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Publication Date

1977-07-01

Submitted to Physical Review

UC-34a
LBL-6643 c./
Preprint

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July 25, 1977

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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THE g_J -FACTOR OF METASTABLE 5S_2 ATOMIC OXYGEN
USING A TIME-OF-FLIGHT, ATOMIC BEAM MAGNETIC RESONANCE METHOD

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ABSTRACT

A time-of-flight, atomic beam magnetic resonance method was used to compare the g_J -factor of $2p^33s\ ^5S_2$ atomic oxygen with the g_J -factor of metastable 2^3S_1 atomic helium in magnetic fields of 3209 and 4228 gauss. The metastable oxygen and helium atoms were produced in a pulsed radio-frequency discharge source and after traversing the apparatus were detected by electron emission from a tungsten surface. By collecting data only in a given interval of the time-of-flight distribution the O (5S) and He(3S) states were isolated from other discharge products. From 158 pairs of resonances taken with four relative field and hairpin orientations the atomic magnetic g -factor is:

$$g_J(^5S_2, ^{16}O) = \mu_J/J = -2.0020910(10)$$

*Work performed under the auspices of the USERDA.

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I. INTRODUCTION

The present measurement stems from an unexpected observation. When beam source development studies were initiated to produce metastable $N(^6S_{5/2})$ atoms from dissociation of N_2 , a velocity selected Stern-Gerlach deflection experiment showed two magnetic moment peaks at $4\mu_0$ and $2\mu_0$ rather than the expected three peaks at $5\mu_0$, $3\mu_0$ and $1\mu_0$. The cause of this discrepancy was traced to the presence of $O(^5S_2)$ metastable atoms made from O_2 which entered the gas handling system from the atmosphere by permeating a short section of plastic tubing. Although this interference was easily eliminated, the strength of the $O(^5S_2)$ signal and the intrinsic interest in atomic oxygen as a constituent of the atmosphere and as a test case for multi-electron atomic theory compelled the precision measurement reported here.

The ground state configuration of atomic oxygen ($1s^2 2s^2 2p^4$) produces two metastable levels 1D_2 and 1S_0 above the 3P_2 ground state. These states have energies 1.97eV and 4.18eV and lifetimes ≈ 150 sec. and ≈ 15 sec., respectively. Another state 5S_2 is the lowest quintet state of the configuration $1s^2 2s^2 2p^3 3s$ and lies 9.14 eV above the ground state.¹ Two independent lifetime measurements of $O(^5S_2)$ yielded $185 \pm 10 \mu\text{sec}^2$ and $170 \pm 25 \mu\text{sec}^3$

which are consistent with a theoretical calculation $192\mu\text{sec.}^4$ In 1949 Kiess and Shortly, obtained the value $g_J(^5S_2, ^{16}O) = -1.999(2)^5$ from the Zeeman pattern of the visible spectral lines of oxygen. Eighteen years later Brink observed oxygen in an atomic beam apparatus and compared the resonant frequencies of 5S and 3P states to obtain $g_J(^5S_2, ^{16}O) = -1.97(5)^6$. In addition to using a mass spectrometer detector, Brink observed from his source two spectral lines, $3947\text{\AA}$ and $7774\text{\AA}$ that result from transitions which terminate in the 5S_2 state.

The magnetic moment of the comparison helium state used in the current measurement has a long history of study by many techniques. When the present experiment was in progress the best value of the $g_J(^3S_1, ^4\text{He}) = -2.00223735(60)$ was from a previous measurement in this laboratory.⁷ Recently, two new values have been published: $g_J(^3S_1, ^4\text{He}) = -2.00223755(20)^8$ from an optical pumping experiment and $g_J(^3S_1, ^4\text{He}) = -2.00223745(14)^9$ from an atomic beam experiment.

Since both ^{16}O and ^4He have zero nuclear spin, the energy levels shown in Figure 1 are given by the expression $W = -g_J\mu_0 m_J H$. When $\Delta m_J = \pm 1$ transitions are observed the g-factors ratio is $g_J(^5S_2, ^{16}O)/g_J(^3S_1, ^3\text{He}) = \nu(^{16}O)/\nu(^4\text{He})$ where the ν 's are the corresponding resonant frequencies.

II. EXPERIMENT AND PROCEDURE

The atomic beam apparatus employed in this work has been described previously.^{10,11} Modifications to the beam geometry

shown in Fig. 2 permit the observation of both Helium and Oxygen resonances. In the "A" magnet the undeflected $m_J = 0$ state is selected and passes through the "C" magnet transition region. If no transition from this state occurs, the atoms strike a stop wire. On the other hand, if in the r.f. transition region the $m_J = 0$ atoms make a transition to either $m_J = \pm 1$ or ± 2 , the "B" magnet deflects them to the side of the stop wire; and the atoms are counted by the Auger electron detector. This arrangement has the following advantages: a) both the unknown and the calibration atoms have the same trajectory through the radio frequency region, b) flop-in resonances are observed with low, off-resonance background, i.e., the signal increases as the frequency approaches the resonant condition c) single quantum, $\Delta m_J = \pm 1$ resonances are detected in integral J atoms, and d) the method is independent of the differences in deflection characteristics of the two species.

Both 3S_1 helium and 5S_2 oxygen were produced in a pulsed 50MHz radio frequency discharge tube. The active region of the discharge tube, 22cm long and .8cm in diameter, was bent into a U shape. A slit .005 inches wide x .160 inches high in the convex side allowed escape of the metastable beam. The radio frequency through the tube was pulsed on for 40 μ sec about 150 times per second. This procedure permitted the time-of-flight to the detector to be used as a discriminator against photons, high velocity atomic states, and low velocity molecular states. The cold tungsten cathode

surface of a Bendix Magnetic Electron Multiplier emits electrons only when struck by sufficiently excited atoms and thus further discriminates against ground state atoms and molecules. Any charged particles in the beam are deflected from the beam by the various apparatus magnetic fields.

Magnetic field stability and homogenization in the C Magnet region were achieved by using two Klein-Phelps type nuclear magnetic resonance (NMR) systems.¹² One field-modulated system locked the "C" field to a particular value while a second frequency modulated system allowed mapping vertically and horizontally along the beam. The first probe was fixed in position about 2" below the beam while the second probe was attached to the movable radio frequency hairpin structure. By iterating a procedure of mapping the field and setting correction currents in 8 shim coils,¹³ it was possible to reduce the inhomogeneity along a 2 inch length of the beam from 60 ppm to less than 1 ppm.

Radio frequency for inducing transitions was generated by an X-13 reflex klystron oscillator which was locked to harmonics of a HP5105A frequency synthesizer. The output of the oscillator passes through a traveling wave tube amplifier and power leveler before arriving at the 50ohm terminated hairpin structure (see reference 14) where transitions in the beam are induced. The frequency was generated and measured to at least 1 part in 10^8 and was based upon the Atomic Time scale of station WWVB at 60kHz.

The two frequencies for helium and oxygen at 3209 gauss were 8990.3 and 8989.6 MHz, while at 4228 gauss, they were about 11,845.5 and 11,844.7 MHz, respectively. These pairs of frequencies were sufficiently close together so the klystron could be tuned from one to the other by changing only the repeller voltage.

An on-line PDP-11 computer controlled the timing, apparatus parameters, time-of-flight and resonance data collection for the experiment. During data taking with 40 μ sec per channel and a 2.5 meter long apparatus, the time-of-flight spectrum corresponding to the 5S_2 state of oxygen falls between the 6th and 30th channels, while most of the 3S_1 helium atoms fall between the 14th and 35th channels. With this data collection arrangement the inverse relation between observed linewidth and traverse time in the radio frequency region was easily demonstrated. Figure 3 shows a sample 5S_2 oxygen time-of-flight spectrum. For resonance data collection we used only those atoms which arrived at the detector between channel 10 and channel 35, since this range includes most of the slower 5S_2 oxygen atoms and the entire 3S_1 helium peak. Alternately, the helium and oxygen resonances were scanned and recorded at 20 discrete frequencies. Adequate data were collected in two or three minutes on helium and in 10 to 15 minutes on oxygen. Usually six oxygen resonances imbedded between seven helium resonances were taken before altering the experimental conditions.

III. DATA ANALYSIS

In data collection and searching for systematic effects 372 individual helium and oxygen resonances were collected and fitted by least squares methods to a Lorentzian line shape with a constant background. The resonance amplitude, peak frequency and width as well as the background were determined. Figures 4 and 5 show examples of fitted oxygen and helium resonances. All resonances used to determine optimum r.f. powers were discarded, and only five other oxygen resonances were eliminated for various experimental reasons. In an effort to discover possible systematic effects, the remaining data were divided into two groups, one corresponding to a field of 4228 gauss and the other to a field of 3209 gauss. Each of these groups were split into 4 subgroups according to the four possible orientations of the "C" field and hairpin (each may be N = normal or R = reversed). Finally these 4 subgroups were further divided into three smaller groups each having a different hairpin position. The ratio $g_J(^5S_2, ^{16}O)/g_J(^3S_1, ^4He)$ was computed for every oxygen resonance frequency using the average of the two helium resonance frequencies taken just before and immediately after the oxygen resonance. The average value for each of the groups and subgroups provided an indication of the degree of systematic effects and allowed correction for the Millman effect which arises from variation of the r.f. field direction in the transition

region.¹⁵

Results and Discussion

A summary of 158 measurements for the oxygen 5S_2 g_J is given in the histogram of Figure 6. Above the histogram are indications of individual averages for the four field and hairpin orientations as well as the final average. From this analysis we find

$$g_J(^5S_2, ^{16}O)/g_J(^3S_1, ^4He) = 0.9999269(4)$$

When this result is combined with the 3S_1 helium g_J discussed in the introduction, the final g_J of 5S_2 oxygen is

$$g_J(^5S_2, ^{16}O) = \mu_J/J = -2.0020910(10).$$

This value and the .5ppm quoted error cover about 82% of the measurements shown in the histogram in Fig. 6.

The measurement which has been described here is the first precision determination of the g_J factor of the 5S_2 metastable state of atomic oxygen. No accurate theoretical computations have been published with which the measurement may be compared. However, after preliminary results were obtained,¹⁶ R.A. Hegstrom using an approximate but simple computation which works well for 3S_1 He, found that the same procedure predicts the 5S_2 oxygen g_J to within 10ppm.¹⁷

The combination of time-of-flight detection with an atomic beam magnetic resonance apparatus proved to be a

sensitive technique for separating a particular discharge fragment from photons or other species affecting the beam detector.. Additionally, the method allows limited control of the magnetic resonance linewidth by selecting the velocity interval detected.

One of the authors (TI) appreciates the hospitality of the Atomic Beam Group, Department of Physics and Lawrence Berkeley Laboratory of the University of California. He also acknowledges the assistance of a grant from UNESCO.

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Figure Captions

- Figure 1. Schematic of energy vs. magnetic field for Zeeman levels and induced transitions (arrows) of a) the 2^3S_1 state of helium and b) the $5S_2$ state of atomic oxygen. $F = I + J$.
- Figure 2. Trajectory geometry and field configurations of the atomic beam apparatus used in the oxygen g_J measurement. The distance from the source to the detector is about 2.5 meters.
- Figure 3. The time of flight distribution of metastable dissociation fragments from O_2 . Data collection time was 10 minutes. The peaks between channels 6 and 30 correspond to $5S_2$ atoms.
- Figure 4. Least squares fit to an oxygen $5S_2$ resonance curve. Data collection time was 10 minutes.
- Figure 5. Least squares fit to a $3S_1$ helium resonance curve. Data collection time was 2 minutes.
- Figure 6. Histogram of all oxygen $5S_2$ g_J determinations. "N" and "R" refer to normal and reverse orientations of the C field or of the r.f. hairpin.

H

H

XBL748-3946

Fig. 1

XBL749-4208

Fig. 2

XBL 776-9245

Fig. 3

XBL 746-1087

Fig. 4

Fig. 5

XBL749-4303

Fig. 6

U S E N E R G Y R E S E A R C H A N D D E V E L O P M E N T A D M I N I S T R A T I O N

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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