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Observation of the Forbidden $2^3S_1 \rightarrow 1^1S_0$ Spontaneous Emission Line from Helium and Measurement of the Transition Rate*

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The extremely forbidden transition $2^3S_1 \rightarrow {}^1S_0$ at 625.56 Å has been observed in a He afterglow using time-resolved high-resolution spectrophotometric techniques. The spontaneous radiative transition rate was determined by measuring the photon emission rate from a known number of metastables at pressures of 0.05, 0.30, and 0.75 Torr. The value measured is 2.4×10^{-4} sec^{-1} with an experimental uncertainty of a factor of 3.

The single-photon transition rate of the $2^3S_1 \rightarrow 1^1S_0$ transition in He had been thought to be so small that it was unobservable.[1] However, Gabriel and Jordan[2,3] identified solar x-ray lines corresponding to the $2^3S_1 \rightarrow 1^1S_0$ transitions of several of the heliumlike ions from C V to Mg XI. This stimulated theoretical work[4-6] which predicted relativistically induced magnetic dipole transitions with a strong dependence on the nuclear charge; the calculated transition rates range from 1.27×10^{-4} sec^{-1} for helium to 2×10^{8} sec^{-1} for iron.

Marrus and Schmeider[7] have experimentally determined the radiative lifetime of the 2^3S_1 state in Ar XVII to be 172 ± 30 nsec, in reasonably good agreement with theory. Thus, a measurement of the radiative lifetime of He I, predicted as 8000 sec, coupled with the measurements of Marrus and Schmieder would provide a test of the theory over more than 10 orders of magnitude. In addition to the desirability of testing the concepts of the theory *per se*, the numerical accuracy of the theory is also of some interest. The ratio of the intensity of the $2^3S_1 \rightarrow 1^1S_0$ to the $2^3P \rightarrow 1^1S_0$ transitions in heliumlike ions can be used to estimate the electron density of a hot plasma, including the solar corona and cosmic x-ray sources.[3,8] The radiative transition is also a significant source of He metastable depopulation in some gaseous nebulae.[9]

We report here the first observation of the $2^3S_1 \rightarrow 1^1S_0$ transition at 625.56 Å in helium. The radiative decay rate was determined by measuring the photon emission rate from an experimentally known number of metastables. Of some concern was the contribution of collisionally induced radiative transitions between the two states. These were shown to be possibly significant only at the higher pressures (see below).

Figure 1 is a schematic of the experimental apparatus. The metastables were excited in a flowing high-purity He discharge of 1.2 m length and 0.12 m diameter. The discharge was excited by a 250-W commercial radio transmitter at 7 MHz. A differentially pumped slit system admitted light to the 1-m-focal-length normal-incidence spectrometer (McPherson model 225). The concave grating was gold coated and had 2400 lines mm^{-1}.

The grating transmission, averaged over the total area and both polarizations, was $(4.3\pm1.0)\%$ at 626 Å. The spectral resolution was 0.3 Å for the 0.75- and 0.05-Torr measurements and 0.25 Å for the 0.30-Torr measurements. Detection was by a Bendix Channeltron and pulse-counting electronics. The quantum efficiency was deter-

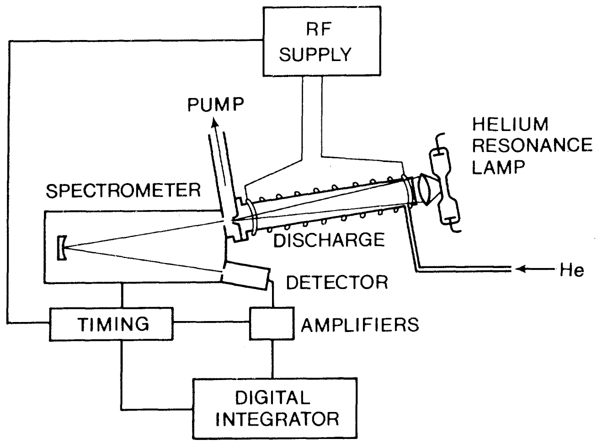

FIG. 1. Schmatic of the experimental apparatus.

mined by calibrating a sodium salicylate phosphor screen against a flowing-argon double ionization chamber at 584 Å. The Channeltron was then calibrated against the screen at the same wavelength. The manufacturer's relative sensitivity curves showed that the sensitivity was the same at 626 and 584 Å.

The weakness of the signal required the integration of successive spectra. This was accomplished by using the nearby 626.82-Å Ne line as a trigger for initiating the sweep of the digital integrator when the spectrometer was sweeping downward in wavelength at 5 Å/min^{-1}.

Although this was a weak low-pressure discharge, continuum radiation completely obscured the weak transition under study. (This radiation, which we have observed out to 640 Å, is probably due to the same He_2 molecule bands observed by Tanaka and Yoshino[10] at shorter wavelengths.) This was solved by turning the rf power to the discharge on and off at 1000 Hz. The continuum decayed in a few microseconds whereas the 2^3S metastable density (see below) decayed in ~0.5 msec. The emission line at 626.6 Å was expected to have the same long ~0.5-msec decay time. By gating the detector pulse-counting circuitry on for 0.5 msec after the rf was shut off, the signal-to-noise ratio was sufficiently increased to permit detection of the transition. Thus, data were obtained with the detectors on in a 0.5-msec interval in the afterglow of each pulse of the discharge while the spectrometer scanned slowly through the spectral region of interest.

The metastable density was determined by measuring the absorption at 3889 Å from the 2^3S_1 to the 3^3P states. A rf-excited He resonance lamp was placed behind the discharge tube as shown in Fig. 1. Absorption of the resonance lines was measured before and after each run by turning the spectrometer to zero order and isolating the 3889-Å line with an interference filter. The metastable density was then obtained by standard methods.[11,12] These total absorption measurements were crosschecked against high-resolution measurements made on a 1.8-m Fastie-Ebert spectrometer with a resolving power of about 250 000. The metastable densities measured by the high- and low-resolution methods were within 25% of each other.

A major difficulty with these measurements was the fact that the 3889-Å line was strongly absorbed in the discharge tube. There were almost 3 optical depths at the strongest part of the complex (because of fine structure) line and the measurements of metastable density were sensitive to small errors in measuring the absorption. In addition, as mentioned previously, data were obtained while the He metastable density was decaying. This required a determination of the time profile of the metastable density. The uncertainties in both these measurements were such that the total uncertainty in metastable population was a factor of 2.5.

The expected signal size, S, given by the number of counts per second the detector should produce when the spectrometer was set for the peak of the line, can be calculated as follows:

$$S = B_{st} A_s A_g R_g QD/F^2 = 0.5 \text{ count/sec},$$

where $B_{st} = NA/(4\pi)$ is the standard brightness of the source, with $A = 1.27\times 10^{-4}$ sec^{-1} the radiative transition rate for the $2^3S \rightarrow 1^1S$ transition, and N the number of metastables in a square centimeter column length of the light source, typically 2.6×10^{12} cm^{-2}; A_s is the area of the slits, 4.5×10^{-3} cm^2(8 mm high); A_g is the area of the grating, 15.0 cm^2; R_g is the reflectivity of the grating, 0.043 ± 0.010; Q is the quantum efficiency of the detector, 0.128 ± 0.030; D is the duty factor (the counters were only turned on when the rf source was turned off), 0.50; and F is the focal length of the spectrometer, 1 m.

This typical signal count rate of 0.5 count/sec was superimposed on a background level of somewhat more than 10 counts/sec. Since the spectrometer was only looking at the 625.6-Å line for about 4 sec out of each 1-min scan, 1000 or more scans were added to obtain a good signal-to-noise ratio.

The results of this experiment at three differ-

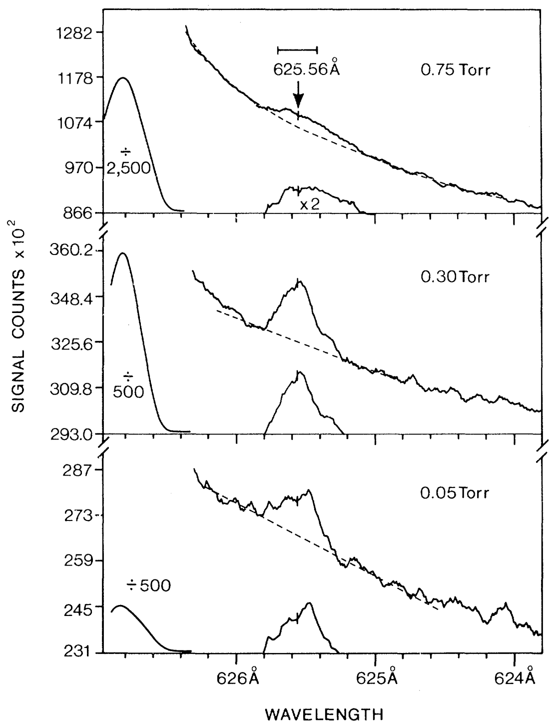

FIG. 2. Emission from the discharges near 626 Å at three different pressures. The strong line is due to Ne. There is clearly a feature at 625.6 Å superimposed on the sloping continuum. The signal counts were recorded in 0.0083-Å intervals. A sliding sum of ten was then taken so that only every 0.083-Å interval contains completely independent data. Note that the ordinate scales for each pressure are different. The bar indicates spectral resolution.

ent source pressures, representing 5780 scans of the spectrometer, are shown in Fig. 2. The large feature at 626.82 Å is a neon impurity line. The predicted location of the 625.56-Å line is indicated by an arrow. There is clearly a feature superimposed on the background at that wavelength.

Because the 625.6 Å signal was so weak, tests were run to determine whether the line observed at 625.6 Å could be a grating ghost of some other strong line. The tests yielded completely negative results.

The feature minus the background is plotted at the baseline of the spectrum for each of the three runs. For the two lower pressures the background level was determined by hand, but for the run at 0.75 Torr, a fourth-degree polynomial fit was made to the baseline. The instrumental half-width (full width at half-maximum) is also indicated.

Runs were taken at three different pressures to determine whether the transition rate measured for the $2^3S \rightarrow 1^1S$ transition was really the radiative transition rate or was the result of neutral-collision-induced transitions. (The electrons and ions were down in concentration by 6 or more orders of magnitude and should have been negligible.) The high-pressure run was made immediately after the low-pressure run to minimize unknown changes in parameters; the 0.3-Torr run was made four months prior. To a first approximation, any collision-induced transition rate should vary linearly with pressure. Thus, of the collision-induced transitions dominated, one would expect the transition rate at 0.75 Torr to be 15 times the transition rate at 0.05 Torr. The transition rates (calculated from the intensity at the peak of the line) are listed below.

Pressure (Torr)	Transition Rate ($\sec^{-1}$)
0.05	2.35×10^{-4}
0.30	2.5×10^{-4}
0.75	3.8×10^{-4}
Theoretical value (Ref. 5)	1.27×10^{-4}

Assuming that the transition rate can be described as having two parts, a spontaneous radiative transition rate and a collisionally induced radiative transition rate which varies linearly with pressure, upper limits can be put on the collision-induced transition rate. If the total difference between the transition rates measured at 0.30 and 0.75 Torr was due to an increase in the pressure-induced transitions (implying a cross section of $\sim 3\times 10^{-26}$ cm^2), then the maximum percentages P of the total transition rate that could have been due to collisionally induced transitions were as follows.

Pressure (Torr)	P %
0.05	4
0.30	20
0.75	40

It should be stressed that, because of the relative uncertainty between the data at the three different pressures, these may be only upper limits. Some support for the existence of a pressure effect is given by the line shape of the 626-Å line. The data taken at 0.75 Torr show a broadening of the He line towards short wavelengths and the data at 0.30 Torr show a small bump on the short-wavelength side, possibly indicating that the line is being pressure broadened at the higher pressures.

For these reasons, it is concluded that pressure-induced transitions do not significantly affect the value of the transition rate taken at 0.05 Torr but may become important at pressures greater than 0.3 Torr.

The experimentally determined spontaneous transition rate is 2.35×10^{-4} sec^{-1}. At present, the experimental uncertainties (a factor of 3) are sufficiently high that this cannot be considered to be in disagreement with the predicted value[5] of 1.27×10^{-4} sec^{-1}. Further work to reduce the experimental uncertainties is in progress.

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Phase Transitions in a Fluid of Biaxial Particles*

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A model is solved for a fluid of biaxial particles within a type of mean-field approximation. The results suggest that the phase diagram of such a fluid exhibits a special critical point where two second-order critical lines meet a first-order phase boundary in a sharp cusp. The features of the phase diagram suggest a new way to look for critical phase transitions and biaxial phases in liquid crystals.

Recently there has been a great deal of interest in critical phenomena in systems with phase diagrams of topological structures which indicate unusual critical behavior.[1,2] There has also been some interest in an as yet unobserved liquid-crystal phase with no long-range order in the position of the constituent molecules,[3] but with long-range orientational order of biaxial (i.e., nonuniaxial) rather than uniaxial symmetry.[4,5] In this Letter, we consider a model for a fluid of biaxial particles within a type of mean-field approximation. The results indicate that the phase diagram of such a fluid contains a critical point different from both ordinary critical points and tricritical points.[6] The special point occurs where two second-order critical lines meet a first-order phase boundary in a sharp cusp. The cusp, which occurs as the behavior of the molecules of the fluid crosses over from rodlike to platelike, is a region of enhanced stability for a biaxial phase. Thus, in addition to special critical behavior, our results also indicate a novel way to change the character of the nematic-isotropic transition and to search for biaxial liquid crystals.

The specific model which we have studied is a lattice model for steric interactions among hard rectangular plates.[5] The structure of the phase diagram, however, is the natural result of the Landau theory of phase transitions for a rotation-