartz window used on the collision chamber.

is the ratio of this area to the distance from the window to the source squared and was much less than the maximum solid angle the spectrometer could accept. From this information we obtain the calibration equation, $N=DPa^2l/50R^2$ where N is the number of photons/sec accepted by the spectrometer and D is the spectrometer dispersion, 16 A/mm. A secondary standard lamp was then attached rigidly to the spectrometer to enable calibration checks to be made.

The spectrometer then was positioned under the collision chamber with the beam observation region being a distance of twice the focal length from the condensing lens. The angle to the beam was then measured to determine the effective length of beam under observation. Knowing the focal length of the spectrometer f and grating area A, which were taken from the manufacturer's specifications, we were then in a position to make absolute measurements. The total photon/sec yield is, of course, $4\pi f^2/A$ times the flux accepted by our spectrometer.

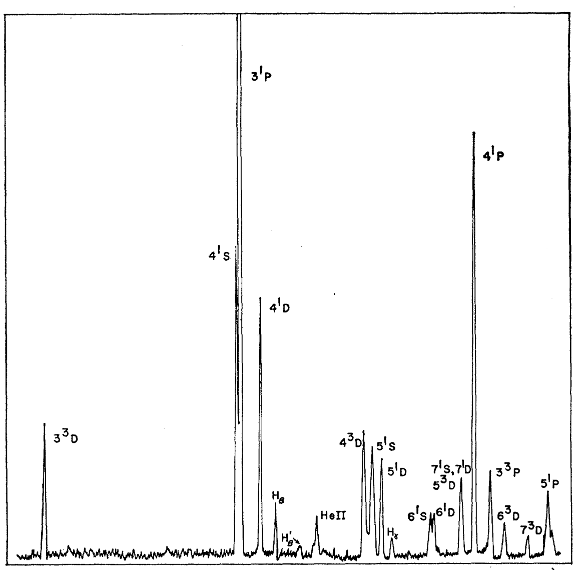

FIG. 4. Spectrogram reproduction from 200-kev proton impact on helium at 26-μ pressure and with a beam current of 0.18 μa. Helium lines are labeled by the upper state. H_β' represents the Doppler-shifted H_β line.

It is extremely difficult to estimate the uncertainty in our measurements. In addition to the uncertainties that other investigators have faced in this type of measurement, we have the uncertainty associated with observing the beam at an angle. Thus we have the disadvantage of angle uncertainties and the disadvantage of having the beam image in a different plane than the entrance slit. The condensing lens was not achromatic but showed a sharp image with white light. It would probably be unrealistic to estimate the uncertainties in our absolute measurements to be less than 40%.

III. RESULTS

Cross section measurements are included in Table I. Spectrograms were obtained at various pressures and currents. The pressure range was generally 2 μ to 30 μ while beam currents of 0.1 μa to 0.26 μa were used. Figure 4 shows a typical spectrogram. Within this limited current range all lines appeared to be linear with current, but only the $2\,^1P-n\,^1S$ lines and He II λ4686 line appeared to be linear with the pressure. The nonlinear behavior of the $2\,^1P-n\,^1D$ and $2\,^3P-n\,^3D$ transitions has been observed by other investigators using electron impact excitation. The explanation put forth is that these $n\,^3D$ and $n\,^1D$ levels are populated from the ground state by collision of the second kind with atoms in the $n\,^1P$ state.[1] We observed the $2\,^3S-3\,^3P$ line which also exhibited a nonlinear behavior which apparently was not observed in a recent electron impact experiment.[2]

To test possible electron excitation, we employed the electron repeller and varied an electric field perpendicular to the beam and viewing direction. No effect was noted in the intensity of the lines. This indicated that a low secondary-electron density existed in the viewing area and that electron excitation was not appreciable.

Excitation of the triplet system is interesting in itself. Direct excitation by proton impact would be in violation of the Wigner spin conservation rule. As long as it is assumed that spin-orbit coupling is very small, we would expect the total spin to be conserved in a system since it is commonly expected that spin dependent forces are too weak to provide the necessary spin flip. However, the well-established collisions of the second kind in which the $n\,^1P-n\,^3D$ transfer reaction takes place in helium represent a violation of the rule. It has been noted that in this case the energy differences between the involved levels are small and therefore a close resonance condition exists which seems to destroy some of the validity of the rule.

An attempt was made to study the $2\,^3P-4\,^3D$ and $2\,^1P-4\,^1D$ lines, in particular, as a function of $2\,^1S-4\,^1P$ line. It was assumed that both the $4\,^3D$ and $4\,^1D$ levels

[1] R. Wolf and W. Maurer, Z. Physik **115**, 410 (1940).
[2] D. Stewart and E. Gabathuler, Proc. Phys. Soc. (London) **74**, 473 (1959).

were populated directly and by collisions of the second kind. Defining the apparent line cross sectional σ' through the equation $P=p\sigma' nl$ (where P is the number of photons/sec, p is the number of photons/sec, n is the atom density, and l is the beam path under observation), we assume $\sigma'=\sigma_D+(\sigma_C\sigma'_1 nv/A)$. The first term represents the line cross section for direct excitation and the second term represents the excitation through the collision process. In the second term, σ_C is the collision cross section for the line production, σ'_1 is the apparent cross section for the $2\,^1S-4\,^1P$ line; A is the transition probability[3] associated with the $2\,^1S-4\,^1P$ line; n is the atom density and v is the mean thermal velocity. Figure 5 shows that this assumption seems valid within experimental error. The slopes of the lines give the collision cross section for the $2\,^1P-4\,^1D$ and

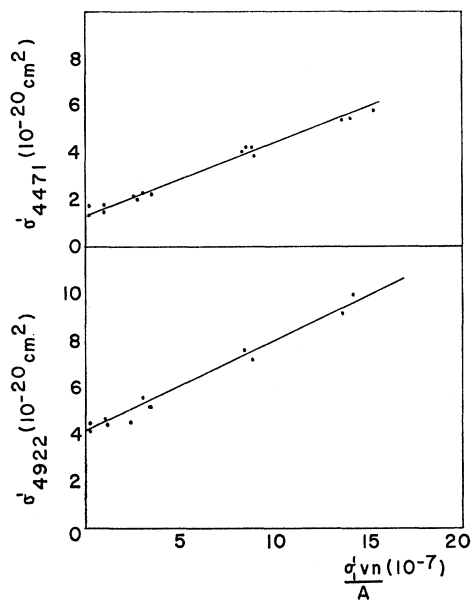

FIG. 5. Plot of the apparent cross sections of the $2\,^3P-4\,^3D$ line (λ4471 A) and the $2\,^1P-4\,^1D$ line (λ4922 A) vs the parameter $\sigma_1' vn/A$ (see text) associated with the $2\,^1S-4\,^1P$ line.

$2\,^3P-4\,^3D$ line production as 42×10^{-15} cm^2 and 29×10^{-15} cm^2, respectively. Table II shows the comparison between our measurements of transfer cross sections with those of other investigators. The cross section involving the $3\,^3P$, $3\,^3D$, and $5\,^1D$ states were obtained by the same analysis as above but with somewhat more scattering of fewer data points. The $3\,^3P$ analysis is particularly bad because of lines in the hydrogen background at low pressures in the region of λ3888. It may be noted that our cross sections appear to be large with respect to the triplet states. One possible explanation is the perturbations produced by the foreign gases in the chamber. If the perturbing influence of foreign atoms is such as to further a breakdown in

[3] E. A. Hylleraas, Z. Physik **106**, 395 (1957). (All He transition probabilities used in calculations are from this source.)

TABLE I. Direct excitation cross sections for 200-kev proton impact on helium in units of 10^{-20} cm^2.

Transition	Measured directly	σ	Level	σ	Inferred[a] Level	σ
$2\,^1P-4\,^1S$	λ5047	8.8	$4\,^1S$	17.5	$4\,^1D$	5.5
$2\,^1P-5\,^1S$	λ4437	3.5	$5\,^1S$	7.2	$4\,^3D$	2.0
$n=3-n=4$, He II	λ4686	1.3	$n=4$, He$^+$	4.3	$3\,^3D$	≈4.5
$2\,^1S-3\,^1P$	λ5016	<7.4	$3\,^1P$	<320	$3\,^3P$	≈1.9
$2\,^1S-4\,^1P$	λ3965	<5.0	$4\,^1P$	<140	$5\,^1D$	≈2.4
$n=2-n=4$, H$_\beta$ (charge exchange)	λ4772	≈0.2$_3$	$n=4$, H^0	0.8		

[a] Obtained by assuming levels are populated by direct excitation and by collisions of the second kind.

L·S coupling, then the spin conservation rule will be relaxed more. Obvious foreign gases are residual H_2 and He^+.

There is evidence that ^3D transfer excitation becomes more pronounced relative to ^1D excitation as n increases. We were unable to resolve the $2\,^3P-5\,^3D$ line even in the second order, but for $n=6$ and 7 we can state that the transfer cross section for ^3D excitation is greater than that for ^1D excitation indicating a further relaxing of the spin conservation rule. We wish to point out here that the energy separations between ^1D and ^3D states are extremely small and, of course, decrease with increasing n. In the absence of the consideration of energy differences and the spin conservation rule we would expect the ^3D transfer excitation to become relatively larger simply because there are more states available in the ^3D levels than in the ^1D level.

It is interesting to note the behavior of other triplet states. There is almost a complete absence of $2\,^3P-n\,^3S$ lines. The $2\,^3P-4\,^3S$ and the $2\,^3S-4\,^3P$ lines appeared very weakly with an apparent cross section at 30 μ of the order of 3×10^{-21} cm^2 for both transitions. Since these line cross sections essentially give the upper level population, it would appear that the ^3P and ^3S states are not populated appreciably. Thus it would appear that the "direct" excitation of the triplet states is greatest in the case of the ^3D states although the evidence is hardly conclusive.

There remains the possibility of a neutral beam component which could explain some of the direct triplet excitation. The beam, however, was magnetically analyzed and charge-exchange calculations show that certainly less than 0.5% of the beam could have been neutralized by charge exchange by the time it reached

TABLE II. Transfer reaction cross sections in units of 10^{-15} cm^2.

Transfer	200-kev proton	Absorption[a]	Electron[b]
$4\,^1P-4\,^1D$	56.7	67.0	12.3
$4\,^1P-4\,^3D$	42.3	15.0	2.6
$3\,^1P-3\,^3D$	≈36.0	11.9	
$3\,^1P-3\,^3P$	≈12.0	2.1	0
$5\,^1P-5\,^1D$	≈23.0	51.0	76

[a] See footnote 1.
[b] See footnote 2.

the observation region. Beam neutralization at the slits is a possibility but we would suspect that this is small, particularly at this energy, but perhaps should not be discounted.

It is to be noted that the ^1S states are strongly excited. It is too bad that a better comparison with the ^1P states cannot be made. We would strongly suspect that the upper limits shown for the $3\,^1P$ and $4\,^1P$ levels represent figures that are better than an order of magnitude higher than the true cross section because of the imprisonment of resonance radiation.[4] It is particularly bad in our case because of the large (4 in.) diameter of our collision chamber and the fact that the lowest pressure at which we could take data was 2 or 3 μ. The apparent cross sections for the $2\,^1S-n\,^1P$ lines were still dropping rapidly at these pressures.

The measured cross section for the simultaneous ionization and excitation of helium[5] into the $n=4$ state of He^+ agrees fairly well with a rough extrapolation of Mapleton's calculations[6,7] and the measured charge-exchange cross section into the $n=4$ state of hydrogen is small but at least the right order of magnitude from what is expected from roughly extrapolating his recent calculations[7] on charge exchange; however, it is difficult to draw conclusions.

ACKNOWLEDGMENTS

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[4] A. V. Phelps, Phys. Rev. **110**, 1362 (1958).

[5] Hydrogen transition probabilities are taken from H. A. Bethe and E. E. Salpeter, *Encyclopedia of Physics* (Springer-Verlag, Berlin, 1951), Vol. 35.

[6] R. A. Mapleton, Phys. Rev. **109**, 1166 (1958).

[7] R. A. Mapleton (private communication). Mapleton estimates for the simultaneous ionization and excitation cross section into the $n=4$ state and the charge-exchange cross section into the $n=4$ state to be 3.5×10^{-20} cm^2 and 3×10^{-20} cm^2, respectively.

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Electron Capture from He$(1s^2)$ by Protons

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The two equivalent forms of Born's approximation, prior and post, are used to calculate the electron capture cross section for protons incident on He$(1s^2)$. These cross sections are calculated for capture into eleven different final states in the energy range 12.5 kev to 1 Mev. Although a rather crude wave function, $(Z^3/\pi a_0^3)\exp[-(Z/a_0)(r_1+r_2)](Z=1.6875)$, is used for He, the prior and post total capture cross sections do not differ by more than twenty percent over the energy range investigated. Estimates of the sum of the cross sections for capture into all s states of the hydrogen atom for the two residual ions, $He^+(1s)$ and $He^+(2s)$, are obtained from an adaption of the s-state sum rule as given in the paper of Jackson and Schiff. As in this work of Jackson and Schiff, it is found that the s states provide the major contribution to the total capture cross section. The calculated cross sections agree fairly well with the experimental values. The cross sections for capture into the state $He^+(1s)+H(1s)$, is roughly 2.5 times larger than the values obtained by Bransden, Dalgarno, and King.

THE cross section for the following process (A) has been calculated in Born approximation by Bransden, Dalgarno, and King.[1]

$$H^+ + He(1s^2) \to H(1s) + He^+(1s). \qquad (A)$$

In their calculation, the prior interaction was used and the Born matrix element was evaluated approximately. In the present paper, the cross section for reaction (A) is calculated in Born approximation with both forms of the interaction, prior and post. In addition, the prior and post Born cross sections are calculated for capture into ten other final states. A comparison of the results of this paper and those of BDK will be presented later. It is a well-established fact that the prior and post cross sections are equal provided that exact atomic wave functions are used in the Born matrix elements.[2,3] Since only inexact atomic wave functions exist for atoms other than hydrogen, it is not known which of these two cross sections agree more closely with the exact Born cross section. Although the wave function, $(Z^3/\pi a_0^3)\exp[-(Z/a_0)(r_1+r_2)]$ $(Z=1.6875)$, used for He is rather crude, the prior and post total capture cross sections of this paper do not differ by more than twenty percent over the energy range investigated; moreover, they are in fair agreement with the experimental values. The reason for this apparent success

[1] B. H. Bransden, A. Dalgarno, and N. M. King, Proc. Phys. Soc. (London) **A67**, 1075 (1954). Future references to this paper are denoted by BDK.

[2] J. D. Jackson and H. Schiff, Phys. Rev. **89**, 359 (1953). Future references to this paper are denoted by JS.

[3] E. Gerjuoy, Ann. Phys. **5**, 58 (1958).