## Atomic Lifetimes of Low-Lying Levels in Multiply Charged Ions of Gallium, Germanium, Arsenic, and Selenium

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The foil-excitation technique has been used to study atomic lifetimes in multiply charged ions at moderate ion energies (i.e., below 1 MeV). The emission spectra of foil-excited ion beams of gallium, germanium, arsenic, and selenium at 450-keV initial ion energy showed low-lying transitions in Ga II, Ga III, Ge III, Ge IV, As IV, As V, Se V, and Se VI with sufficient spectral intensity for lifetime determinations. In the Cu I sequence, seven lifetimes of transitions in Ga III through Se VI have been measured, while for the Zn I sequence, eight lifetimes of singlet and triplet levels in Ga II through Se V have been reported. Systematic trends in f values for  $4s^2S-4p^2P$  and  $4p^2P-4d^2D$  transitions in the Cu I sequence and for  $4s^{21}S-4s4p^{1}P$  and  $4s4p^{3}P-4s4d^{3}D$  transitions in the Zn I sequence have been studied and compared with similar trends in the Na I and Mg I sequences. Based upon the experimental results, f values for transitions in Br VII through Sr x and Br VI through Sr IX have been found by extrapolation and compared with theoretical and experimental results for homologous atoms with lower masses.

#### I. INTRODUCTION

In recent years, the foil-excitation technique has been used extensively for systematic measurements of atomic lifetimes of excited levels in neutral as well as ionized atoms. The lifetimes measured with this technique as well as by other experimental methods have considerably improved the accuracy of oscillator strengths for a large number of atomic transitions. Studies of the regularities in the fvalues along isoelectronic sequences were initiated by Wiese and co-workers<sup>1,2</sup> with the purpose of establishing accurate *f* values for transitions which have not been measured or calculated. For a large number of transitions, so far only theoretical values have been available, and often with large discrepancies between the various theoretical approaches.

Accurate experimental data have often resulted in more refined theoretical calculations. An example is the 2s2p  $^{1}P-2p^{21}D$  transitions in the Ber sequence, for which f values calculated by Weiss, <sup>3</sup> Linderberg, <sup>4</sup> and Laughlin and Dalgarno<sup>5</sup> have converged towards the experimental results obtained by means of the foil-excitation technique, and they now agree within the experimental uncertainty.

A number of foil-excitation studies are available for transitions in multiply charged ions, especially for ions belonging to the Na I and MgI sequences. Lifetimes of excited states in low-charge states of sodium, magnesium, and aluminum have been reported by Berry *et al.*<sup>6</sup> and Andersen and coworkers.<sup>7-9</sup> Atomic-lifetime measurements in Si II-Si IV<sup>10</sup> and PI-PV<sup>11,12</sup> have been performed at moderate energies well below 1 MeV by using either an electromagnetic isotope separator or a 600-kV heavy-ion accelerator. With an 0.5-2MeV sulphur beam from a Van de Graaff accelerator, Berry *et al.*<sup>13</sup> have measured lifetimes of transitions in multiply charged ions of sulphur. Their values for transitions in Sv and SvI are, however, considerably lower than predicted by isoelectronic comparisons and may not be correct. In a recent compilation, Smith and Wiese<sup>14</sup> have shown a graphical representation of the systematic trends of f values along isoelectronic sequences up to the MgI sequence. New f values may be derived by interpolation from such data.

With respect to medium- and heavy-mass atoms, very few lifetimes have so far been reported for transitions in multiply charged ions, mainly owing to experimental difficulties at high initial ion energies.

In foil-excitation studies, the initial ion energy has usually been varied according to the ionic charge state studied. A high initial energy favors the excitation of levels in high ionic charges, while levels in neutral and singly ionized species are preferentially populated at low initial ion energies.<sup>8</sup> At high initial energies, a poor spectral resolution, owing to the Doppler effects, and line blending from the large number of charge states being populated cause serious difficulties in the spectral identification. Thus Hallin *et al.*<sup>15</sup> have hardly been able to resolve a ClxII line from a Clx line separated by 80 Å, when a 16-MeV chlorine-ion beam is foil-excited.

Previous studies have shown that excited states in Al111, Si IV, and Pv are populated at energies below 500 keV.  $^{8,10-12}$  Only low-lying transitions are populated with an intensity sufficient for lifetime determinations. However, serious experimental difficulties, such as poor spectral resolution and excessive line blending from a large va-

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riety of charge states, are avoided.

It has been the purpose of the present study to determine atomic mean lives of low-lying excited states in the isoelectronic atoms  $Ga_{II}$ -Se v and  $Ga_{III}$ -Se vI by using a low initial ion energy ( $\leq$  500 keV). At such energies, only few transitions in  $Ga^{*}$  to Se<sup>5\*</sup> ions are accessible for beam-foil studies. In the present case, four isoelectronic sequences were selected with the purpose of searching for systematic trends in isoelectronic and homologous sequences.

### **II. EXPERIMENTAL TECHNIQUE**

With the 600-kV heavy-ion accelerator at the University of Aarhus, 450-keV ion beams of Ga, Ge, As, and Se were foil-excited, and the lifetimes of selected levels measured. The ion accelerator is equipped with a universal ion source. The ion beam of gallium was obtained the same way as described for aluminum by a reaction where the volatile chloride is synthesized from the oxide by means of carbon tetrachloride.<sup>8</sup> The ion beams of germanium, arsenic, and selenium were obtained by heating various chemical compounds to certain temperatures in a small, electrically heated furnace connected with the ion source. For the following charge materials, the approximate furnace temperatures are indicated: GeI<sub>4</sub> (150 °C), As<sub>2</sub>S<sub>3</sub> (100  $^{\circ}$ C), and Se (elemental) (120  $^{\circ}$ C).

In the present study, typical beam currents were 0.1  $\mu$ A with a circular beam diameter of 1-2 mm, and 5- $\mu$ g/cm<sup>2</sup>-thick carbon foils were used. Because of the short mean lives measured, the carbon foils were moved by means of a step-motor equipped with a control unit to ensure a stepwise movement of the foils of a few tenths of a millimeter. The radiation emitted downstream of the

TABLE I. Spectral transitions used for the measurement of lifetimes.

Ion	Transition	Wavelength measured (Å)
Sevī	$4s^2S - 4p^2P$	844,887
Asv	-	1029,988
Geıv		1229
Ga III		1495
Asv	$4p^2P-4d^2D$	734
Ge IV		915,938
Ga III		1294
Sev	$4s^{2} S - 4s4p P$	759
As IV		892
Ge III		1088
Ga 11		1414
Sev	$4s4p^{3}P-4s4d^{3}D$	615
As iv		748,762
Ge III		995
Gan		1515

foil was dispersed with a 0.5-m model 235 McPherson-Seya-Namioka spectrometer with a Bendix channeltron detector (model 33029-X) for measurements in the extreme ultraviolet region (500-1300 Å), while the wavelength region beyond 1300 Å was measured with either a sodium-salicylate-coated EMI-6256S or a Bendix-762X channeltron detector.

#### **III. RESULTS**

#### A. Spectral Transitions

In studies of multiply charged ions, blending of lines from other charge states may be a serious problem, even at moderate energies, and therefore only the strong transitions can be studied. In the Cu<sub>I</sub> sequence, the  $4s^{2}S-4p^{2}P$  and the  $4p^{2}P$ - $4d^{2}D$  transitions were investigated, whereas in the Zn I sequence, the  $4s^{2}IS-4s4p^{1}P$  and the  $4s4p^{3}P_{1/2}$ - $4s4d^{3}D$  transitions were studied. The spectral resolution was sufficient to resolve the doublet transitions, but not the triplet transitions in all cases. Even so, it has not been possible to measure the lifetimes of all transitions because of line blending from other charge states. The spectral transitions, which have been utilized in the present study, are listed in Table I.

In Ga11, the 1495-Å line from the  $4s \, {}^{2}S_{1/2}$ - $4p \, {}^{2}P_{3/2}$  transition was well separated from the weak spectral lines at 1505-1515 Å in Ga II ( $4s4p \, {}^{3}P$ - $4s4d \, {}^{3}D$ ). The spectral line measured at 1294 Å is a blend of the  $4p \, {}^{2}P_{3/2}$ - $4d \, {}^{2}D_{3/2}$  and  $4p \, {}^{2}P_{3/2}$ - $4d \, {}^{2}D_{5/2}$ transitions, but it is reasonable to assume identical mean lives for the two upper states.

A partial scan of the observed emission spectrum in Gerv is shown in Fig. 1. Concerning the  $4s^{2}S-4p^{2}P$  transitions, the 1189-Å line cannot be measured owing to blending from  $5s^2S-6p^2P$  transitions at 1183 Å. The lifetime was exclusively based upon measurements at several wavelengths around 1229 Å in order to minimize the effect from the 1237-Å line from the 4s4p  $^{3}P_{2}$ -4s4d  $^{1}D$  transition in Gem. This intercombination line is assumed to have a lifetime much longer than the low-lying states in Gerv and thus should not interfere with the present measurement. For the  $4p^2P-4d^2D$ transitions in Ge IV, the  $4p^2 P_{1/2} - 4d^2 D_{3/2}$  transition at 915 Å and a blend of  $4p \, {}^2P_{3/2} - 4d \, {}^2D_{3/2}$ , <sub>5/2</sub> transitions at 938 Å were studied. An unassigned line was present at 908 Å (Fig. 1).

In Fig. 2 are shown partial scans of the observed emission spectrum for arsenic from 700 to 765 Å and from 885 to 1035 Å. In Asv, the lifetime measurement of the 4p <sup>2</sup>P state was based upon the 988- and 1029-Å transitions well resolved from other lines in the emission spectrum. The 734-Å line from the 4d <sup>2</sup>D state was resolved from a weak spectral line at 742 Å (As IV).

In Sevi, it was possible to measure the lifetime



FIG. 1. Partial spectrum observed downstream of the exciter foil with a 450-keV germanium-ion beam.

of the  $4p^2P$  state based upon both the 844- and 887-Å transitions, which were well resolved from a weaker 840-Å spectral line in Sev. The strongest of the observed transitions from the  $4d^2D$  levels were at 606 and 608 Å, but these lines could not be sufficiently separated from the  $4s4p^3P-4s4d^3D$ transitions in Se v at 602 and 613 Å.

For the singlet transitions in the ZnI sequence, the observed lines in GaII, GeIII, ASIV, and SeV are all from the 4s4p<sup>1</sup>P level. They were all well resolved from weak neighboring lines. An example is shown in Fig. 2, where the singlet transition in ASIV at 892 Å is much more intense than an 888-Å



FIG. 2. Partial spectrum observed downstream of the exciter foil with a 450-keV arsenic-ion beam.

line in AsIII.

In the case of the triplet transitions in the ZnI sequence, the 4s4p<sup>3</sup>P-4s4d<sup>3</sup>D transitions with sufficient intensity for lifetime measurements were observed, but very often the spectral line selected was blending with spectral lines from the same multiplet.

In GaII, the lifetime measured was based upon the 1515-Å line from  $4s4p^{3}P_{1}-4s4d^{3}D_{1,2}$ . The stronger transitions at 1536 Å could not be used owing to blending from a 1534-Å line from  $4s^{2}S$ - $4p^{2}P$  in GaIII. The spectral line utilized in GeIII (995 Å) is an admixture of  $4s4p^{3}P_{1}-4s4d^{3}D_{1}$  and  $4s4p^{3}P_{1}-4s4d^{3}D_{2}$  transitions not quite resolved from the  $4s4p^{3}P_{0}-4s4d^{3}D_{1}$  transition at 989 Å (Fig. 1). In AsIV, lifetime measurements have been performed on spectral lines at 748 and 762 Å. Both these lines are admixtures of lines depopulating the  $4s4d^{3}D_{1}$  and  $4s4d^{3}D_{2}$  levels. In SeV, the 615-Å line  $(4s4p^{3}P_{2}-4s4d^{3}D_{3})$  used for the measurement was well resolved from a neighboring line at 608 Å  $(4p^{2}P-4d^{3}D$  in SeVI).

### **B.** Lifetime Measurements

The atomic mean lives are evaluated from the decay of spectral intensities downstream of the exciter foil. The velocities of the excited ion beams may be either determined experimentally or calculated from theoretical stopping theory. A detailed discussion on this subject has been prepared for publication elsewhere.<sup>9</sup>

In the present study, the energy-loss corrections used are those theoretically estimated, as discussed in Ref. 9. For 450-keV ion beams of Ga, Ge, As, and Se, the energy loss corresponds to a velocity of the excited beam in the range  $1.03-1.07 \times 10^8$  cm/sec.

Cascading is a serious problem in all foil-excitation studies. In this study, only strong low-lying transitions have been measured, and it has there-

 TABLE II.
 Measured lifetimes in the Cui and Zni sequences.

Ion	Level	au (nsec)	au long cascade (nsec)
Sevi	$4p^2P$	$0.65 \pm 0.06$	•••
Asv	$4p^2P$	$0.66 \pm 0.10$	
Geıv	$(\hat{4p^2P})$	$0.90 \pm 0.10$	• • •
GaIII	$4p^2P$	$1.15 \pm 0.1$	•••
Asv	$4d^2D$	$0.35 \pm 0.06$	2
Geıv	$4d^2D$	$0.40 \pm 0.05$	2.5
Gam	$4d^2D$	$\textbf{0.48} \pm \textbf{0.08}$	2.5
Sev	$4s4p^{1}P$	$0.27 \pm 0.05$	2
Asıv	$4s4p^{1}P$	$0.32 \pm 0.03$	> 5
Ge III	$4s4p^{1}P$	$0.39 \pm 0.06$	3
Gan	$4s4p^{1}P$	$0.65 \pm 0.08$	3
Sev	$4s4d^3D$	$0.23 \pm 0.05$	2.5
As w	$4s4d^3D$	$0.36 \pm 0.04$	3
Ge III	$4s4d^3D$	$0.45 \pm 0.05$	2
Ga 🏾	$4s4d^3D$	$1.1 \pm 0.2$	> 5

fore not been difficult to subtract the cascading component. In cases where the cascading level has a shorter mean life than the level studied, such as the  $4^2P$  levels in the Cu<sub>I</sub> sequence, a growing-in close to the foil is observed. The cascade-corrected mean lives are shown in Table II. Included in the table are the experimentally measured mean lives of long-lived cascading components. For the  $4p^2P$  levels, no long-lived cascading component was observed.

### C. Evaluation of the f Values

The atomic lifetimes listed in Table II have been converted into atomic oscillator strengths by using formula

$$f_{ik} = 1.4992 \times 10^{-16} \lambda^2 (g_k/g_i) A_{ki}$$

where  $\lambda$  is the wavelength in Å and  $A_{ki}$  the transi-

tion probability evaluated from the measured lifetimes. It has been assumed that the levels in the multiplets have identical mean lives. Consequently, the statistical weights  $g_k$  and  $g_i$  used for the upper and lower level, respectively, apply to the combined multiplets under the assumption of pure LS coupling. The evaluated f values for  ${}^2S-{}^2P$  and  ${}^2P-{}^2D$  transitions in the Cu<sub>I</sub> sequence are shown in Table III. For the Zn<sub>I</sub> sequence, the fvalues for  ${}^1S-{}^1P$  and  ${}^3P-{}^3D$  transitions are listed in Table IV.

For a correct *f*-value evaluation it is necessary to know the branching ratios within the multiplets. No reliable data exist for the very ultraviolet (UVU) transitions studied in the present work. But is it possible to obtain a check on the validity of the *LS* coupling by observing relative intensities in the emission spectrum. Thus, for 988- and 1029-Å transitions from  $4s \, {}^2S-4p \, {}^2P$  in As v (Fig. 2), the observed spectral intensity ratio 988/1029 is 2.4  $\pm$  0.5. When making a rough correction for differences in detection efficiency, the *LS* intensity ratio of 2 is obtained within 25% accuracy.

### **IV. DISCUSSION**

In Tables III and IV are included f values evaluated for transitions in Zn<sub>I</sub>, Zn<sub>II</sub>, <sup>16</sup> and Cu<sub>I</sub>.<sup>17</sup> These f values are based upon the lifetimes obtained by foil-excitation technique. For comparison, f values for transitions in homologous atoms in the Na<sub>I</sub> and Mg<sub>I</sub> sequences have also been included in the tables.

It is also shown in Tables III and IV that for medium-mass atoms in the Cu<sub>I</sub> and Zn<sub>I</sub> sequences, f values exhibit a systematic trend along the sequence. A comparison of the homologous atoms in the Na<sub>I</sub> and Mg<sub>I</sub> sequences shows that transitions in homologous atoms often have identical f values within the experimental uncertainties. This is the

	Cu <sub>1</sub> sequence	e			Na I sequence	e NBS
Ion	Transition	f value	Ion	Transition	f value	value <sup>a</sup>
Cur	$4s^2S-4p^2P$	0.64 <sup>b</sup>	Naı	$3s^2S-3p^2P$	0.96 <sup>c</sup> 0.92 <sup>d</sup>	0.98
ZnII	- 1	0.60 <sup>e</sup>	Mg II	•	0.78 <sup>d</sup> 0.83 <sup>f</sup>	0.94
GaIII		0.88	Alm		0.75 <sup>d</sup>	0.88
Gerv		0.75	Si rv		0.73 <sup>g</sup>	0.80
As v		0.69	Ρv		0,80 <sup>h</sup> 0,57 <sup>i</sup>	0.67
Sevi		0.52	SVI		$0.53^{j} 0.14^{k}$	0.64
ZnII	$4p^2P-4d^2D$		MgII	$3p^2P-3d^2D$	$0.85^{d} 1.02^{f}$	0.92
Ga III	F	0.88	Alm		0,72 <sup>d</sup>	0,94
Geiv		0.54	Sirv		0,70 <sup>g</sup>	0.84
Asv		0.39	Pv		0.63 <sup>h</sup>	0.69
<sup>a</sup> Refere	nce 2.	<sup>d</sup> Reference 6.	<sup>f</sup> Reference 7.	hRefe	erence 11.	<sup>j</sup> Reference 19.
<sup>b</sup> Refere	nce 17.	<sup>e</sup> Reference 16.	<sup>g</sup> Reference 10	<sup>i</sup> Refe	erence 18.	<sup>k</sup> Reference 13.
<sup>c</sup> Refere	nce 9.					

TABLE III. Comparison of f values in the Cui and Nai sequences.

	Znıseq	uence		Mg I sequence				
Ion	Transition	f value	Ion	Transition	f value	NBS value <sup>2</sup>		
Znı	$4s^{21}S - 4s4p^{1}P$	1.35 <sup>b</sup>	Mgı	$3s^{2}S - 3s^{3}pP$	2.4° 1.67 <sup>d</sup>	1.81		
Ga11	· ·	1.39	AlII	-	1.9°	1.84		
Ge III		1.38	Si 111		1.7°	1.70		
Asıv		1.12	Prv		1.8 <sup>f</sup>	1.60		
Sev		0.96	Sv		0.24 <sup>g</sup> 1.6 <sup>h</sup>	1.46		
Gan	$4s4p^{3}P - 4s4d^{3}D$	0.53	Al 11	$3s3p^{3}P - 3s3d^{3}D$	0.96°	0.90		
Ge III	-	0.55	SiIII	-	0.87°	0.89		
AsIv		0.40	P rv		0.47 <sup>f</sup>	0.80		
Se v		0.42	Sv	· · · · · · · · · · · · · · · · · · ·	• • •	0.70		
<sup>a</sup> Reference 2. <sup>b</sup> Reference 17.		<sup>c</sup> Reference 6. <sup>d</sup> Reference 7.	<sup>e</sup> Reference 10. <sup>f</sup> Reference 11.		<sup>2</sup> Reference 13. <sup>h</sup> Reference 19.			

TABLE IV. Comparison of f values in the Zn I and Mg I sequences.

case in the Cu<sub>I</sub>-Na<sub>I</sub> sequences (Table IV) for all the  $4s {}^{2}S-4p {}^{2}P$  transitions except for Cu<sub>I</sub> and Na<sub>I</sub>. The values previously reported for Pv <sup>11</sup> and S vI <sup>13</sup> do not fit this systematic trend.

A similar trend has previously been observed for a number of transitions in Ga1, In1, and Tl1.  $^{20}$ 

The  $4p^2P-4d^2D$  transitions in the Cu<sub>I</sub> sequence show systematically lower f values than in the Na<sub>I</sub> sequence, with the exception of Ga<sub>III</sub> and Al<sub>III</sub>. In the Zn<sub>I</sub> sequence, the f values are significantly lower than for the Mg<sub>I</sub> sequence. The present data also seem to show a general trend for the f values



FIG. 3. *f*-value systematics for  $4s {}^{2}S-4p {}^{2}P$  (solid line) and  $4p {}^{2}P-4d {}^{2}D$  (dashed line) transitions in the Cui sequence.

in the Cu<sub>I</sub> and Zn<sub>I</sub> sequences to decrease much more rapidly with increasing ionic charge than in the Na<sub>I</sub> and Mg<sub>I</sub> sequences.

Only a few theoretical studies exist on oscillator strengths of the ionized atom in the Cu<sub>I</sub> and Zn<sub>I</sub> sequences. Thus Zilitis<sup>21</sup> has reported values for the  $4s^{2} {}^{1}S {}^{-}4s4p {}^{1}P$  and  $4s4p {}^{3}P {}^{-}4s4d {}^{3}D$  transitions in the Zn<sub>I</sub> sequence almost a factor of 2 larger than the present values. Also, Warner<sup>22</sup> has calculated *f* values for transitions in Zn<sub>I</sub>, Ga<sub>II</sub>, Ge<sub>III</sub>, and As<sub>IV</sub> considerably higher than the present data, but in agreement with Zilitis's calculations.

There is no doubt, however, that the theoretical calculations yield too high f values. For  $4s^{2}$  <sup>1</sup>S-4s4p <sup>1</sup>P in Zn I, three other f values reported previously are in agreement with the present result.<sup>17</sup>

The study of the f values along an isoelectronic sequence has two perspectives: (i) It is possible by interpolation to obtain reliable f values for transitions which cannot be measured because of experimental difficulties; (ii) it is also possible to perform extrapolations to even higher-charge states, where a combination of the wavelength region for the transitions and the short lifetimes makes a direct measurement difficult from an experimental point of view. Figures 3 and 4 show a graphic representation of the *f*-value systematic obtained for transitions in the Cu<sub>I</sub> and Zn<sub>I</sub> sequences. An attempt to extrapolate to ions with higher charge states is indicated in the figures. In all cases studied. the *f* values of the hydrogenic ions are zero, facilitating the extrapolation procedure. For the ions Brv11 through Srx and Brv1 through  $Sr_{1X}$ , the extrapolated f values are listed in Table V for the  ${}^{2}S{}^{-2}P$  and  ${}^{1}S{}^{-1}P$  transitions, respectively. For the homologous atoms with lower masses, the f values collected in Refs. 1 and 2 are included in order to compare f values in homologous atoms.

For Clv1 through Ca1x, Wiese *et al.*<sup>2</sup> have used the charge-expansion technique of Crossley and



FIG. 4. *f*-value systematics for  $4s^{21}S-4s4p$  <sup>1</sup>*P* (solid line) and 4s4p <sup>3</sup>*P*-4s4d <sup>3</sup>*D* (dashed line) transitions in the ZnI sequence.

Dalgarno, <sup>23</sup> which includes a limited configuration mixing. For some of the transitions listed in Table V, the dependence of the oscillator strength on the nuclear charge has served as an aid in estimating the uncertainties which usually are quoted to be within 10%. Recently, Bashkin and Martinson<sup>24</sup> reported mean lives in Cl II through Cl VII. For the 3p <sup>1</sup>P level in Cl VI, they measured a lifetime 0.21±0.03 nsec, corresponding to an *f* value of 0.96, in good agreement with the present value (0.88) predicted for  $4s^{2} S - 4s4p$  <sup>1</sup>P transitions in Br VI. In this case, the theoretically estimated *f*  value of 1.28 for the  $3s^{2} S - 3s 3p P$  transition in Clv1 adopted by Wiese *et al.*,<sup>2</sup> with a quoted uncertainty of 10%, seems to be some 30-40% too high.

For Clvn through Cax, the f values listed in Table V are based on the calculations of Stewart and Rothenberg, <sup>25</sup> who employed a scaled Thomas-Fermi potential, and the calculations of Crossley and Dalgarno.<sup>23</sup>

Bashkin and Martinson<sup>24</sup> have measured the lifetime for the 3p <sup>2</sup>P level in ClvII to be  $0.55\pm0.05$ nsec, corresponding to an f value of 0.52, which is close to the predicted value (0.55) for the 4s <sup>2</sup>S-4p <sup>2</sup>P transition in BrVII. For FVII through Mg x and FVI through Mg IX, the calculations of Weiss<sup>26</sup> (self-consistent field) and the charge-expansion calculations by Naqvi and Victor<sup>27</sup> are utilized as a source, together with the lifetime experiments by Berkner *et al.*<sup>28</sup> for FVII and NeVIII.

The estimated uncertainties are better than 10% for FvII and NeVIII, whereas the f values for FvI through Mg IX are estimated with uncertainties up to 50%. From the systematic trends observed in Table V, there is a good agreement between the fvalues extrapolated from the present study for  ${}^{2}S-{}^{2}P$  transitions in BrVII through Sr X and the f values in Ref. 2 for ClVII through CaX. For the  ${}^{1}S-{}^{1}P$ transitions, the extrapolated f values in BrVI through Sr IX are significantly lower than those quoted for ClVI through CaIX.<sup>2</sup>

It has been shown that an f-value systematic may be obtained also for multiply charged mediummass atoms. From the homologous trends observed in the present study, it is possible to evaluate reliable f values for a number of transitions in homologous and isoelectronic atoms. A study of the systematic trends along homologous and isoelectronic sequences may be of value for the improvement of the theoretical estimates of atomic transition probabilities.

The present study has also shown the possibility of obtaining reliable f values for transitions in highly charged ions. Instead of performing foilexcitation studies with severe experimental difficulties involved, it has been possible, by extrapola-

TABLE V. Homologous trends in f values of multiply charged ions.

${}^{2}S-{}^{2}P$ transitions					$^{1}S-^{1}P$ transitions						
Ion	f value extrapolated	Ion	f value <sup>a</sup>	Ion	f value <sup>a, b</sup>	Ion	f value extrapolated	Ion	f value <sup>a</sup>	Ion	f value <sup>a, b</sup>
BrvII	0.55	Clvn	0.63	FvII	0.17	Brvı	0.88	Clvi	1.28	Fvi	0.62
KrvIII	0.50	Arviii	0.57	NevIII	0.15	Krvu	0.83	Arvn	1.21	Nevn	0.57
Rbıx	0.47	Kr IX	0.54	Na ix	0.14	RbvIII	0.78	KvIII	1.14	Navm	0.35
Srx	0.45	Cax	0.53	Mg x	0.13	$\operatorname{Sr}\mathbf{I} \mathbf{X}$	0.75	Carx	1.09	Mg IX	0.32

<sup>a</sup>Reference 2.

<sup>b</sup>Reference 1.

tion and comparisons between homologous atoms, to evaluate consistent f values for transitions in ions with higher charge states than those studied experimentally in the present investigation.

<sup>1</sup>W. L. Wiese, M. W. Smith, and B. M. Glemon, Atomic Transition Probabilities, NBSNSRDS-4 (U. S. GPO, Washington, D. C., 1966), Vol. I.

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### PHYSICAL REVIEW A

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# Multiphoton Ionization of Atomic and Molecular Hydrogen at 0.53 $\mu$

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This work reports multiphoton ionization and dissociation of molecular hydrogen under the influence of laser radiation at  $0.53 \mu$ . The six-photon ionization probability of hydrogen atoms is derived for laser radiation acting upon atomic hydrogen from a molecular hydrogen beam which is up to 80% dissociated by radio-frequency power. The experimental sixphoton ionization probability of atomic hydrogen has been found to be in good agreement with the corresponding probability calculated using time-dependent perturbation theory if the statistical properties of the incident light are taken into account.

### I. INTRODUCTION

The nonlinear interaction between an intense beam of photons generated by a Q-switched laser and rare gases or alkali-metal atoms at low pressure leads to ionization of these atoms through the simultaneous absorption of several guanta if the laser radiation is sufficiently intense.<sup>1-5</sup> Multiphoton-ionization processes have been the subject

of a considerable amount of recent theoretical work, especially within the framework of timedependent perturbation theory.<sup>6-11</sup> The simultaneous absorption of  $K_0$  photons by an atom corresponds to a direct transition between the ground state and the continuum,  $K_0$  being the next integer greater than the ionization energy  $E_i$  of the atom divided by the photon energy  $E_{b}$ . The multiphotonionization probability W is proportional to  $\Gamma^{K_0}$ .