HARVARD COLLEGE OBSERVATORY
CAMBRIDGE, MASSACHUSETTS 02138

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ABSOLUTE TRANSITION PROBABILITIES OF LINES IN THE SPECTRA OF ASTROPHYSICAL ATOMS, MOLECULES, AND IONS

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Principal Investigator: W. H. Parkinson
Co-Investigator and Principal Scientist: Peter L. Smith
Co-Investigator: K. Yoshino

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The Harvard College Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

that is used to produce λ1222 Å. In the four-wave sum mixing scheme [Tomkins and Mahon, Opt. Lett. 7, 304 (1982)], the energy of three photons is added to produce one VUV photon: $2\omega_1 + \omega_2 = \omega_3$. Ground state OH can absorb 2 photons at $\omega_1 = 31964\ \mathrm{cm}^{-1}$ (or 3128 Å) to reach the repulsive $1^2\Sigma^-$ state, or 3 photons at ω_1 to reach many bound and repulsive states at ~95900 cm^{-1} (11.89 eV). We will soon install a LiF prism to remove all radiation but that at 1222 Å from the OH cell and, then, search for the $D^2\Sigma^- - X^2\Pi$ fluorescence.

2.2 H_2CO (Formaldehyde): No progress.

2.3 CO (Carbon Monoxide):

High-resolution measurements of absorption by the C(0) - X(0) and E(0) - X(0) bands of CO at ~1080 Å were completed in early March of 1984. The data have yet to be analyzed. John Black reports that accurate values of these f-values are needed more than ever in order to establish the dominant photodissociation channels for CO.

3. PROGRESS REPORTS: ATOMIC INTERSYSTEM LINE A-VALUES

3.1 A-Values for the $^2P^o - {}^4P$ Multiplet of Si II:

3.1.1 Lifetime measurements:

The Si II $^2P^o - {}^4P$ intersystem multiplet at ~2340 Å is seen in emission in cool stars. These lines are not density sensitive there, but future, high-resolution observations of other objects with HRS are likely to show density sensitivity (Carole Jordan, personal communication).

Preliminary measurements of a Si II metastable level lifetime were presented in Semi-Annual Report 14. A monochromator was used to isolate one line of the multiplet. The apparatus was less sensitive than predicted, so we turned to a laser excitation technique.

In this new method, Si^+ ions were produced by electron bombardment of SiH_4 as before. Ion creation was followed by a 90 msec delay during which all levels, including the metastable, decayed to the ground term. Then laser radiation that was tuned to one of the intersystem line wavelengths was used to 'pump' Si^+ ions from the ground term to one of the ^4P_J metastable levels. The radiative lifetime was measured by counting fluorescent photons from the decay of the excited level. Only very preliminary results have been obtained.

We will return to study of the Si II intersystem lines after we have finished development of our laser-plasma source of ions (see Sect. 3.2 and attached paper described in Item 5.2 iii). This technique should allow us to create a pure silicon-ion plasma and eliminate concern about possible emission from molecular ions.

3.1.2 Branching ratios in Si II:

Branching ratios are required in order to obtain transition probabilities from lifetimes of levels that have several decay channels. In order to measure decay branching ratios for the metastable levels of Si II and other ions that we have studied, we are collaborating with Dr. M. C. E. Huber (Institut fur Astronomie, ETH-Zurich). Huber's facility is the only one devoted to VUV branching ratio measurements of astrophysical interest. The first spectra showed contamination by molecular bands. Huber has borrowed the hollow cathode used by U. Litzen (Lund) in his study of the Si I spectrum [Ark. Fys. 31, 453 (1966)]. Its design permits operation at high temperatures that outgas the molecules. No branching ratio measurements have yet been made.

3.2 A-Value for the $^1S_0$ - $^3P^o_1$ Line of Al II

Our measurement of the lifetime of the $^3P^o_1$ level of Al^+ differs from our previous lifetime measurements in the way that the ions are produced: the Al^+ ions are generated in a laser-produced plasma (LPP) rather than by electron bombardment of gases.

We have constructed a new, wire-mesh ion trap that pumps out faster speed than our old, solid-walled trap. We have created and stored aluminum ions and studied the creation and storage processes as well as the emission from the stored ions.

Preliminary evidence indicates that Al^+ ions are indeed stored and that there is fluorescence with a decay time similar to that expected. The fluorescence is enhanced if the plasma is bombarded with the electron beam that is used for creation of ions from gases. A number of tests and improvements have to be performed before definitive measurements of the Al II metastable level lifetime can begin.

This work was described in a paper, titled Measurement of the A-value of the $3s^2\ ^1S_0 - 3s3p\ ^3P_1^o$ Intersystem Transition in Al II at 2670 Å: A Progress Report, that was presented at IAU Colloquium No. 86. A copy is attached (see Item 5.2.iii).

4. PROGRESS REPORT: RESEARCH IN SUPPORT OF FUSE/COLUMBUS

Appendix A of The Final Report of the Science Working Group for the Far Ultraviolet Spectroscopic Explorer, titled Recommendations for Research and Technology Development, points to a need for an accurate value of the $^3He/^4He$ 584 Å isotope shift. Planning for FUSE (a.k.a. COLUMBUS) requires this value in order to determine whether this satellite spectrometer could measure D/H and $^3He/^4He$ ratios in the same parcels of gas and, thus, set important constraints on big-bang cosmology.

We considered the possibility of measuring the isotope shift in our laboratory and discussed the accuracy of existing data with some of our colleagues. We established (with the help of George Victor, CFA, and Gordon Drake, U. Windsor) that a value could be calculated from data in the literature $\Delta\lambda(^3He - ^4He) = 0.030$ Å (= 15.4 km sec^{-1}). F. Tomkins (Argonne) pointed out that Herzberg [Proc. Roy. Soc. Lond. A. 248, 309 (1958)] had measured the shift, obtaining $\lambda = 0.0301 \pm 0.0005$ Å.

These data were provided to the SWG for FUSE through Don York (U. Chicago).

5. PAPERS AND PRESENTATIONS

5.1 Papers Published and In Press

i) Measurements of Transition Probabilities for Spin-Changing Lines of Atomic Ions Used in Diagnostics of Astrophysical Plasmas, Peter L. Smith, B. Carol Johnson, H. S. Kwong, and W. H. Parkinson, Physica Scripta T8, 88 (1984).

5.2 Papers Presented at Meetings

i) Progress Report on the Measurement of the Radiative Lifetimes of ${}^4P_J$ Multiplet in Si+,
H. S. Kwong and B. C. Johnson,
presented at the American Physical Society Division of Electron and Atomic Physics meeting, Storrs, CT, June 1984.

ii) Measurements of the Radiative Lifetimes of the ${}^4P_J$ Multiplet in Si^+,
H. S. Kwong and B. C. Johnson,
presented at the 164th meeting of the A.A.S., Baltimore MD, June 1984.
[cf., Bull. Am. Astron. Soc. 16, 509 (1984)]

iii) Measurement of the A-value of the $3s^2\ {}^1S_0 - 3s3p\,{}^3P_1{}^o$ Intersystem Transition in Al II at 2670 Å: A Progress Report,
B. Carol Johnson and H. S. Kwong,
presented at I.A.U. Colloquium No. 86, the Eighth International Colloquium on EUV and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas, Washington, D.C., August, 1984.

Physica Scripta. Vol. T8, 88–94, 1984

Measurements of Transition Probabilities for Spin-Changing Lines of Atomic Ions Used in Diagnostics of Astrophysical Plasmas

Peter L. Smith, B. Carol Johnson, H. S. Kwong and W. H. Parkinson

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, U.S.A.

and

Randall D. Knight

Ohio State University, Columbus, OH 43210, U.S.A.

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Abstract

The intensities of ultraviolet, spin-changing, "intersystem" lines of low-Z atomic ions are frequently used in determinations of electron densities and temperatures in astrophysical plasmas as well as in measurements of element abundances in the interstellar gas. The transition probabilities (A-values) of these lines, which are about five orders of magnitude weaker than allowed lines, have not been measured heretofore and various calculations produce A-values for these lines that differ by as much as 50%. A radio-frequency ion trap has been used for the first measurements of transition probabilities for intersystem lines seen in astronomical spectra. The measurement procedure is discussed and results for Si III, O III, N II, and C III are reviewed and compared to calculated values. Discrepancies exist; these indicate that some of the calculated A-values may be less reliable than has been believed and that revisions to the electron densities determined for some astrophysical plasmas may be required.

1. Introduction

Spin-changing (intersystem) transitions in low-Z atoms and ions are seen in the spectra of a variety of astronomical objects: examples are the sun, hot stars [1], novae [2], cool stars [3, 4], symbiotic stars [5], binary stars [6–8], variable stars [9–11], Herbig–Haro objects [12], H II regions [13, 14], planetary nebulae [15, 16], quasars and galaxies, including Seyfert galaxies [17–19], the interstellar gas [20, 21], and in the plasma torus of Io [22]. The intersystem lines most commonly seen are those of C^+, C^{2+}, N^+, N^{2+}, N^{3+}, O, O^{2+}, O^{3+}, Mg^+, Al^+, Si^+, Si^{2+}, and S^{3+}. These lines are primarily in the ultraviolet and, as a consequence, most of the observations have been made from satellites, such as IUE [23] in the case of objects other than the sun.

These lines are frequently used to determine electron densities and temperatures in astrophysical plasmas. Numerous review papers discuss these techniques, especially the use of intersystem lines in the study of the solar transition zone, the thin region between the chromosphere and the corona, where the temperature rises from 10^4 K to 10^6 K. Dufton and Kingston [24], Feldman [25], Dere and Mason [26], Jordan [27], Doschek and Feldman [28], and Dupree [29] are representative of recent reviews.

Spin-changing lines are forbidden by the selection rules for electric–dipole transitions but can occur as a consequence of spin–orbit interactions. For highly-ionized species, intersystem line transition probabilities (A-values) can approach those of allowed lines, i.e., of the order of $10^8\ s^{-1}$, but, for light elements in low charge states, the A-values are 4 to 6 orders of magnitude smaller. The upper levels of these transitions have lifetimes of the order of 0.1 to 10 ms and are said to be metastable.

Intersystem lines are usually weak in laboratory light sources because the metastable levels are collisionally de-excited before they radiate. However, in many of the diffuse plasmas studied by astronomers, the collisional de-excitation rate of these levels is of the same order of magnitude as the radiative decay rate and the "semi-forbidden", intersystem lines can be comparable in intensity to allowed ones. When such conditions exist, line intensity ratios of allowed to intersystem transitions – or intersystem to electric quadrupole or magnetic dipole, "forbidden" transitions (see Section 3.4 for an example) – become sensitive indicators of electron density.

Measurements of temperature employ intensity ratios for lines with different upper level energies [see 24–29]. Intersystem lines are not necessary but are frequently used.

A large number of diagnostic lines is required because none gives unambiguous results. Some line ratios involve ions formed in regions of different density, temperature, or optical depth; some require spectrometer detection efficiency calibration over a wide range of wavelength; some diagnostic lines are blended with other emissions, both line and continuum; some ions are influenced by charge transfer; and some lines saturate detectors. As a consequence, many diagnostic approaches are used and many fundamental atomic data, specifically A-values and electron impact excitation and de-excitation rates, are required. The accuracies with which the electron density and temperature in the plasmas can be inferred by line-ratio techniques depend directly upon the precision and completeness of these atomic data.

Because they are weak, intersystem lines are also useful in determination of interstellar gas phase abundances [see 20, 21]. For abundant species, such as C^+, C^{2+}, N, N^+, N^{2+}, O, Al^+, Si^+, and Si^{2+}, resonance lines are frequently saturated and multiplet components are blended. However, the intersystem lines are unsaturated at the highest column densities studied to date. Reliable transition probabilities are required if accurate column densities are to be determined from measured equivalent widths. The lack of accurate determinations of abundances currently impedes studies of important physical properties of the interstellar gas and grains, as well as studies of the evolutionary cycling of matter between stars, gas, and grains.

This paper reviews the first measured values for the transition probabilities of the intersystem lines that are used in gas phase abundance determinations or in density and temperature diagnostics for astrophysical plasmas with temperatures between 10^3 K and 10^5 K and electron densities between $10^5\ cm^{-3}$ and $10^{12}\ cm^{-3}$. Until now, astronomers have had to rely on calcu-

Table I. *Metastable level lifetimes measured using ion traps*

Ion	Upper level	Lifetime[a] (s)		Reference
Si^{2+}	$3s3p\ ^3P_1^o$	6.0 (−5)[b]	Intersystem E1	[32]
Li^+	$1s2s\ ^1S_0$	5.0 (−4)	2 photon	[33]
He^+	$2s\ ^2S_{1/2}$	1.2 (−3)	2 photon	[34]
O^{2+}	$2p^3\ ^5S_2^o$	1.2 (−3)[c]	Intersystem E1	[35]
N^+	$2p^3\ ^5S_2^o$	4.5 (−3)[d]	Intersystem E1	[36]
C^{2+}	$2s2p\ ^3P_1^o$	1.4 (−2)[e]	Intersystem E1	[37]
Cu^+	$3d^94s\ ^3D_3$	5.0 (−1)	E2	[38]
Ba^+	$5d\ ^2D_{5/2}$	1.8 (1)	E2	[39]
Ba^+	$5d\ ^2D_{3/2}$	4.7 (1)	E2	[40]
Li^+	$1s2s\ ^3S_1$	5.9 (1)	M1	[41]

[a] Number in parentheses in power of 10; i.e., 6.0 (−5) = 6×10^{-5}.
[b] See Section 3.1.
[c] See Section 3.2.
[d] See Section 3.3.
[e] Preliminary; see Section 3.4.

lated values; discrepancies of 50% or more exist among them (see tables in Section 3). Even in the cases where different calculations agree, the accuracies of the results cannot be assessed in the absence of measured values. The comparisons of our laboratory *A*-values to calculated ones in Section 3 show that the accuracy of the latter may have been overestimated in some cases.

2. Method of measurement

2.1. *Apparatus and procedure*

The intersystem line transition probabilities were determined by measuring the lifetimes of the metastable upper levels, i.e., by direct observation of the time dependence of the intensity of the decay photons. (In cases where an upper level has several decay channels, this procedure gives only the sum of the *A*-values).

The ions were held in a radio-frequency "ion trap", a form of potential well which constrains ions to a limited volume, of the order of 1 cm^3 in our case. The principles of ion storage have been discussed by Dehmelt [30] and by Wineland, Itano, and Van Dyck [31]. Because the pressure in ion traps is low, the environment is approximately collision-free and the trapped ions can decay radiatively before being collisionally de-excited. A number of metastable level lifetimes that have been measured using ions traps are given in Table I.

Our ion trap, shown schematically in Fig. 1, and measurement procedures have been described briefly by Kwong et al. [32]. A somewhat different, earlier version of our apparatus and methods have been described by Knight [36]. The cylindrical, stainless steel ion trap has a diameter and height of 3.3 cm. A mesh-covered hole, 1.25 cm in diameter, permitted observation of the radiative decays. A MgF_2, f/5 lens focussed the decay photons onto the photomultiplier tube (PMT). Wavelength resolution was provided by selecting different photocathodes and by employing filters.

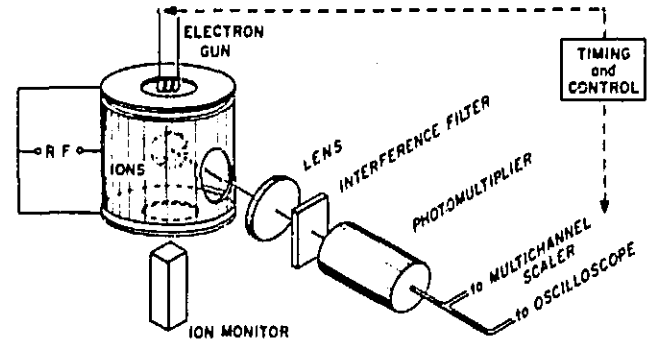

Fig. 1. Schematic diagram of ion trap. All components except the photomultiplier (PMT) were in the high vacuum chamber. The PMT was in another evacuated chamber separated from the first by an MgF_2 window. The ion monitor was a magnetic electron multiplier.

Pressures in the vacuum chamber were measured with an uncalibrated, nude, ionization gauge that we estimated to be accurate to within a factor of three on an absolute basis. The base pressure of the system was 2×10^{-10} Torr. When the electron gun was on, we estimated that the partial pressure of residual gas within the trap itself may have been as high as 10^{-8} Torr because localized heating increased the outgassing rate in a region where apertures restricted the pumping speed.

The voltage applied to a radio-frequency trap has the form $V(t) = U_0 + V_0 \cos(\Omega t)$. U_0, V_0, and Ω can be selected to optimize the storage of a particular charge-to-mass ratio (see discussion of the stability diagram" for radio-frequency ion traps by Wineland et al. [31]). Our trap was operated with various parameters that produced potential well depths ranging from 6 to 25 eV; typical values were $10\,\mathrm{V} \leqslant U_0 \leqslant 40\,\mathrm{V}$, $200\,\mathrm{V} \leqslant V_0 \leqslant 500\,\mathrm{V}$, and $\Omega/2\pi \approx 1$ MHz.

The sequence of events that comprised one operating cycle of the trap is shown schematically in Fig. 2. The ions were created by electron bombardment of gases at pressures ranging from 10^{-9} to 10^{-6} Torr in the trap. A pulse of electrons, at most 0.1 mA at 200 to 350 eV, created ions for a period of the same order of magnitude as the metastable lifetime. Following the creation and storage of the ions, there was a delay period of at least 50 μs during which allowed transitions occurred and species with unwanted charge-to-mass ratios drifted out of the

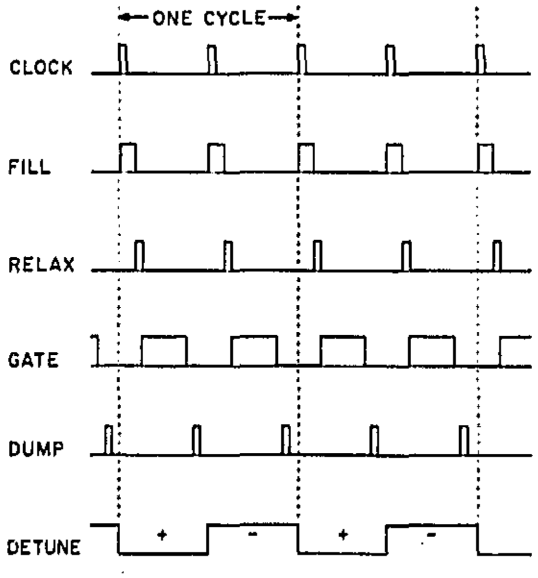

Fig. 2. Ion trap timing sequence (schematic). The clock pulses were at 5 ms to 100 ms intervals. During the FILL period, the electron beam dissociated the target gas and created the ions. During the RELAX period, allowed transitions occurred and untrapped species drifted out of the trap. Photons were detected while the GATE was on. The trap was emptied during the DUMP period by attracting the ions through the lower, end-cap electrode onto the ion monitor (cf. Fig. 1). On alternate half-cycles the trap was DETUNED, so that no ions were stored. Signal plus background were accumulated during the first halves of the cycles; background was subtracted during the second halves.

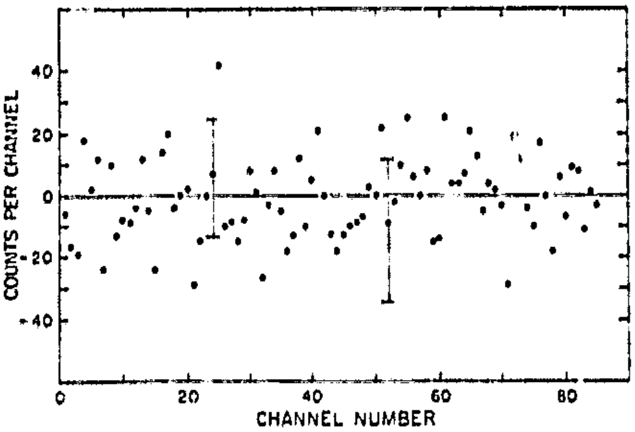

Fig. 3. Test of the add/subtract mode of operation. C^{2+} was stored in the trap but the 1909 A intersystem line and the 2325 A intersystem multiplet of C^+, which was also stored, were blocked with filters. The average value of zero demonstrates that the add/subtract mode of operation has no systematic asymmetry. Typical statistical uncertainties are shown. The negative values result from cases where $B_i < B_i'$ (cf. Section 2.2).

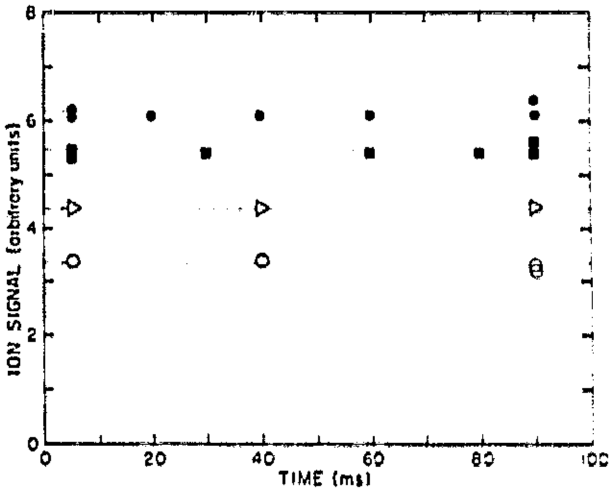

Fig. 4. Ion monitor signal as a function of storage time. C^+ ions were monitored. CO was used as the source gas: solid symbols indicate a pressure of 8×10^{-8} Torr; open symbols, 8×10^{-9} Torr. The circles indicate data obtained with a 9 V spherical well; the squares a non spherical well with a mean depth of 9 V; and the triangles, a non-spherical well with a mean depth of 16 V.

trap. After the delay period, signals from detected photons were counted with a multichannel scaler (MCS) for a period up to 8–10 lifetimes in duration. When the measurement period was over, the ions were ejected from the trap onto a magnetic electron multiplier which monitored their number. This completed the first half of a cycle.

On the subsequent half-cycle, the d.c. voltage, U_0, was changed to a value that made the trap repulsive for all ions and the create–delay–detect–dump cycle was repeated. On these alternate half-cycles, the "background" signal, for example from decay of metastable levels in neutral species and/or from PMT dark counts, was subtracted from those previously accumulated by the MCS. By using this method, any background is subtracted in a way that is insensitive to slow drifts in the operating conditions of the trap. This "add/subtract" mode of operation has been tested by using an optical filter to block the radiation from the decay of a metastable level; the remaining signal showed no time dependence. Data from one such test are given in Fig. 3. If the background was much less than the signal, the trap was used in an "add/add" mode and the ions of interest were stored during both halves of the cycles.

The measurement procedure described above gives the total rate of change of the number of metastable ions in the trap. Consequently, processes other than radiative decay have to be considered. Collisional loss processes are discussed in the remainder of this section. Processes that would repopulate the metastable level are considered in Section 2.3.

The principal mechanism for loss of ions from the trap is charge-changing collisions. We measured the ion monitor signal for times up to 100 ms after creation of the ions. The storage times were always significantly greater than the lifetimes being measured (see Fig. 4). This test of the storage time for all ions is a necessary, but not sufficient, indication that metastable ions were not lost through processes other than radiative decay. Because the principal mechanisms for loss of metastable ions involve collisions with the residual gas or with the source gas, which is estimated to be at least 10^6 times more abundant than the metastable ions, the decay rates were measured over a range of source gas pressures and with several gases (cf. Section 3). The use of several source gases assured that the decays studied were those desired and not spurious, slow decays in molecular ions produced from the target gas.

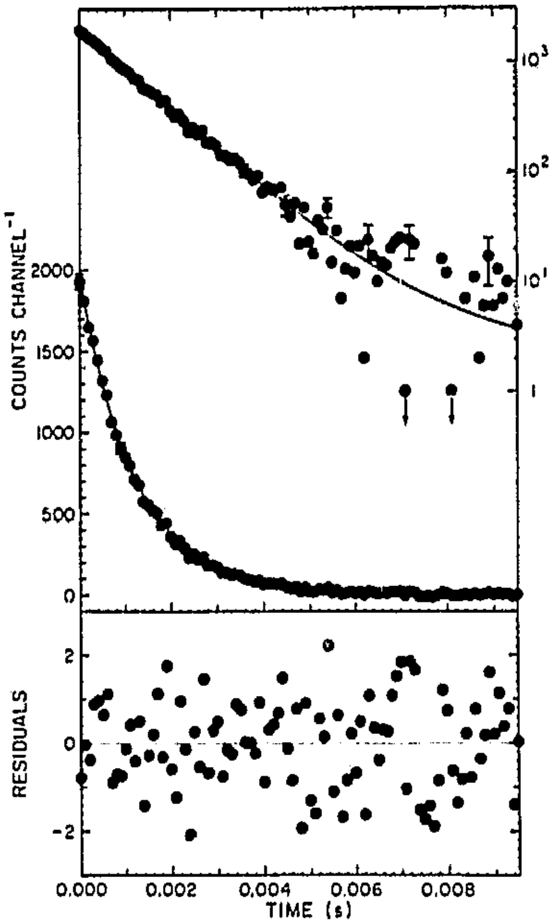

Fig. 5. Decay curve for the $^3P_{1,2}$–$^5S_2^o$ transition of O III. Nine curves obtain with the same source gas pressure, viz., O_2 at 4.8×10^{-8} Torr, were summed to give the data shown. There were 3.8×10^6 cycles of the trap. The first 5 channels were deleted before fitting and are not shown here. The fitting parameters are $A_1 = 840 \pm 11$, $A_2 = 155 \pm 138$, $\alpha_1 = 2973 \pm 58$ and $\alpha_2 = 14 \pm 18$. The uncertainties quoted are statistical only and are at the 90% confidence level. For these data, $2B = 56$. For the fit, $\chi^2/\nu = 1.02$ with $\nu = 92$. Kolmogorov–Smirnov two-sample tests [44] showed no time-dependent correlation in the residuals at the 95% level of confidence.

2.2. *Analysis of data*

The accumulated signal in each channel, i, of the MCS consisted of $[(S_i + B_i) - B_i'] \equiv N_i$. $(S_i + B_i)$ is the sum of the signal plus the background counts that were detected during all of the first halves of the trap cycles; B_i' is the sum of the background counts detected during the second halves of the cycles, i.e., when ions were not being stored. We assumed that $B_i \approx B_i'$, so that $S_i \approx N_i$. $(S_i + B_i)$ and B_i' were not explicitly available for use in the analysis but, in addition to N_i, the total number of counts, $T = \Sigma_i (S_i + B_i) + \Sigma_i B_i'$, was known.

A non-linear, weighted, least-squares procedure, based on [42], was used to fit the data to a two-exponential decay function: $I_i = \alpha_1[\exp(-A_1 t_i)] + \alpha_2[\exp(-A_2 t_i)]$. Fits to a single-exponential plus a constant term were also used. A possible origin for the second decay (or the constant term) is discussed in Section 2.3.

The statistical uncertainty for each N_i, i.e., the weight for the fitting procedure, was $\sigma_i = [(S_i + B_i) + B_i']^{1/2}$. Because S_i, B_i, and B_i' were not explicitly known, approximations were necessary. For each set of trap parameters, we studied the background in ancillary measurements with the trap in the repulsive mode for both halves of the cycle.

In some of these measurements, the background showed no time dependence; for these, B_i and B_i' were given by $B_i \equiv B_i' = [T - \Sigma_i N_i]/2 i_{\max} \equiv B$, where $i_{\max}$ was the number of channels used. In this case, σ_i was approximated by $\sigma_i = [I_i^0 + 2B]^{1/2}$, where I_i^0 is the value of I_i calculated using the initial values of the parameters.

In other cases, the ancillary measurements of the background showed it to have a time dependence that could be fitted adequately with a single exponential decay plus a constant term: $\alpha_b[\exp(-A_b t_i)] + \beta_b$. The weights for the fits to the metastable level decay data were then given by $\sigma_i = [I_i^0 + 2B_i]^{1/2}$, where $B_i = \eta[\alpha_b \exp(-A_b t_i) + \beta_b]$. The normalization constant, η, is calculated from $\frac{1}{2}[T - \Sigma_i N_i] = \eta\, \Sigma_i [\alpha_b \exp(-A_b t_i) + \beta_b]$.

For most fits, the values of reduced χ^2 differed from 1.0 by amounts within the expected range. Uncertainty limits for the measured decay rates at the 90% level of confidence were calculated using the method of Lampton et al. [43], who prescribe a general procedure for estimating joint confidence volumes for correlated parameter fits.

Values for data obtained with the same source gas and pressure showed no dependence upon well depth except at some of the higher pressures used in measurements on N II (see Section 3.3). Therefore, in order to improve the signal-to-noise ratio, decay curves obtained with the same source-gas pressure were summed. An example of a decay curve comprised of the sum of a number of measurements and the fit to it are given in Fig. 5. Linear fits of the measured decay rates at functions of pressure (Stern–Volmer plots) were extrapolated to zero pressure in order to determine the radiative decay rates.

2.3. *Uncertainties*

There are a number of effects that could lead to systematic errors but none appears to influence the results significantly.

Extrapolation of the measured decay rates to zero pressure required estimates of the rates for loss of metastable ions through collisions with the residual gas (see Section 2.1). Uncertainties in these estimates had a negligible impact on the radiative rate determination for all measurements made with residual gas pressure of 10^{-8} Torr in the trap, i.e., for all measurements except those described in Section 3.3.

Cascade repopulation of the upper level, which has influenced some other lifetime measurements, is unlikely in this work because the production mechanism, viz. collisional dissociation of a molecule, does not populate efficiently the high-lying levels of atomic ions. The second exponential components of the decay curves discussed in Sections 3.1 and 3.2 are thought to be blends rather than cascades. None of the blends is positively identified; most are attributed to decays from metastable levels in molecular and/or atomic ions that are trapped along with the primary species being studied.

The work of Johnson et al. [35] discusses blended decays that are both longer and shorter than the primary lifetime and considers the possibility that a two-exponential fit to the data may not be appropriate. The maximum total possible error is estimated to be about 6% at the 90% level of confidence. This value, which is typical of the more accurate of our intersystem line A-value measurements, comprises statistical uncertainty, from the fits to the decay curves and from the fit to the Stern–Volmer plot; uncertainties in time base, the correction for loss of metastable ions through collisions with the residual gas, in the modelling of the background and the concomitant impact on the uncertainties in the decay curve data, and in the subtraction of a short-lived decay; and an estimate of the impact on the result of using a model other than a two exponential decay. Other laboratory results are uncertain by as much as ± 20%. Nevertheless, these measured values are at least as accurate as the calculated A-values and, therefore, can be used to assess the calculational techniques.

3. Review of results

Lifetime measurements for metastable levels in Si^{2+}, O^{2+}, and N^+, are complete and work on C^{2+} is in progress. Some comments on the results and comparisons with calculated values are presented in this section.

3.1. *The* $3s^2\ ^1S_0$–$3s3p\ ^3P_1^0$ *line of* Si III *at* 1892 Å

The $3s3p\ ^3P^0$ term of Si III comprises 3 levels but only one, $^3P_1^0$, decays by an electric dipole transition, which is at 1892 Å. Nicholas and colleagues [45–47] have used intensity ratios containing this line for determinations of electron density in the solar transition zone. References [1, 3–5, 7–9, and 16] discuss IUE spectra that show this line.

We have measured the transition probability of the 1892 Å line of Si III [32]. Si^{2+} ions were produced by electron bombardment of SiH_4 and SiF_4 at pressures ranging from 2×10^{-7} Torr to 6×10^{-7} Torr. Interference filters were used to eliminate the radiation from the ^2P–$^4P^0$ intersystem multiplet of Si II at 2335 Å. The signal-to-background ratio in the first, 10 μs-wide channel was 3:1. B_i showed no time dependence nor was there any dependence of the fitted lifetimes upon source gas, pressure, or well depth. Our measured transition probability, $A = (1.67 \pm 0.10) \times 10^4\ s^{-1}$, is more accurate than calculated values. The comparison in Table II shows that any discrepancies are less than the estimated uncertainties in the results.

3.2. *The* $2s^2 2p^2\ ^3P_{1,2}$–$2s2p^3\ ^5S_2^0$ *lines of* O III *at* 1661 *and* 1666 Å

Doschek et al. [50] and Bhatia, Doschek, and Feldman [51]

Table II. *Comparison of measured and calculated values of the transition probability for the* ${}^1S_0$–${}^3P^0_1$ *line in* Si III

Method	A (10^4 s^{-1})	Ratio	Uncertainty (s^{-1})	Reference
Measurement	1.67	–	± 0.10	[32]
Semiempirical model potential	1.78	0.94	± 0.36	[48]
Configuration interaction	1.46	1.14	Note (a)	[49]
Hartree–Fock	1.61	1.04	Factor 3/2	[20]
Distorted wave	2.25	0.74	Factor 2	[45]

[a] Uncertainty was not stated in [49]; see comment in Section 3.2.

have used the O III intersystem lines in studies of the solar atmosphere. Nussbaumer and Storey [52] consider these lines in the spectra of gaseous nebulae, symbiotic stars, and quasars. References [3–8, 10, and 14–17] report IUE observations of these lines.

Johnson et al. [35] present lifetime measurements for the $2s2p^3\,{}^5S^0_2$ level in O III. This decays to both $2s^22p^2\,{}^3P_1$ and ${}^3P_2$ so only the sum of the two A-values can be determined. Both O_2 and CO, at pressures ranging from 10^{-8} Torr to 3×10^{-7} Torr, were used as source gases. Decay curves obtained using O_2 source gas (see Fig. 5) showed very little background signal or second exponential decay. Those obtained using CO source gas showed a time-dependent background and a strong second exponential decay. The latter may be attributed to decays from metastable C^+ ions that would also have been stored in the trap (see Section 2.3). Lifetimes obtained using both gases were identical within the experimental uncertainties.

Johnson et al. [35] obtained a value of $821 \pm 51\,s^{-1}$ for the sum of the A-values for the 1661 Å and 1666 Å lines from the metastable ${}^5S^0_2$ level. This result is compared to calculated values in Table III. The measured value is more accurate than all of the calculated ones and is larger than all values except that of Cowan et al. [20], which has a large uncertainty of ± 50%. The significance of the other discrepancies is hard to assess because the accuracies of most calculations are not stated in the published presentations. However, several of the authors have suggested, in personal communications, that the typical uncertainty should be about ± 20%. In this case, the measured result agrees also with the value of Nussbaumer and Storey [52].

Doschek et al. [50] used the A-values of Bhatia et al. [51] for solar electron density determinations. If the branching ratio of [51] is correct, our work would imply a correction of 34% should be made to the A-values used by [50] with a concomitant increase of about 50% to the electron densities that were determined. One of the line intensity ratios used by Doschek et al. comprises the C III intersystem line at 1909 Å and the O III 1666 Å line. This ratio is, therefore, doubly sensitive to the accuracy of the A-values used. Our work on the C III intersystem line is discussed in Section 3.4.

3.3. *The* $2s^22p^2\,{}^3P_{1,2}$–$2s2p^3\,{}^5S^0_2$ *lines of* N II *at* 2140 *and* 2143 Å

Emission from the metastable ${}^5S^0_2$ level of N^+ was prominent in the spectrum of Nova Corona Austrina A 1981 [10] and is thought to be responsible for a significant feature in the ultraviolet spectra of aurorae [55]. The lines have not been seen in the sun.

The first measurement of the lifetime of a metastable level in our laboratory was that of N^+ by Knight [36], who obtained a value of 4.2 ± 0.6 ms. This is equivalent to a value of $238 \pm 34\,s^{-1}$ for the sum of the A-values for the two decays from this level. Knight [36] also confirmed values, obtained from auroral studies, of the cross sections for production of N^+ by electron bombardment and for quenching of metastable N^+ by N_2.

The work of Knight [36] did not use the add/subtract data collection system. The residual gas pressure in his work was at least 5×10^{-7} Torr, which is 50 times greater than that used for the measurements described in the two previous subsections. Subsequent studies in our laboratory have indicated that Knight [36] may have underestimated the quenching rate by the residual gas and, therefore, obtained a lifetime that was too short by an amount that was slightly greater than his estimated limit of uncertainty. We are continuing to study this problem.

3.4. *The* $2s^2\,{}^1S_0$–$2s2p\,{}^3P^0_1$ *line of* C III *at* 1909 Å

C III is homologous to Si III; the $2s^2\,{}^1S_0$–$2s2p\,{}^3P^0_1$ line at 1909 Å is orders of magnitude stronger than the other lines of the multiplet. The 1909 Å line has been used in a number of studies of the solar transition zone [56–58] and is seen in IUE spectra of a wide variety of objects [1, 3–6, 9, 10, 12–19]. The ${}^1S_0$–${}^3P^0_2$ line at 1907 Å is also seen, for example in planetary nebulae, and can be used along with the 1909 Å line for density determinations [59, 60]. This $\Delta J = 2$, "forbidden" line has an A-value that is 10^4 times smaller than that of the 1909 Å intersystem line [60] and, thus, the lifetime of the latter can be measured without concern about the blend with the 1907 Å decay.

Kwong et al. [37] have presented preliminary results for the 1909 Å line A-value. CO and CH_4 at pressures from 5×10^{-8} Torr to 2×10^{-7} Torr were used as source gases. The measure-

Table III. *Measured and calculated values of the transition probability for the* $2s^22p^2\,{}^3P \leftarrow 2s2p^3\,{}^5S^0$ *doublet of* O III *at* 1660.8 *and* 1666.2 Å

	A (s^{-1})				
Method	1661 A	1666 A	ΣA (s^{-1}) (see note a)	$\frac{821\ s^{-1}}{\Sigma A}$	Reference
Measurement	–	–	821 ± 6.2%	–	This work
Configuration interaction	157	440	597	1.38	[51]
Multiconfiguration-Dirac–Fock	120	421	541	1.52	[53]
Configuration interaction	212	522	734	1.12	[52]
Configuration interaction	174	423	597	1.38	[54]
Hartree–Fock	377	1105	1482 ± 50%	0.55	[20]

[a] Uncertainties for most calculated values are not stated; see comment in Section 3.2.

ments were complicated by the presence of strong C II intersystem line emission at 2325 Å and, when using CO as a source gas, by intersystem line emission from O III as well. Several interference filters were employed and, as a result of their low transmission and of the small *A*-value for the transition, the count rates and the signal-to-noise ratios were low. The preliminary work indicates that the measured *A*-value is $75 \pm 20\ \mathrm{s}^{-1}$, slightly smaller than calculated values [20, 53, 60–62].

4. Concluding remarks

A radio-frequency ion trap has been employed for the first measurements of lifetimes of metastable levels in low-*Z* atomic ions that have spin-changing (intersystem) lines which are seen in astronomical spectra. The *A*-values that can be obtained from the measured lifetimes are used in studies of electron density and temperature in astronomical plasmas. In most cases, the measured values are more accurate than the calculated values used in these diagnostic procedures heretofore. Differences between the measured and calculated results indicate that the uncertainty in some of the latter may have been underestimated and, as a consequence, the results of some of the determinations of electron density for astrophysical plasmas should be reconsidered.

These measurements are being extended to other ions that have intersystem lines that can be used for astrophysical plasma diagnostics. In particular, Si II, C II, and Al II are being studied. The density sensitivity of the C II intersystem lines has been discussed by Stencel et al. [4]. The intersystem multiplets of Si II and C II comprise several upper levels with similar but different lifetimes. A spectrometer will be employed in order to resolve the various lines so that their lifetimes can be measured. The work on the Al II intersystem line, which has been seen in IUE spectra by Hack [5] and by Jordan, Ferraz, and Brown [63], will be the first in which we study an ion that cannot be formed readily by electron bombardment of a molecule. The Al^+ ions will be created in a laser-produced plasma.

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ABSOLUTE TRANSITION PROBABILITIES OF LINES IN THE SPECTRA OF ASTROPHYSICAL ATOMS, MOLECULES, AND IONS

1. REVIEW OF SCIENTIFIC OBJECTIVES

Our laboratory astrophysics research program comprises measurements of fundamental atomic and molecular data--in particular, of absolute transition probabilities [A-values, or f-values] for ultraviolet lines.

The molecular transitions that we are studying are ones that have been, or could be, used for observations of molecules in diffuse interstellar clouds; determinations of physical conditions in such clouds, especially abundances and temperatures, require accurate A-values for rotational lines of molecules.

The other A-values that we are measuring are for spin-changing (intersystem) lines in low-Z, singly- and doubly-charged atomic ions. These lines are also used in interstellar cloud abundance determinations, but, because their intensities in astrophysical plasmas depend upon the electron densities there, the atomic data that we are measuring are of most value in quantitative application of density diagnostic techniques.

2. PROGRESS REPORTS: MOLECULAR ROTATIONAL LINE LINE A-VALUES

2.1 OH (Hydroxyl):

Our study of the lifetimes of levels in the $D^2\Sigma^-$ state of OH continues in collaboration with F. S. Tomkins and P. M. Dehmer (Argonne Nat. Lab.). Successful tests of the OH production apparatus, by remeasurement of lifetimes for levels in the $A^2\Sigma^+$ state, and of the VUV (λ1222 Å) laser have been reported earlier. We have not, however, yet detected fluorescence from OH radicals excited by the laser to the $D^2\Sigma^-$ state. The explanation may involve destruction of the OH by the intense laser radiation at longer wavelengths

MEASUREMENT OF THE A-VALUE OF THE $3s^2\ ^1S_0$ — $3s3p\ ^3P^o_1$ INTERSYSTEM TRANSITION IN Al II AT 2670 Å: A PROGRESS REPORT

B. Carol Johnson and H.S. Kwong
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138

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MEASUREMENT OF THE A-VALUE OF THE $3s^2\ {}^1S_0$ — $3s3p\ {}^3P_1^o$ INTERSYSTEM TRANSITION IN Al II AT 2670 Å: A PROGRESS REPORT

B. Carol Johnson and H.S. Kwong[1]
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138

INTRODUCTION

Ratios of intensities of spectral lines produced in the radiative decay of collisionally-excited levels of atomic ions are versatile indicators of electron density in astrophysical plasmas when one of the lines involves a metastable level (see the review by Feldman 1981 and references therein). Radiative transition probabilities (A-values) and electron excitation cross sections are necessary for accurate, quantitative analyses of these plasmas. The work reported here is part of a program of measurements of astrophysically interesting A-values and radiative lifetimes (see the review by Smith *et al.* 1984); until we began, such anaylyses of astrophysical plasmas depended upon unconfirmed calculated A-values.

Here we report preliminary laboratory study of the intersystem line at 2670 Å in Al II. This line is seen in pre-main sequence stars and symbiotic stars. Brown, de M. Ferraz, and Jordan (1984) observed the Al II] line in T Tauri and included the line in their derivation of the emission measure distribution. They predict line ratios involving Al II] and resonance lines will be density sensitive for $n_e \gtrsim 10^{11}$ cm^{-3}. Recent calculations of the A-value for the $3s^2\ {}^1S_0$ — $3s3p\ {}^3P_1^o$ transition in Al$^+$ are 2680±50% s^{-1} and 3450 s^{-1} by Cowan, Hobbs, and York (1982) and Laughlin and Victor (1979), respectively.

EXPERIMENTAL METHOD

In our measurements, radiative lifetimes are determined by monitoring the time dependence of the radiative decay from metastable ions stored in a cylindrical, radio frequency (rf) ion trap. In previous work (see, for example, Johnson, Smith, and Knight 1984 or Kwong *et al.* 1983), metastable ions were created by electron bombardment on source gases. In this measurement, Al$^+$ ions are produced in a laser plasma, generated by focussing the output of a Q-switched Nd:YAG laser onto a target mounted on the ring electrode of the rf ion trap. Knight (1981) demonstrated that singly charged metal ions produced using this technique were stored in an electrostatic ion trap.

The components of the experiment are indicted in Figure 1 and a timing diagram detailing the sequence of events for each laser pulse is given in Figure 2. The Nd:YAG laser is operated at 10 Hz. The 1.06 μ

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[1] Permanent Address: Department of Physics, University of Nevada, Las Vegas, 4505 Maryland Parkway, Las Vegas, NV 89154.

laser output is focussed, by a lens external to the vacuum system, onto an Al target after passing through the ion trap. The laser power delivered to the target area of ~ 2×10^{-4} cm^2 in the ~ 10 ns wide pulse is 1.0 to 2.5 MW. The threshold for plasma production is observed at a power density of ~ 3 $GWcm^{-2}$.

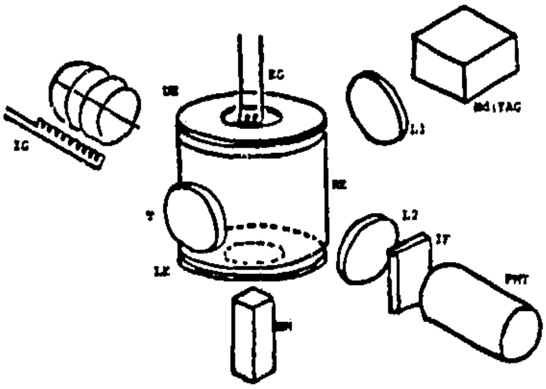

FIGURE 1. Schematic of the experiment. EG = electron gun, Nd:YAG = laser, L1 = lens to focus laser output onto target, T = target, IG = nude ionization gauge, UE = upper electrode, RE = ring electrode, LE = lower electrode, L2 = lens to focus stored ion fluorescence onto PMT, IF = interference filter, PMT = photomultiplier tube, EM = electron multiplier.

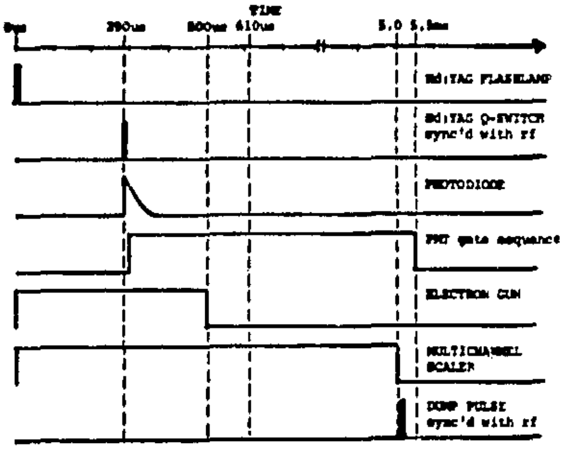

FIGURE 2. Timing sequence for each laser shot. The sequence repeats at 10 Hz. The gain on the PMT becomes constant at the location marked 610 μs.

The plasma is monitored by observing the voltage generated by the collector current of a nude ionization gauge. The temporal behavior of the neutral and ionized component of the plasma is estimated from these data. The plasma-produced stored ions are monitored by "dumping" the ions out of the trap onto an electron multiplier.

Emission from the Al plasma is studied using a 0.3 m scanning monochromator with a RCA 1P28 photomultiplier tube on the exit slit; a prism spectrograph and spectroscopic plates; or a 1P28 photomultiplier tube. For radiative lifetime measurements, (in Al II this corresponds to a measurement of the A-value for the $3s^2\ ^1S_0$ — $3s3p\ ^3P^o_1$ transition, since there is only one decay channel for the $^3P_1$ level), fluorescence from trapped, metastable Al^+ is detected using a solar blind EMR 541Q-05M photomultiplier tube (PMT). A 55 Å FWHM filter centered on 2660 Å with 16 % transmission at 2670 Å limits the bandpass of the system.

Preliminary work indicates emission associated with the laser plasma is strong enough to damage the PMT. Therefore, the PMT is protected by gating the photocathode off during plasma production. Photon counts representing Al II 2670 Å fluorescence are time analyzed using a multichannel scaler with 10 µs resolution.

RESULTS

Temporal studies of the plasma using the ionization gauge indicate that the plasma velocity is approximately 10^6 cms^{-1}; the ions travel faster than the neutrals; and the vacuum system recovers to the base pressure of $1x10^{-8}$ Torr about 10 µs after plasma production. The plasma production efficiency, as determined by the resonance emission lines, the signal observed on the ionization gauge, and the stored ion signal, increases if the laser is focussed to a fresh target area by adjusting the lens external to the vacuum chamber approximately every 1000 laser shots. Spectroscopic studies of the plasma indicate that there is very little continuum from 2000 to 5000 Å. Resonance lines in Al I and Al II have been identified; the strongest emission occurs at 3082 and 3092 Å (the $3p\ ^2P^o$ — $3d\ ^2D$ multiplet in Al I), 3586 Å (the $3d\ ^1D$ — $4f\ ^1F^o$ multiplet in Al II), and 2632 Å (the $3p^2\ ^1D$ — $4f\ ^1F^o$ multiplet in Al II). This latter emission passes through the bandpass filter that is used to isolate the Al II] 2760 Å fluorescence, however it is separated temporally from the intersystem fluorescence by the multichannel scaler.

Ions are trapped following plasma production. The threshold for the stored ion signal is coincident with the threshold for plasma production as determined from the ionization gauge signal. The charge-to-mass ratio of the stored ions inferred from the trap potentials (see Wineland, Itano, and Van Dyck 1983 for a discussion of the stability diagram for rf ion traps) and time-of-flight measurements on the stored ion signal indicates the ions are Al^+ and Al^{++}. Fluorescence within the bandpass of the detection system from stored ions is observed (see Figure 3). The fluorescence is not present if the trap is made to be unstable for storage of Al^+ ions while holding all other conditions fixed. The fluorescence seems to increase if the laser produced plasma is crossed with an electron beam of ~ 200 eV energy, ~ 50 µA current, and 500 µs duration. The data in Figure 3 give a decay rate that is consistent with calculations of the A-value of the intersystem transition in Al^+. However, the data are preliminary and it is premature to quote a measured decay rate.

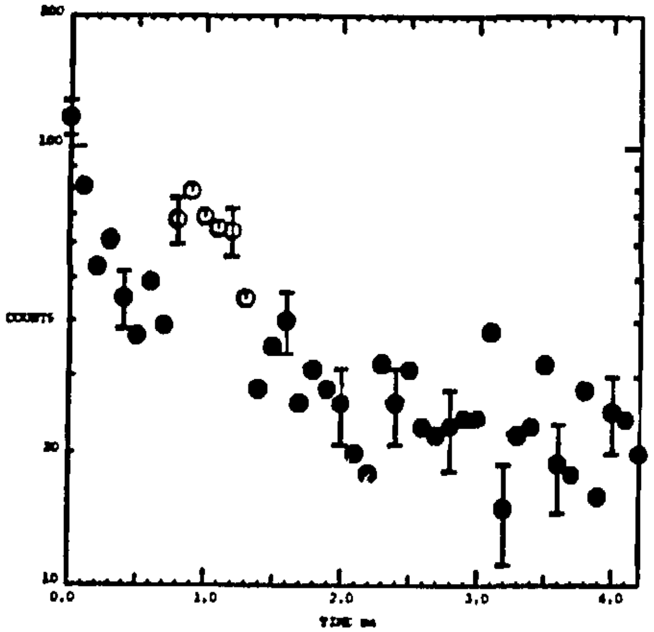

FIGURE 3. Time behavior of fluorescence observed for stored Al^+ ions. The data have been binned in 100 μs channels. Data plotted using open circles are contaminated by noise from the laser.

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