A vacuum ultraviolet atomic beam light source
by Glenn Alden Govertsen

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Physics

Montana State University

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Abstract:

An atomic beam light source designed and constructed primarily for the vacuum ultraviolet is described. The light source produced spectra of argon and air in the extreme ultraviolet. A study was made of the excitation functions of the Ar II lines at 920 Å and 932 Å. Also included is an unexpected pressure dependence of the Ar I resonance lines.

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Date August 5, 1969

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Head, Major Department

Chairman, Examining Committee

Graduate Dean

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ABSTRACT

An atomic beam light source designed and constructed primarily for the vacuum ultraviolet is described. The light source produced spectra of argon and air in the extreme ultraviolet. A study was made of the excitation functions of the Ar II lines at 920 Å and 932 Å. Also included is an unexpected pressure dependence of the Ar I resonance lines.

I. INTRODUCTION

The past decade shows an increase in the experimental work done with gaseous atomic beams. Some earlier references are found in 1942. Bassey and Simpson¹ review some of the then current work in molecular beams. Also, Mack and Barkofsky² describe various aspects of design and use of gaseous atomic beam apparatus. No further literature is found dealing with this subject until 1956. King and Zacharias³ then describe many experimental beam techniques and new applications of molecular beams. A paper delivered by R. W. Stanley⁴ in 1960 is the first of a growing number of references to gaseous atomic beams.

The recent work shows a variety of techniques. Odintsov⁵ provides information on the use of an atomic beam as a light source. He presents a discussion of beam source collimation and of Doppler widths of spectral lines obtained from such a light source. Hanes⁶ also describes an atomic beam source using a new collimation technique. His multi-channeled collimator and others will be discussed separately in a later section. Kleinpoppen, Krüger and Ulmer⁷ excite a Hydrogen beam with electrons to study the Balmer- α radiation. Stoner⁸ also studies Balmer spectral lines using an atomic hydrogen beam. More recently, the experimental techniques and construction of an atomic beam light source by Stanley^{9,10} and Larson¹⁰ at Purdue University provide the basis for the light

source built here at Montana State University.

Much of the geometry of Stanley's sources is incorporated into our design. Most noteworthy is the collimation system that the physicists at Purdue produced for the atomic beam. The use of etched copper foils in forming an "aimed" beam produces high beam densities in the excitation region without increasing the pumping load. This technique has been used successfully in the production of an Argon beam in the MSU light source.

The major difference in the atomic beam source at MSU comes in the spectral region under investigation. This study is concerned mainly with the extreme vacuum ultraviolet region. Most of the work done thus far has been with the resonance lines of Argon I, at $1048.22 \text{ \AA}$ and $1067.66 \text{ \AA}^{11}$, and the $919.78 \text{ \AA}$ and $932.05 \text{ \AA}^{11}$ lines of Argon II. Thus by producing emission lines in this spectral region we have a vacuum ultraviolet atomic beam light source.

The title of a paper in a Soviet journal indicates that a different type of vacuum ultraviolet light source has been constructed.¹² Apparently an ultrasonic gas jet excited by an electron beam is the source of radiation.

II. THEORY

Several considerations are important in understanding the usefulness and effectiveness of an atomic beam source. Stanley⁹ defines the radiance of a spectral line, of wavelength λ , as

$$B_{\lambda} = c Q_{\lambda} \int n(x) j_e(x) dx.$$

Here c is a constant; Q_{λ} is the excitation cross section; and $n(x)$ and $j_e(x)$ are the atomic number density and electron flux density. The coordinate x denotes the direction of observation. A very detailed derivation of both $n(x)$ and $j_e(x)$ is included in Stanley's⁹ paper. Only selected points will be discussed here, and only $n(x)$ will be calculated for the MSU atomic beam source.

The important aspects of the source are the collimation, the transmittance of the multi-channelled collimator and the width of an individual channel. The maximum beam density occurs when the mean free path of the gas atoms equals the single channel width. The following relation is derived using the geometry of the present source and its collimating assembly.

$$n = \frac{T}{6C\sigma\Delta a}$$

See the Appendix for the derivation of this result. Here n is the maximum number density in the beam; T is the transmittance; C is the collimation; σ is a cross section involving

the effective atomic diameter; and Δa is the width of a single channel. Consider now the product na (a = total width of collimator assembly). This gives the number of atoms per unit area. For the MSU source the following conditions exist: $a = 1\text{mm}$, $\Delta a = .012\text{mm}$, $T = 45\%$, $C = 20$ and $1/6\sigma = 2.2 \times 10^{12}$ atoms/cm² for argon atoms. The atomic beam thus theoretically contains a maximum of 4.08×10^{12} atoms/cm².

The collimation, C , has significance in predicting the reduction of the Doppler broadening of a spectral line. Consider a beam defined by two collimating slits. The first has a width a_1 in the direction of observation and the second has a width a_2 . If the distance between the two slits is designated by d_1 , then the collimation $C = 2d_1/(a_1 + a_2)$. This is the reciprocal of the maximum angle that the atoms make toward the direction of observation. In the present source $C = 20$. The argon atoms at room temperature correspond to a Doppler width¹³ of 187mk ($1\text{mk} = 10^{-3}\text{cm}^{-1}$). Using the atomic beam with $C = 20$, this width is reduced to $\frac{187}{C} = 9.4\text{mk}$.

III. EXPERIMENTAL PROCEDURE

See Figures 1, 2. The entire atomic beam apparatus including the monochromator is first evacuated by three vacuum pumps. A beam of Argon atoms is then collimated into an excitation region. An electron gun directs a sheet of electrons perpendicular to the atomic beam direction to excite the argon atoms. The light emitted by these atoms is analyzed by a monochromator which views the light perpendicular to both the electron and atomic beams.

Apparatus Description

The Atomic Beam

The Beam is produced in a copper tube using a VacTronic variable leak valve to regulate the amount of gas atoms in the beam. The beam passes through two apertures in reaching the excitation region. The first aperture, the oven slit, is 10mm long and 1mm wide. It consists of an "aimed" multi-channelled collimator similar to that produced by Stanley and Larson.¹⁰ The second aperture or collimating slit is 8mm long and 1mm wide. This slit is in the wall separating the oven region from the excitation chamber. Each chamber is pumped separately. (See Figure 2) The distance separating the two apertures is 8mm. The 1mm widths of the slits are in the direction of the monochromator. The copper tube, including

THE ATOMIC BEAM LIGHT SOURCE
FIG. 1

CROSS SECTION OF THE ATOMIC BEAM LIGHT SOURCE

FIG. 2

the multi-channelled collimator can be moved using an adjustable bellows so that the beam intensity in the excitation region may be maximized before taking a spectral scan.

The concept of a multi-channelled collimator has been discussed in the literature.^{3,6,9,10} The collimator in the present atomic beam source follows the design of Stanley and Larson.¹⁰ This multi-channelled collimator is constructed by stacking forty layers of .001 inch (.025mm) beryllium copper foil. Each foil has forty rectangular grooves formed by photoetching. They are aimed to focus in the excitation region at a point 30mm from the base of the collimator. The size of an individual foil is 16mmx3.5mmx.025mm. The individual channel cross-sectional dimensions are .25mmx.012mm. Dense beams are possible since the maximum beam density is governed by the mean free path of the atoms equaling the narrow dimension of the channel. The ratio of open area to closed area after etching and stacking forty foils is approximately 45%. This defines the transmittance.

The Electron Gun

The electron gun design is based on an electron gun constructed by Robiscoe.¹⁴ See Figure 3. A permanent magnet houses the electron gun thus, the magnetic field acts as a collimator for the electron beam. The slotted anode contains the excitation region for the atomic beam. See Figure 3(b).

(b.) GEOMETRY OF ATOMIC BEAM IN THE E-GUN

(a.) E-GUN IN MAGNET
ELECTRON GUN ASSEMBLY

FIG. 3

As electrons leave the filament, the anode voltage accelerates them towards the anode. The magnetic field collimates them into a sheet. A slit cut in the copper anode faces the monochromator for viewing radiation. The various parts of the gun assembly are insulated from the magnet and each other by a block of boron nitride. Current and voltage connections are made with vacuum feed throughs in the wall of the chamber. The magnetic field in the excitation region is roughly 1000 gauss. The anode consists of a machined copper block. The cathode is constructed by spot welding a .008 inch tungsten filament on two .020 inch tungsten support. A shield is connected to one of the magnet pole faces to block out direct radiation from the heated filament to the monochromator. Also, all parts of the electron gun assembly visible to the monochromator are optically blackened with graphite.

The magnet is suspended on two roller bearings allowing lateral movement in order to maximize light reaching the monochromator from the excitation region. This lateral adjustment can be done while the system remains under a vacuum by means of a small rack and gear on a rotatable feed through. Thus the radiant output of the light source can be maximized by proper adjustment of both the atomic beam and the electron gun position.

The geometry of the beam and the electron gun allow the

monochromator to analyze the light at 90° to both the electron and atomic beam motions. This reduces the Doppler broadening of the spectral lines.

An anode current regulator¹⁵ is used to maintain a constant anode current in the electron gun throughout the experiment. For instance at an anode voltage of 100 volts a constant anode current of any value from 0 to 15 MA can be maintained.

Detection System

A McPherson model 215 vacuum monochromator with one meter path length scans the spectral lines and allows the various ultraviolet lines to be studied. The slits are kept narrow so as to resolve the two resonance lines of argon and the two ion lines. Typical slit widths were .150 mm for the entrance slit and .200mm for the exit slit.

Sodium salicylate is deposited on the pyrex window of the RCA 4523 photomultiplier tube. The phosphorescent properties¹⁶ of this film on the window enables the tube to detect radiation in the extreme ultraviolet. The photomultiplier is operated at 1300 volts negative. The photomultiplier current is measured with a Keithley 601 electrometer.

Vacuum System

Three NRC diffusion pumps, two of them four inches in

diameter and the other one three inches, are used to evacuate the entire assembly. The small pump operates without a trap on the oven chamber. One four inch pump evacuates the excitation chamber and utilizes a Granville Phillips Cryosorb liquid nitrogen trap. The monochromator is pumped by the other four inch pump and uses a NRC molecular sorbent baffel type 0317-4 charged with zeolite. Typical base pressures are 2×10^{-6} Torr in the oven chamber, 3×10^{-6} Torr in the monochromator and 4×10^{-7} Torr in the excitation chamber.

IV: MEASUREMENTS AND RESULTS

Initial Experiments

Obtaining a spectral trace showing the expected resonance lines of Argon was of prime importance. Figure 4 shows one of the early spectral scans using the argon atomic beam. The two lines at $919.78 \text{ \AA}$ and $932.05 \text{ \AA}$ are the emission lines from the first excited state ($3s3p^6$) to the ground state ($3s^23p^5$) of singly ionized argon. (Ar.II) These wavelengths plus the ionization potential of an argon atom correspond to threshold energies of 29.238 eV and 29.059 eV respectively. The $1048.22 \text{ \AA}$ and $1066.66 \text{ \AA}^{11}$ lines are the resonance lines from the first excited state ($3s^23p^54s$) to the ground state ($3s^23p^6$) of the argon atom. (Ar.I) These wavelengths correspond to excitation energies of 11.827 eV and 11.623 eV respectively. The apparently greater intensity of the ion lines compared to the resonance lines stems from the operating conditions for this spectral scan. A very dense beam was used causing the background Argon pressure in the excitation chamber to be high (on the order of 3×10^{-5} Torr). Therefore self-absorption of the resonance lines occurs.

A spectral scan using air as the molecular beam produced the emission spectrum seen in Figure 5. Some of the nitrogen and oxygen lines are noted in this extreme vacuum ultraviolet region.

SPECTRAL SCAN WITH ARGON BEAM

FIG. 4

ANODE VOLTAGE 200 V
ANODE CURRENT 10mA
CHAMBER PRESSURE 1.3×10^{-5} TORR

SPECTRAL SCAN WITH AIR MOLECULAR BEAM

FIG. 5

Secondary Electron Effect

The linearity of current with light intensity is demonstrated for the two ion lines. See Figure 6. The lack of quadratic behavior eliminates the possibility of secondary electron excitation of the atomic beam. The linearity starts to diverge in the 12-14 ma region. At these anode currents some electrons reach the anode without being collimated and traveling through the excitation region. (See Figure 3).

Excitation Functions

The relative optical excitation functions of the two Argon II lines are shown in Figure 7. The excitation functions for a given spectral line show the relative intensity of that line as a function of the electron energy for constant atom density and constant electron current.¹⁷ The plot begins at the threshold energy for the lines. At present no references to excitation functions of these Argon II lines have been found in the literature.

Pressure Dependence of the Argon I Resonance Lines

An unexpected pressure dependence of the Ar I resonance lines appeared in testing the operational ability of the atomic beam light source. See Figures 8-10. This behavior was duplicated a number of times. This effect is not

INTENSITY VS. CURRENT FOR ARGON II

FIG. 6

ANODE CURRENT 5 mA
CHAMBER PRESSURE 3×10^{-5} TORR

— o — 920 Å
— x — 932 Å

EXCITATION FUNCTIONS OF 920 Å AND 932 Å LINES OF ARGON II

FIG. 7

INTENSITY VS. PRESSURE FOR 1048.22 Å OF ARGON I

FIG. 8

INTENSITY VS. PRESSURE FOR 1066.66 Å OF ARGON I

FIG. 9

Anode Voltage 100 V
Anode Current 10 mA

RATIO OF INTENSITIES VS. PRESSURE FOR ARGON I
FIG. 10

completely understood although some possibilities are suggested. Before analyzing the data, the argon pressure readings had to be corrected.^{18,19}

The pressure behavior of the two lines showed some similarities. For instance, the curves climb quite rapidly as the beam density is increased until a relative maximum occurs. The intensities then trail off to a relative minimum point before increasing somewhat linearly with pressure. This behavior suggests a combination of effects. Absorption causes an exponential decrease in radiation when the background pressure increases. The amount of absorption depends on the density and thickness of the absorbing background gas. However, along with this absorption there may occur a re-emission of the resonant photons. This type of scattering is set forth in the theory of Milne²⁰ concerning the diffusion of radiation through a gas. Zemansky²¹ applied Milne's theory to the quenching of radiation by an infinite slab of absorbing gas. Adapting his theoretical results to the present data may show the relative importance of the scattering process in interpreting the pressure dependences of the Ar I lines.

Also of interest is the ratio of the intensities under the same background pressure changes. See Fig. 10. A partial explanation stems from the differing oscillator strengths for the two transitions resulting in different absorption coefficients. The absorption process gains importance again as the

background pressures increase. The oscillator strengths for the two lines are .228 and .059 for 1048 Å and 1067 Å respectively.²² The ratio of these oscillator strengths is thus ~4. It appears that the data for the two lines (Figures 8, 9) scales with pressure according to the inverse ratio of their oscillator strengths. For instance, the relative maximum for 1048 Å is about 3×10^{-6} Torr while for 1067 Å it occurs at 12×10^{-6} Torr. This observation about the oscillator strengths might be substantiated by the discussion of Mitchell and Zemansky²³ since the absorption coefficient is proportional to the oscillator strength. They noted that at low pressures the scattered radiation emerging from a thickness of absorbing gas is proportional to the absorption coefficient.

V. CONCLUSION

The atomic beam light source has functioned well and has produced atomic emission lines in the vacuum ultraviolet. More important perhaps than the results obtained with initial experiments with argon are the possibilities for future use contained in such a light source. For instance, most of the rare gases could provide an effective atomic beam for resonance work. The pressure dependences of resonance lines also offer interesting material for future study due to their unexplained behavior.

APPENDIX

APPENDIX

The derivation of the maximum beam density is given in Stanley's paper.⁹ The following discussion parallels his derivation but uses the geometry of the MSU light source.

Consider the atomic beam to originate in a high pressure region called the oven. The beam passes through the oven aperture into a region of much lower pressure. See Figure 11. The number density, n , at a point c is the desired quantity.

$$n = n_1 \frac{(a_1 b_1)}{4\pi d_2^2} \quad (1)$$

Corresponding to Figure 11, a_1 and b_1 are the narrow and wide dimensions of the rectangular oven aperture. The quantity n_1 is the number density inside the oven and $\frac{a_1 b_1}{d_2^2}$ is the solid angle subtended by the aperture. Of course the mean free path, L , of the atoms in the oven must be larger than a_1 for molecular effusion to occur (Equation (1) has already assumed molecular effusion). Now consider δ as the effective atomic diameter, then

$$L = \frac{1}{\sqrt{2}\pi\delta^2 n_1} \quad (2)$$

Define a constant $\sigma = 4\sqrt{2}\pi\delta^2$. From (2) we have

$$L = \frac{4\pi}{\sigma n_1} \quad \text{or} \quad n_1 = \frac{4\pi}{\sigma L} \quad (3)$$

For a maximum n_1 we set $L = a_1$ so

$$n_1 = \frac{4\pi}{\sigma a_1} \quad (4)$$

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COLLIMATION OF AN ATOMIC BEAM

FIG. II

Substituting into (1), the beam density becomes

$$n = \frac{b_1}{\sigma d_2^2} \quad (5)$$

The long dimension of the slit, b_1 , is approximately $d_2/2$.

Thus we arrive at

$$n = \frac{1}{2\sigma d_2} \quad (6)$$

A second collimating aperture with dimensions a_2 and b_2 is placed between point c and the oven aperture. This second aperture allows only a small number of the atoms from the oven to reach the excitation region. The collimation of the beam is

$$C = \frac{2d_1}{a_1 + a_2} \quad (7)$$

In the present source $a_1 = a_2 = a$ and $d_1 = d_2/3$ so

$$C = \frac{d_2}{3a} \quad \text{or} \quad d_2 = 3aC \quad (8)$$

Combining (8) and (6) we have

$$n = \frac{1}{6\sigma Ca} \quad (9a)$$

Thus the number density per unit area is

$$na = \frac{1}{6\sigma C} \quad (9b)$$

If a multi-channeled collimator with channel width Δa replaces the oven aperture we find that

$$n_1 = 4\pi(\sigma\Delta a) \quad (11)$$

With the multi-channeled collimator not all the area included in the overall dimensions $a_1 \times b_1$ transmits atoms. The transmittance T is the ratio of open area to closed area. Using T and (11) we arrive at the final results for n .

$$n = \frac{T}{6C\sigma\Delta a} \quad (12a)$$

The number density per unit area is

$$n_a = \frac{Ta}{6C\sigma\Delta a} \quad (12b)$$

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