decay.

[40]A possible systematic error which could account for Schmidt's large excess-range effect is a small increase in the measured length of "stopping" or "connecting" tracks. A measured Σ^- length that is too long leads to a lower-than-"true" value of the Σ^- mass. Schmidt's experimental stopping-Σ^--range distribution, read from Fig. 10 of Ref. 32, is 1.08 ± 0.04 cm. If his Σ^- range were systematically long by about one-half the radius of a bubble ($\approx 200\,\mu$), his result would be consistent with ours. On the other hand, the same type of systematic measuring error for stopping protons from Σ^+ and Λ decays would lead to increases in the masses above their "true" values. These mass changes would, however, be a second-order effect because the proton ranges are part of a seven-parameter fit with other quantities, including a fixed proton mass, involved.

[41]R. A. Burnstein, T. B. Day, B. Kehoe, B. Sechi-Zorn, and G. A. Snow, Phys. Rev. Letters 13, 282 (1964). In this earlier determination of the Σ^- mass, a value of 1196.9 ± 0.36 MeV was determined from range measurements on stopping Σ^-, compared to a value of 1197.0 ± 0.24 MeV not using the Σ^- range. This result implies an excess range for the Σ^- of $30 \pm 200\,\mu$ which is not a statistically significant measurement.

[42]The number of Σ^+ which survive to $\beta = 0.02$ is $\approx 4\%$ of those produced and only $\approx 1\%$ survive to $\beta = 0.01$; the corresponding numbers for Σ^- are 26 and 12% based on Σ^+ and Σ^- lifetimes. The Σ^+ event rate is further reduced from the Σ^- rate by a factor of about 4 because only one-half as many Σ^+ are produced in K^-, p interactions at rest, and half of these Σ^+ decay via the uncharged pion mode, $\Sigma^+ \to p + \pi^0$.

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Lifetimes of Some Doubly Excited Levels in Neutral Helium†

H. G. Berry,* I. Martinson, L. J. Curtis,‡ and L. Lundin
Research Institute for Physics, 104 05 *Stockholm*, *Sweden*
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We have searched for radiative transitions from doubly excited levels in He I, using the beam-foil method. The spectra showed the $1s2p\,^3P$-$2p^2\,^3P$ transition at 320.4 Å and some weaker lines, which are also interpreted as transitions from the doubly excited system. Radiative lifetimes were measured for three lines. Our value for the $2p^2\,^3P$ level, 0.080 ± 0.007 nsec, is in agreement with the recent theoretical value of 0.0803 nsec. The possibilities of observing transitions from doubly excited levels in the He I isoelectronic sequence are briefly discussed.

INTRODUCTION

Evidence of doubly excited states in neutral helium was first obtained from studies of the arc spectrum of helium[1,2] and from energy-loss measurements in electron-helium collisions.[3] Compton and Boyce[1] and Kruger[2] reported unidentified spectral lines at 309.04 and 320.38 Å. The former remained unclassified, whereas Kruger tentatively assigned the latter to the $1s2p\,^3P$-$2p^{2}\,^3P$ transition in He I. This identification was later supported by Wu's calculations[4] of auto-ionization probabilities for various doubly excited terms in helium, of which those of the type $2pnp\,^1P$, ^3P, and $2pnd\,^1D$, ^3D are not expected to auto-ionize via Coulomb interaction.

In recent years, the auto-ionizing doubly excited He I levels have been the subject of many experimental and theoretical investigations. The review article by Fano[5] gives a detailed list of references. Using synchrotron radiation to excite neutral helium, Madden and Codling[6,7] observed four Rydberg series in the doubly excited ^1P system. Two of the series converged to the $n = 2$ limit of He$^+$ and were described by Cooper *et al.*[8] as $sp2n \pm (n \geq 3)$, being symmetrized mixtures of the $2snp$ and $2pns$ series members. Several of these and other doubly excited levels have also been observed as resonances in electron-helium[9–13] and ion-helium[14] collisions. Most of the doubly excited levels observed so far can autoionize to the continua above the $1s\,^2S$ ground state of He$^+$. From their Fano-type line profiles,[15] Madden and Codling[7] were able to deduce the auto-ionization probabilities for the $2s2p\,^1P$ and $sp23+\,^1P$ levels, obtaining good agreement with theory.[16] The radiative deexcitation probabilities for several auto-ionizing ^1P and ^3P states have been calculated by Knox and Rudge[17] and Dickinson and Rudge.[18]

Experimental and theoretical results for the non-auto-ionizing doubly excited He I states are not as numerous. The energy of the $2p^2\,^3P$ level has been calculated by, among others, Holøien,[19] Midtdal,[20] and Drake and Dalgarno.[21] Their eigenvalues give further support to the assignment of the 320-Å line. Drake and Dalgarno have also calculated the energy of the $2p3p\,^1P$ level and the lifetimes of both these levels. They identify the 309-Å line, observed by Compton and Boyce,[1] as the $1s3p\,^1P$-$2p3p\,^1P$ transition. The need for further experimental studies of such exactly quantized doubly excited levels has been emphasized by Holøien.[22] This article describes an investigation of these levels, using the beam-foil technique.

EXPERIMENT

We accelerated beams of He^+ to energies between 200 and 500 keV in a 2-MV Van de Graaff accelerator and directed them through a thin exciter foil (typically 10 $\mu g/cm^2$). Initially only carbon foils were used, but we found that by evaporating a very thin metal layer (e.g., Al, Cu, or Ag) on the downstream side of the foil, the light output increased by a factor of 2 or more. The radiation emitted by the foil-excited He atoms and ions was dispersed with a 3-m grazing incidence spectrometer of the Siegbahn type, equipped with a 540 1/mm grating. Reference 23 presents a more detailed description of the experimental arrangement. The photons were counted in a single-channel analyzer and the lifetimes were measured by recording the intensity decrease of the spectral lines with the distance from the foil. Data were accumulated for a fixed amount of charge, collected in a Faraday cup, and 0.1 dark counts were subtracted for each second of data accumulation. To check the experimental accuracy, the decay of the strong 303.8-Å line in He II ($1s\ ^2S$-$2p\ ^2P$) was measured after most measurements of the doubly excited levels, using the same foils and same beam particle energies. The results for the lifetime of the $2p\ ^2P$ level were within 5% of the theoretical value 0.0998 nsec.[24]

RESULTS

Wavelengths

Figure 1 shows a partial spectral scan around the 303.8-Å line. The linewidths of 1 Å are essentially instrumental in origin, the line broadening due to the scattering in the foil being about 0.1 Å at the beam energies used.

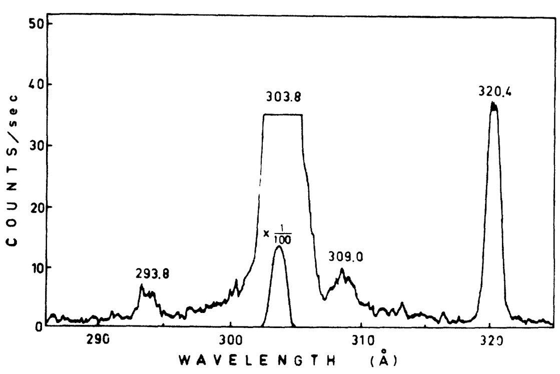

FIG. 1. Beam-foil spectrum of helium between 285 and 325 Å. The incoming beam-particle energy was 240 keV. The photons were detected with a Bendix channeltron movable on the Rowland circle. The detection system was designed by Dr. H. Oona, University of Arizona.

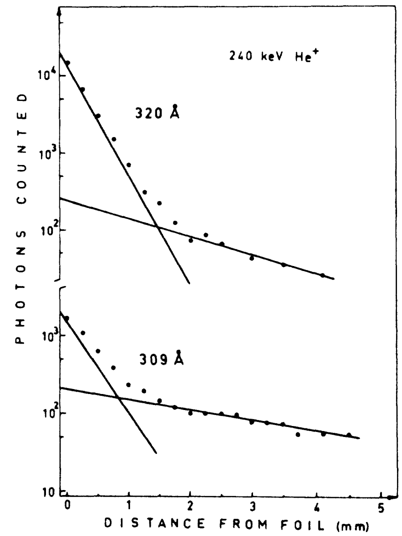

FIG. 2. Decays of the $2p^2\ ^3P$ (320Å) and $2p3p\ ^1P$ (309 Å) levels in He I.

The $1s2p\ ^3P$-$2p^2\ ^3P$ transition (320 Å) was clearly seen in all spectra. The intensity ratio 320 Å/303 Å was 0.014 at 320 keV and decreased to 0.009 at 500-keV incoming particle energy, consistent with the fact that the lines belong to different ionization stages. Other weak lines were also observed, and are given in Table I. Our experimental wavelength uncertainties are less than 0.5 Å, except for the weakest lines, which are accurate to within ± 1 Å. These wavelength uncertainties together with the limited knowledge of the non-auto-ionizing doubly excited levels makes identifications difficult. However, we present in Table I some tentative classifications, using the energies calculated in Refs. 17, 18, 21, and the unpublished $2p3p\ ^3P$ eigenvalue of -1.1356256 Ry.[22] The $sp23$-^1P terms are expected to be nearly stable against auto-ionization[8] and their radiative deexcitations to singly excited ^1S terms could be the origin of some of the weak lines in our spectra. The line at 309.0 Å in the beam-foil spectra is probably the $1s3p\ ^1P$-$2p3p\ ^1P$ transition. The corresponding triplet transition $1s3p\ ^3P$-$2p3p\ ^3P$ has a theoretical wavelength of 305.8 Å.[22] We noticed an unresolved wing at 306 Å in the strong 303-Å line, which could be this transition. We have tentatively classified the line observed at 293.8 Å as the $1s2s\ ^1S$-$sp23-{}^1P$ transition. Also considered were the $1s2p\ ^1P$- $2p3p\ ^1P$ and $1s2p\ ^3P$-$2p3p\ ^3P$ transitions, which have calculated wavelengths of 295.2 and 291.1 Å, respectively,[21,22] but these values differ too much from the observed wavelength. However, we observed a very weak line at 295.2 Å, whereas no transitions could be observed around 291 Å. It is interesting that transitions from the $2p3p\ ^3P$ level are not more prominent in our spectra, but it is pos-

TABLE I. Transitions and radiative lifetimes of doubly excited levels in He I.

Observed wavelength (Å)[a]	Transition	Calculated wavelength (Å)	Lifetime of upper level (nsec) This work	Theory
285 ± 1	$1s2s\,^3S$-$sp23$-$\,^3P$ (?)	285.3[b]		
293.8	$1s2s\,^1S$-$sp23$-$\,^1P$	294.0[c]	0.116 ± 0.020	0.36[c]
295.2	$1s2p\,^1P$-$2p3p\,^1P$	295.2[d]		
306 ± 1	$1s3p\,^3P$-$2p3p\,^3P$ (?)	305.8[e]		
309.0	$1s3p\,^1P$-$2p3p\,^1P$	309.0[d]	0.105 ± 0.015	0.0975[d]
311.0	$1s3s\,^1S$-$sp23$-$\,^1P$	311.0[c]		
320.4 ± 0.3	$1s2p\,^3P$-$2p^2\,^3P$	320.3[d]	0.080 ± 0.007	0.0803[d]

[a]The transitions listed here appeared reproducibly in all spectral scans at 240 keV, and were not attributed to instrumental reflections or ghosts. The wavelength uncertainties are ± 0.5 Å, unless otherwise noted.
[b]Reference 17.
[c]Reference 18.
[d]Reference 21.
[e]Reference 22.

sible that the lowest non-auto-ionizing singlet and triplet states $2p3p\,^1P$ and $2p^2\,^3P$ are preferentially populated at the beam-foil interaction. In Table I, we also give preliminary classifications of a few additional lines, also observed in the beam-foil spectra. Kruger's tables[2] include also a line at 357.5 Å. We searched for this line but found no indications of it in our spectra.

Lifetimes

We were able to follow the intensity decays of the spectral lines at 320, 309, and 294 Å. The results are given in Table I. Figure 2 shows two examples of decay curves. The decay of the $2p^2\,^3P$ level (320 Å) was measured at 240 and 500 keV and the value 0.080 ± 0.007 nsec is the mean value of five measurements. The inverse of this value, $(1.25 \pm 0.11) \times 10^{10}$ sec^{-1}, is in excellent agreement with the sum of probabilities for transitions from $2p^2\,^3P$ to $1s2p$, $3p$, and $4p\,^3P$, 1.245×10^{10} sec^{-1}, calculated by Drake and Dalgarno.[21] The $2p^2\,^3P$ level may also decay to the auto-ionizing level $2s2p\,^3P$, at a wavelength of 9400 ± 20 Å, but this has not been observed. The close agreement between this work and theory suggests that the probability for the $2s2p\,^3P$-$2p^2\,^3P$ transition is comparatively low. The decay curve in Fig. 2 indicates that the 320-Å line has a weak cascade contribution, corresponding to a lifetime of approximately 1 nsec. The cascading may be due to transitions from the $2p3d\,^3D$ level, the energy of which has been calculated by Becker and Dahler.[25] Possible radiative transitions $2p^2\,^3P$-$2p3d\,^3D$ should have a wavelength of about 3000 Å. In a beam-foil experiment, using 83-keV He^+ from an isotope separator, a few weak lines were observed,[26] which may originate from doubly excited D terms. The decay curves for the 309-Å line infer a lifetime of 0.105 ± 0.015 nsec for the $2p3p\,^1P$ level, which agrees with the theoretical value of 0.0975 nsec.[21] The effects of cascading were more pronounced, with a cascade lifetime of 1.2 nsec, the origin of which is unknown. Measurements of the 294-Å transition yielded a lifetime of 0.116 ± 0.020 nsec, which differs from the radiative lifetime of 0.36 nsec for the $sp23$-$\,^1P$ level, estimated by Dickinson and Rudge.[18] However, if the auto-ionization channel is not completely closed, a shorter experimental lifetime is plausible.

He I ISOELECTRONIC SEQUENCE

The $1s2p\,^3P$-$2p^2\,^3P$ transition has been observed in Be III (78.662 Å) by Goldsmith[27] and in B IV, C V, and O VII by Edlén and Tyrén.[28] The experimental wavelengths agree very well with Drake and Dalgarno's calculations for the He I isoelectronic sequence.[21] The Be III transition appears also in spark spectra, taken with our grazing incidence spectrograph.[29] Goldsmith has identified radiative transitions from the auto-ionizing $2s2p\,^3P$ and $2p^2\,^1D$ levels in Be III. In the beam-foil spectra of helium, no He I transitions from these levels could be observed. This is hardly surprising, however, because in He I their auto-ionization probabilities are expected to be orders of magnitude higher than the radiative decay constants.

Work is in progress to extend the beam-foil studies of doubly excited terms to higher members of the He I isoelectronic sequence.

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*Present address: Faculté des Sciences, Université de Lyon, 69 Villeurbanne, France.

‡On leave of absence from the University of Toledo, Toledo, Ohio 43606.

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Analytic Self-Consistent-Field Wave Functions for the $(3d)(4s)$ Configuration of the Transition-Metal Ions

James M. Minor and Raymond W. Mires
Department of Physics, Texas Technological University, Lubbock, Texas 79409
(Received 23 November 1970)

The Roothaan method has been used to calculate analytic self-consistent-field functions for the excited $(3d)(4s)$ configuration for the first-row transition-metal ions which normally have a $(3d)^2$ ground configuration. Wave functions are calculated for both ^1D and ^3D multiplets arising from the excited configuration. The separations of these two multiplet levels from the ground $(3d)^2\ ^3F$ level deviate from experiment by 3–8%.

INTRODUCTION

In two recent publications[1,2] the effect of electron correlation on the multiplet structure of open-shell atoms and ions was investigated. The electron configurations of interest were $(2p)^2$ and $(3d)^2$, and the starting point for all of the calculations was the self-consistent-field (SCF) functions. The results were very satisfying and prompted an extension of the method to the case of two nonequivalent electrons outside of closed shells. For this purpose, the $(3d)(4s)$ excited configuration of those transition-metal ions which normally have a $(3d)^2$ ground configuration was chosen. However, the SCF functions for the ^1D and ^3D levels arising from this excited configuration were not available. This and the need for such functions in optical studies and configuration interaction calculations made it apparent that the SCF functions for this configuration should be generated and made available in the literature.

In this paper, the results of an SCF calculation based on the expansion method[3] are reported for the two multiplet levels of the $(3d)(4s)$ configuration of the transition-metal ions Ti III through Ni IX. For the first three ions in this series, the results are compared with experimental data. All the computation was done in double precision on an IBM 360/50