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HANLE EFFECT IN $2^1P$ HELIUM.

The University of Michigan, Ph.D., 1969
Physics, atomic

University Microfilms, Inc., Ann Arbor, Michigan

# HANLE EFFECT IN $2^1P$ HELIUM

by

Edward Strauss Fry

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in
The University of Michigan
1969

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## ACKNOWLEDGMENTS

It is a pleasure to acknowledge my sincere appreciation to Dr. W. L. Williams for his continued guidance and encouragement in this work.

I would also like to thank Dr. C. W. Hendee of Bendix Corporation for supplying the Channeltron multipliers, and Warren Wilson for his assistance in constructing part of the equipment.

The support of this research by the U. S. Atomic Energy Commission and the University of Michigan Office of Research Administration is also gratefully acknowledged.

Finally, I wish to thank my wife, Deborah, for her patience and encouragement.

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## ABSTRACT

The oscillator strength for the resonance ($1^1S$-$2^1P$) transition in atomic helium has been determined from a measurement of the lifetime of the $2^1P$ state. This lifetime was obtained using a modified zero field level crossing (Hanle) method. The scattering sample was a thermal velocity beam of $2^1S$ metastable atoms. Resonant 2 micron ($2^1S$-$2^1P$) radiation is absorbed by the $2^1S$ atoms, which are excited to the $2^1P$ state. This state then primarily decays to the ground $1^1S$ state with the emission of resonance (584Å) radiation. The lifetime of the $2^1P$ state was determined from measurements of the magnetic field dependence of the 584Å intensity. This new technique eliminates the problem of constructing a vacuum ultraviolet resonance lamp. The measured lifetime $\tau(2^1P)$ is $(5.69 \pm 0.23) \times 10^{-10}$ sec. The resulting absorption oscillator strength for the resonance transition is $0.270 \pm 0.011$. This oscillator strength agrees with the theoretical value.

# I. INTRODUCTION

An important test of approximate two-electron wave functions is provided by an experimental check of the predicted oscillator strengths or f values. Those f values predicted for transitions between the ground state ($1^1S$) and the $n^1P$ states of helium are extremely sensitive to the choice of wave functions. This sensitivity is demonstrated by the wide variations in the results of early calculations (Dalgarno and Lynn 1957). Recently, two-electron wave functions based on high order approximations have been obtained. (Pekeris 1958, 1962a, b; Pekeris, Schiff and Lifson 1962). Energy eigenvalues obtained from these wave functions agree with experimental values having errors of at most several parts per million. The f values determined with these wave functions (Schiff and Pekeris 1964) exhibited excellent internal consistency in that the results obtained from dipole length, velocity and acceleration matrix elements agreed within 0.02%. The results of several other authors are comparable (Dalgarno and Stewart 1960; Salpeter and Zaidi 1962; Green, Johnson and Kolchin 1966; Weiss 1967).

The sensitivity of the calculated f value to the choice of the approximate wave function is especially strong for the resonance ($1^1S$-$2^1P$) transition in helium. Kuhn

and Vaughan (1964) reported an experimental f value for this transition from an interferometric profile analysis of spectral lines terminating in the $2^1P$ state. They obtained a value some 30% larger than the Schiff and Pekeris (1964) theoretical value. This discrepancy was rather surprising considering the apparent accuracy of the wave functions used to obtain the calculated result. Over the next several years the experimental data were confirmed, but were analyzed with an inclusion of resonance broadening effects. Vaughan (1966a, b) has shown that if the Schiff and Pekeris f value is used, then the experimental data are in agreement with resonance broadening theory. Korolyov and Odintsov (1965) also used interferometric techniques to study light produced by electron bombardment of an atomic beam. Under the conditions most favorable for determining the line width they obtained an f value with ≈5% error limits. However, it disagrees with the theoretical value by ≈6%.

In the present experiment the f value for the resonance transition in $^4He$ is determined from a measurement of the lifetime of the $2^1P$ state. This lifetime was measured by utilizing a zero field optical level-crossing or Hanle effect technique (Mitchell and Zemansky 1934; Lurio, deZafra and Goshen 1964). The Hanle method offers distinct advantages in that Doppler broadening effects are generally negligible and the measurements do not require a knowledge of the density of sample atoms in the low density limit. The inherent disadvantage is that it requires an intense nonself-reversed

source of the resonance radiation. Normally this would be a serious problem for the present experiment since the strong radiative transition from the $2^1P$ state is in the vacuum ultraviolet (584Å). However this problem was eliminated by using a modified Hanle method described previously (Williams and Fry 1968). In this method resonant $2^1P$-$2^1S$, 2μ radiation is incident on a sample of $2^1S$ metastable helium atoms. The emitted $2^1P$-$1^1S$, 584Å radiation is observed as a function of magnetic field. The construction of a nonself-reversed source of resonance radiation is not a serious problem for the 2μ radiation.

## II. THEORY

Level crossing phenomena can be described in terms of a quantum-mechanical theory of interference effects due to Breit (1933). The Breit formula has been discussed by several authors (Franken 1961; Rose and Carovillano 1961). It gives the rate $R(\hat{f},\hat{g})$ at which resonance radiation of polarization $\hat{f}$ is absorbed and radiation of polarization $\hat{g}$ is re-emitted by a sample of atoms (see Fig. 1). Specifically, we have

$$R(\hat{f},\hat{g}) \propto \sum_{\substack{\mu,\mu' \\ m,m'}} \frac{f_{\mu m} f_{m\mu'} g_{\mu' m'} g_{m'\mu}}{1-i\tau\left(\frac{E_\mu - E_{\mu'}}{\hbar}\right)} \quad , \tag{1}$$

where $\mu$ and $\mu'$ refer to excited state magnetic sublevels; $m$ and $m'$ refer to magnetic sublevels of the ground state; $f_{\mu m} = \langle \mu | \hat{f}\cdot\vec{r} | m \rangle$, etc. are dipole matrix elements; $E_\mu$ is the energy of the $\mu^{th}$ excited sublevel, etc.; and $\tau$ is the mean lifetime of the excited state. There are resonant effects when $E_\mu = E_{\mu'}$, that is when the energy levels cross. When they cross at zero magnetic field the phenomenon is called the Hanle effect. Generally, the initial as well as the final state is the ground state. However, for the case in which the initial and final states are different, Breit (1933) has pointed out that (1) is still valid provided m

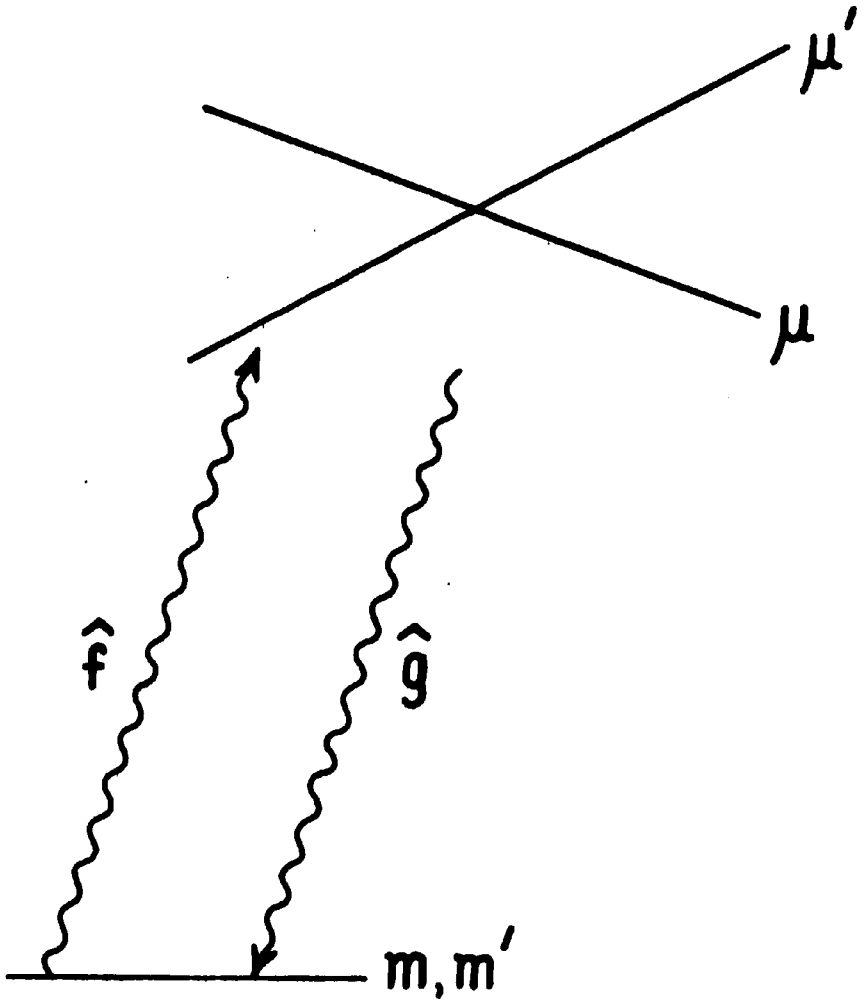



Fig. 1. Energy level diagram for the Breit formula. The ground states are m and m′. The excited states designated $\mu$ and $\mu'$ cross at some specific value of magnetic field. Radiation of polarization $\hat{f}$ is absorbed and radiation of polarization $\hat{g}$ is re-emitted in the fluorescence process.

is restricted to magnetic sublevels of the initial state and m′ to sublevels of the final state. This generalization is important to the present experiment.

Figure 2 shows the spherical coordinate system used to evaluate R. Here the magnetic field H is along the z axis; $\theta$, $\varphi$ are respectively the polar and azimuthal angles of the incident light direction; and $\theta'$, $\varphi'$ are similar angles for the observed light direction. Several authors (Lurio, deZafra and Goshen 1964; Anderson 1965) have outlined the calculation of the required matrix elements. For a Hanle effect level crossing, the scattering rate in a $J = 0 \rightarrow J = 1 \rightarrow J = 0$ transition is given by

$$R \propto \left[(2-\sin^2\theta') + \frac{\sin^2\theta'\cos^2(\varphi'-\varphi)}{1+x^2} + \frac{x\sin^2\theta'\sin^2(\varphi'-\varphi)}{1+x^2}\right] \quad (2)$$

$$x = 2g_J\mu_o H\tau/\hbar \ ,$$

where $\tau$ and $g_J$ are the mean lifetime and g value of the excited state, respectively. In Eq. (2) it is assumed that the incident light has polarization vector $\hat{f}$ parallel to the y-axis (perpendicular to the magnetic field) and the observed light is detected without regard to polarization. The field dependence is produced by interference between the $m = \pm 1$ substates of the $J = 1$ state. Note also that this result is independent of the angle $\theta$ of the incident light.

The geometry of the present experiment requires the average of Eq. (2) over symmetric solid angle contributions

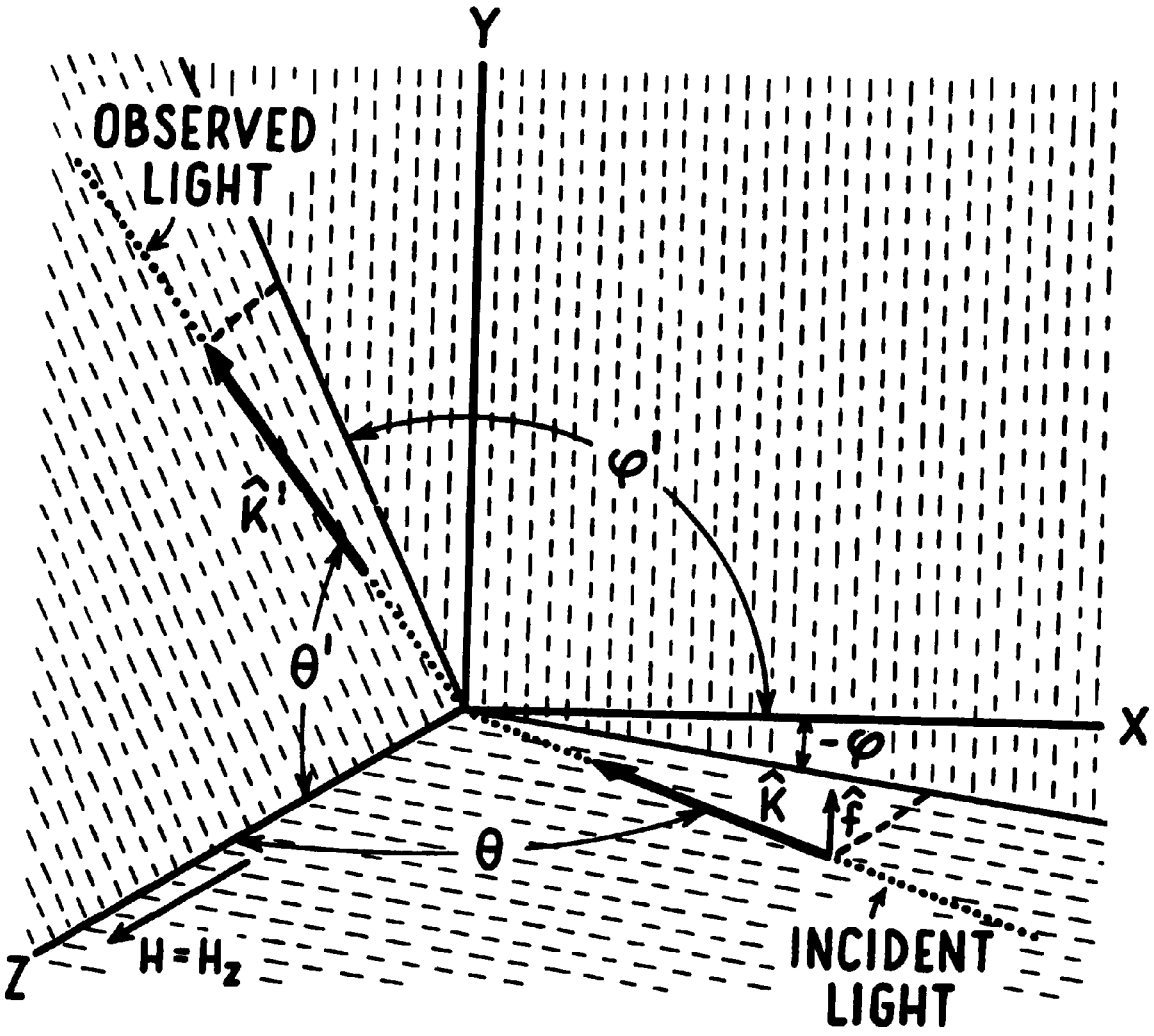



Fig. 2. Coordinate system used to evaluate the Breit formula. $\varphi$ and $\varphi'$ are the azimuthal angles in the x-y plane; $\theta$ and $\theta'$ are the polar angles with respect to the z axis.

centered about a $90°-90°-90°$ geometry (mutually perpendicular incident light direction, observation direction, and magnetic field). We evaluate

$$\overline{R} = \frac{\int R d\Omega}{\int d\Omega} \quad , \tag{3}$$

where $d\Omega = \sin\theta \sin\theta' d\theta d\theta' d\varphi d\varphi'$ and the limits of integration are:

$$\varphi: -\alpha, +\alpha \qquad \varphi': (\pi/2 - \beta), (\pi/2 + \beta)$$
$$\theta: (\pi/2 - \gamma), (\pi/2 + \gamma) \qquad \theta': (\pi/2 - \delta), (\pi/2 + \delta) \; .$$

Here $\alpha$, $\beta$, $\gamma$, and $\delta$ are small angles defining the extent of departure from exact $90°-90°-90°$ geometry. The result is

$$\overline{R} \propto \left[ \left( \frac{2\alpha}{\sin 2\alpha} \right) \left( \frac{2\beta}{\sin 2\beta} \right) \left( \frac{3+\sin^2\delta}{3-\sin^2\delta} \right) - \frac{1}{1+x^2} \right] \quad . \tag{4}$$

In the limit $(\alpha, \beta, \gamma, \delta) \to 0$ or perfect $90°-90°-90°$ geometry, Eq. (4) reduces to the usual inverted Lorentzian result

$$\overline{R} \propto \left[ 1 - \frac{1}{1+x^2} \right] \quad . \tag{5}$$

Recalling that the above results are obtained for polarized incident light, it is seen that Eq. (5) does give the expected result, $\overline{R} = 0$, when $H = 0$ $(x = 0)$. However, it is also seen that the more general Eq. (4) does not necessarily yield $\overline{R} = 0$ when $H = 0$. The important point to be made here is that inclusion of the symmetric solid angle effects adds a field independent background to the inverted Lorentzian of Eq. (5). In general for unpolarized incident light,

these effects reduce the ratio of field dependent to field independent signal from that ratio obtained for perfect geometry.

Setting $x = 1$, the relationship between the excited state lifetime and the half-width at half-maximum, $H_{\frac{1}{2}}$, of the inverted Lorentzian line is obtained,

$$\tau = \frac{\hbar}{2g_J\mu_o H_{\frac{1}{2}}} \quad . \tag{6}$$

# III. EXPERIMENT

## A. Method

Figure 3 shows an energy level diagram of the low lying states of $^4$He together with the allowed electric dipole transitions. To determine the $2^1P$ lifetime, the usual Hanle experiment would involve scattering 584Å radiation from a sample of ground state helium atoms. Unfortunately, this radiation is in the vacuum ultraviolet region of the spectrum where windows can only be made from thin films. This limitation makes construction of a suitable light source a difficult problem.

A second approach would be to treat the $2^1S$ metastable state as a "ground state" and scatter 2μ radiation, a wavelength for which optical instrumentation is readily available. This is analogous to the work of Colegrove, Franken, Lewis, and Sands (1959) in which 1μ radiation is scattered from $2^3S$ metastable atoms. However, the transition probability for decay of the $2^1P$ excited state to the $1^1S$ ground state by electric dipole radiation is more than 1000 times greater than the transition probability for decay to the $2^1S$ metastable state. Therefore, the intensity of scattered 2μ radiation would be vanishingly low.

These problems were avoided by performing a modified

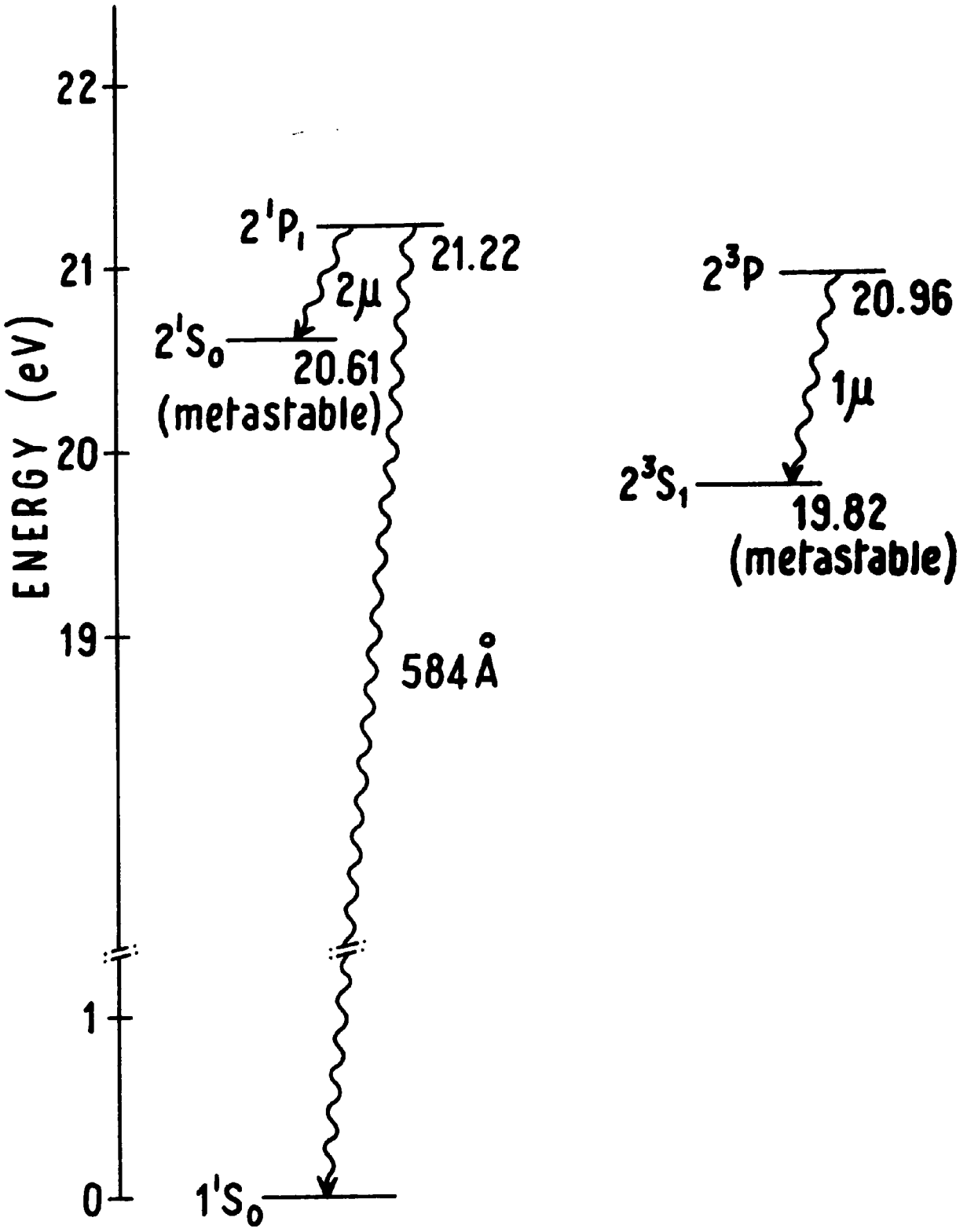



Fig. 3. Low-lying energy levels of helium and the allowed electric dipole transitions. The numbers below a level give its energy in eV relative to the ground state.

Hanle type level crossing experiment in which the incident and scattered radiations are of different wavelengths. Specifically, resonant $2^1P$-$2^1S$, $2\mu$ radiation was used to excite helium atoms from the $2^1S$ metastable state to the $m = \pm 1$ substates of the short-lived $2^1P$ state. The intensity of the 584Å radiation emitted during the decay of this state was then measured as a function of magnetic field. $H_{\frac{1}{2}}$ and hence, $\tau(2^1P)$, were determined from the resulting inverted Lorentzian line shapes.

## B. Apparatus

A diagram of the experimental apparatus is shown in Fig. 4. Metastable helium atoms were produced in the electron gun region by electron bombardment and then collimated into a beam. The cross section for $2^1S$ metastable production is $\approx 10^{-18}$ cm$^2$ (Holt and Krotkov 1966). The resulting beam flux is $\approx 10^4$/sec $2^1S$ atoms moving at thermal velocities. Resonant $2^1P$-$2^1S$, $2\mu$ light from a helium discharge lamp illuminated the beam in the central region of the Helmholtz pair. The 584Å radiation was detected at 90° to the direction of this incident radiation. The Helmholtz pair provided a magnetic field parallel to the metastable beam and perpendicular to the directions of both the incident ($2\mu$) and scattered (584Å) radiations.

The electron gun is a simple diode in which the filament serves as cathode. The filament is a 2.5 cm long, 0.2 mm diameter thoriated tungsten wire. It was heated by passing a dc current of 4.5 A through it. The anode

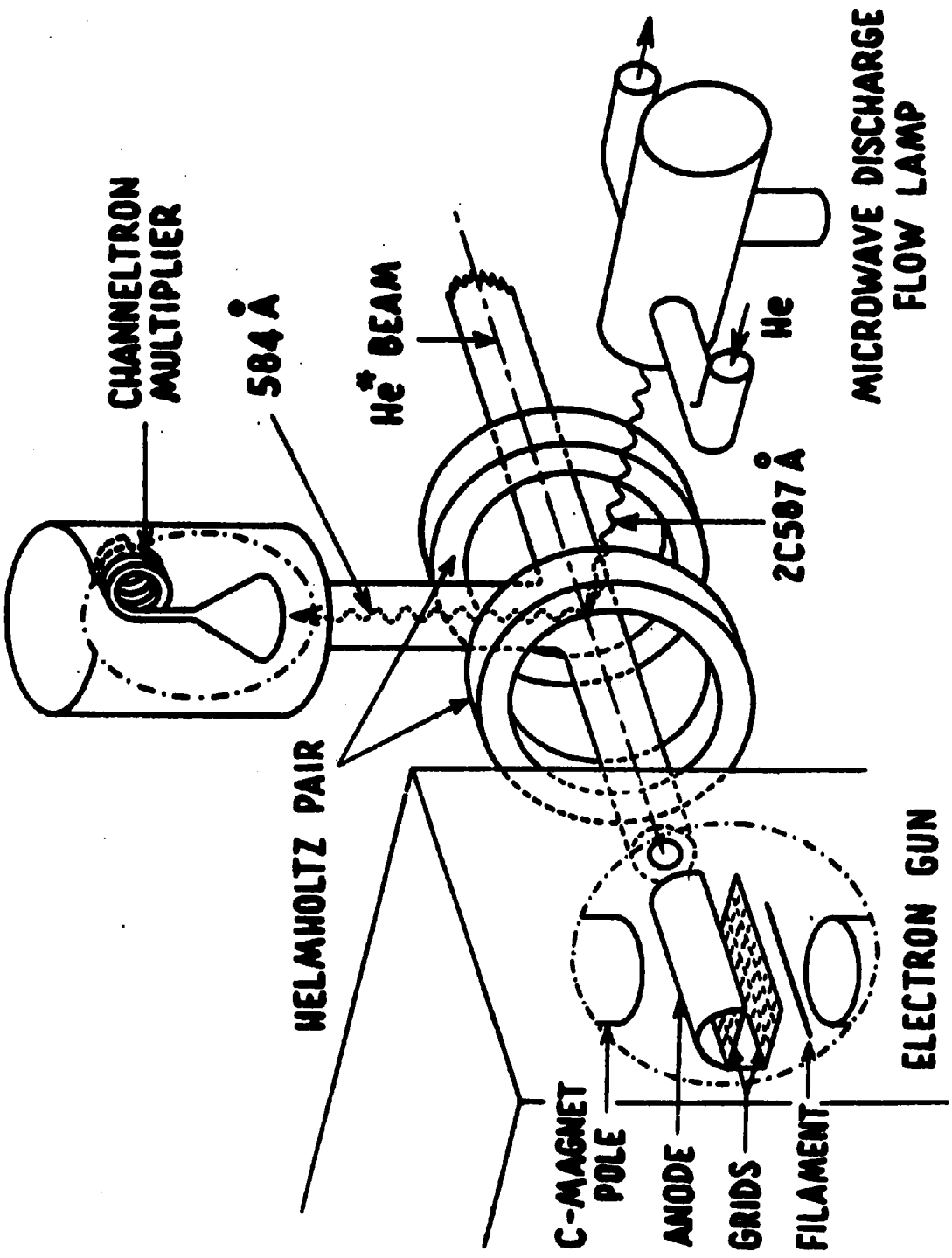



Fig. 4. Experimental arrangement for the modified Hanle effect experiment.

is a semi-cylindrical piece of 0.1 mm thick stainless steel to which two tungsten grids are attached. Electrons emitted by the filament are accelerated toward the anode by the first of these grids; the second, together with the anode, forms an electric field free region through which the electrons pass. This assembly is placed between the poles of a permanent magnet which has a field of $\approx$300 G and serves to collimate the electrons between the filament and anode. Typically, the anode voltage was +40 volts with respect to the filament, and the corresponding emission current was 2 mA. The electron gun stability was improved by heating the anode to a dull red glow before each data session. This was accomplished by passing an ac current of 60 A through the anode.

The electron gun assembly was enclosed in a box containing helium gas whose pressure was varied between $5 \times 10^{-4}$ and $3 \times 10^{-3}$ Torr. This box was located inside the vacuum system. Opposite the electric field free region between the upper grid and the anode, there was a 5mm diameter hole in the box through which helium atoms in various states could diffuse. These atoms were collimated into a beam which passed along the axis of the Helmholtz pair. It is reasonable to assume the beam contained only ground state ($1^1S$) and metastable ($2^1S$ and $2^3S$) helium atoms, since at thermal velocities ($\approx 10^5$ cm/sec), an atom excited to an optically decaying state travelled a very short distance ($\approx 10^{-2}$ cm) before decaying with a typical lifetime ($\approx 10^{-7}$ sec). The distance between the collimating hole in the electron gun box and the center of the scattering region was 10 cm.

The scattering region was a 3/4" diameter Pyrex tube coaxial with the metastable beam. At a right angle to this tube and halfway between the Helmholtz coils a second Pyrex tube led to the detector chamber. By means of two adjustment screws the scattering region could be rotated, thereby moving the detector and altering the angle $(\varphi'-\varphi)$ between the detector and lamp. The base pressure in the vacuum system was $1 \times 10^{-7}$ Torr. When helium was let into the electron gun box this pressure would rise to between $3 \times 10^{-6}$ and $2 \times 10^{-5}$ Torr.

A Bendix Channeltron electron multiplier was used for detection of the 584Å radiation. When 2500 volts is applied across this device, it has a gain of $\approx 10^7$ with noise of 0.1 cts/sec. It has a window from 2Å to 1400Å with a quantum efficiency of ≈25% at 584Å (Johnson 1966). The detecting surface is the inside of a cone which is 1 cm in diameter at the open end. This open end was 15 cm from the metastable beam. However, the effective solid angle was somewhat increased due to reflection of 584Å radiation from the walls of the interconnecting $\frac{1}{2}$" Pyrex tube.

Resonant $2\mu$ light was obtained from a helium flow lamp which was in a microwave cavity powered by a Raytheon Microtherm diathermy machine. Helium at a pressure of ≈1 Torr flowed through a 5 mm diameter quartz tube placed in cavity no. 5 of those described by Fehsenfeld, Evenson, and Broida (1965). The $2\mu$ radiation produced was directed towards the metastable beam by means of a hollow, polished

aluminum light pipe. Since this light pipe was of a divergent type, it not only increased the intensity of 2μ light which is incident on the beam, but also decreased the angle of divergence of the reflected light. Fig. 5 shows two cross sections of the light pipe. These illustrate respectively the path of typical light rays, and the path of a light ray which exits at the maximum possible angle, $\Theta_m$, with respect to the light pipe axis (Wolfe 1965). For transmitted radiation with $\Theta \approx \Theta_m$ the intensity is greatly reduced since it must undergo several reflections with ≈10% loss in intensity at each reflection. The light pipe was 4 cm long. It had an entrance width of 0.5 cm, an exit width of 1 cm, and $\Theta_m$ was 33°. The lamp was placed at the entrance to the light pipe so that light from nearly a $2\pi$ solid angle was collected. A Polaroid HR infrared polarizer between the large end of the light pipe and the beam polarized the incident light perpendicular to the Helmholtz field.

The magnetic field was monitored by measuring the voltage across a 0.1 Ω manganin resistor which was in series with the Helmholtz coils. The field calibration was made by measuring the field with a Rawson rotating coil gaussmeter whose claimed 0.1% accuracy was verified by comparison with a low-field proton resonance probe. The axial magnetic field variation over the scattering region was 0.5%. The field from the electron gun magnet together with the earth's magnetic field contributed 1.5 G perpendicular to the axis of the coil.

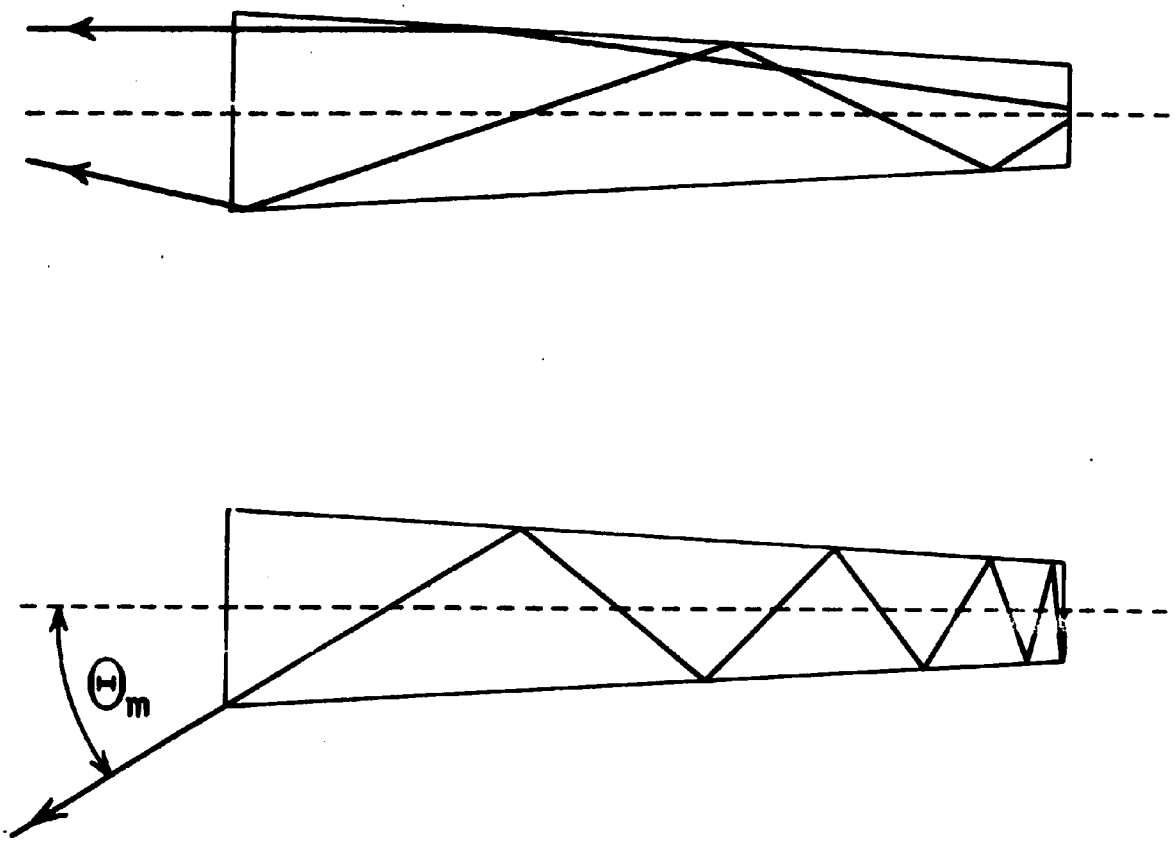



Fig. 5. Light pipe cross-sections showing the path of typical light rays. The second of these indicates the path of a light ray which exists at the maximum angle $\Theta_m$ with respect to the light pipe axis.

## IV. RESULTS

Preliminary experiments provided an unambiguous verification that the process observed is absorption of 2μ radiation followed by emission of 584Å radiation. A filter which transmitted a 0.05μ band centered at 2.059μ was inserted between the lamp and the beam. The Hanle signal was still observed, although reduced in amplitude. When the above filter was replaced by one that had an absorption band at 2μ, the Hanle signal was absent. Finally, when the discharge lamp was run with $^3$He, no Hanle signal was observed. This last result is expected since the wavelength of the 2μ line in $^3$He is shorter than that in $^4$He by ≈0.9Å (Fred, Tomkins, Brody and Hamermesh 1951), or ≈25 times the natural 2μ absorption breadth.

A typical set of 584Å counting rates is presented in Fig. 6. The data for negative and positive fields are the counting rates for opposite directions of the field. This set of data was taken at a helium pressure of $6 \times 10^{-6}$ Torr. The background count rate that arises when there is a metastable beam in the machine and the 2μ lamp is off is produced mainly by the scattering of 584Å radiation originating in the electron gun region. This count rate can be estimated as follows. The resonant absorption cross section for 584Å radiation is given by $\sigma = \lambda^2/2\pi \approx 5 \times 10^{-12}$ cm$^2$. For

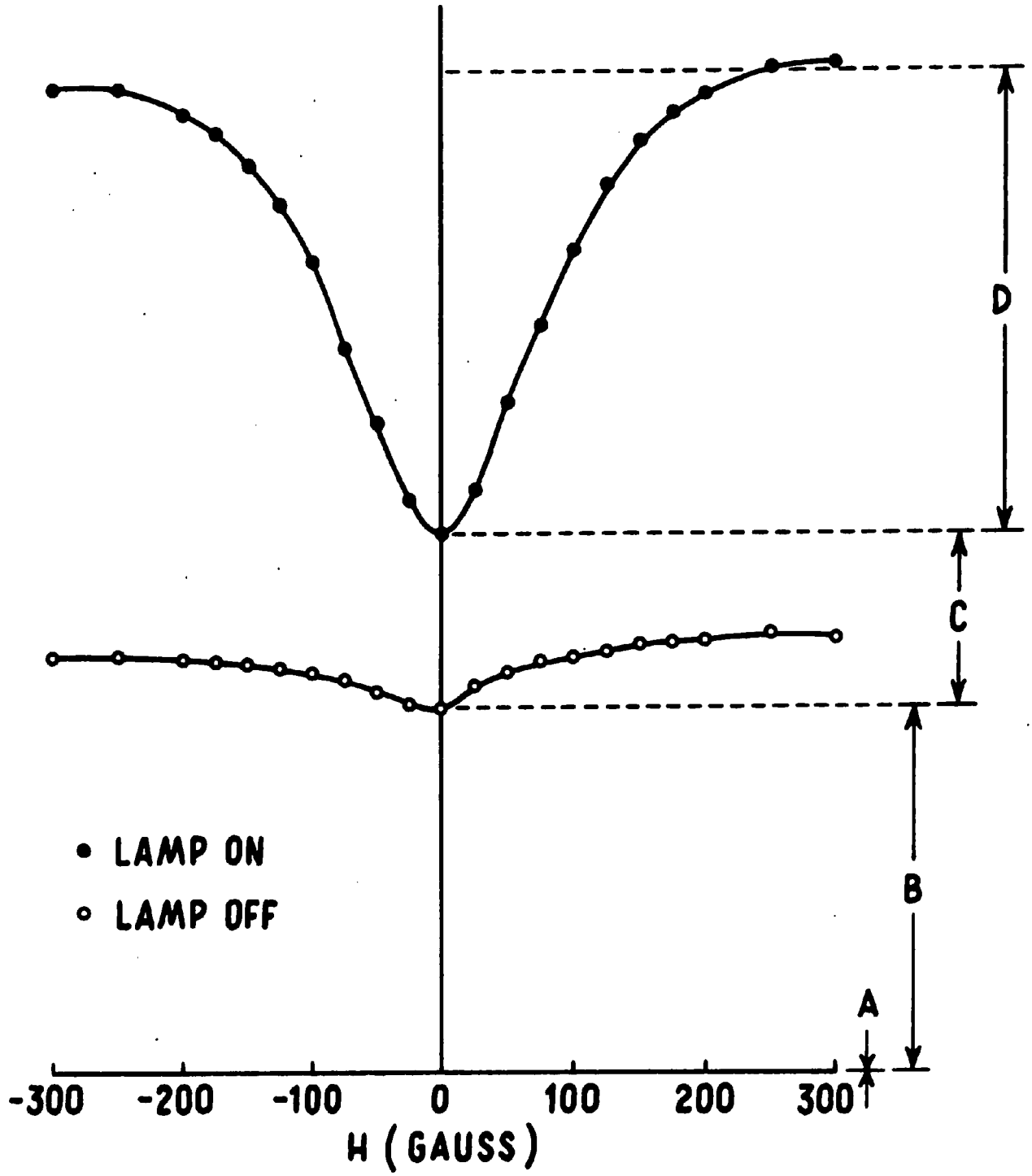



Fig. 6. Typical 584Å count rates

| | | |
|---|---|---|
| A: | Dark count rate (no metastable beam) | .1 counts/sec |
| B: | Background count rate (with metastable beam) | 57 counts/sec |
| C: | Net fluorescence at zero field | 27 counts/sec |
| D: | Field dependent signal (fitted Lorentzian amplitude) | 75 counts/sec |

a pressure of $6 \times 10^{-6}$ Torr, the density of helium atoms is $\approx 2 \times 10^{11}/cm^3$. The 584Å flux was measured and found to be $\approx 10^5$ photons/sec. Using these values together with a 1.0 cm length for the scattering region and the solid angle factor of $10^{-3}$, the calculated background count rate is ≈100 counts/sec. For an order of magnitude estimate, this compares favorably with the observed value of 57 counts/sec.

In this background scattering process the incident light direction is parallel to the magnetic field and perpendicular to the observation direction, a $0°-90°-90°$ geometry. For such a geometry and with unpolarized incident light, there should be no magnetic field dependence of the scattered intensity. However, the small Lorentzian-like field dependence superimposed on the background count rate of Fig. 6 would be expected if the incident 584Å radiation was partially polarized. Therefore, its polarization was measured. This was done by measuring at zero magnetic field the scattering rate for the 584Å radiation at various positions in a plane perpendicular to the light direction. These measurements indicate ≈25% polarization in a direction parallel to the velocity of the exciting electrons in the electron gun. This direction is also parallel to the observation direction for the data of Fig. 6. For this polarization and geometry the amplitude of the field dependent signal should be one-third the amplitude of the zero field count rate. Thus the amplitude of the background field dependent signal should be ≈19 counts/sec. This compares satisfactorily with the observed value of ≈10 counts/sec.

The shape of the background field dependent signal is badly distorted. This distortion could not be removed by adjusting the geometry. It is possibly due to the fact that along with the 584Å radiation entering the scattering region, there are also charged particles. The presence of these is inferred from the effect of electric fields on the background counting rates. The magnetic field also affects the motion of these charged particles, and this effect can not be separated from the magnetic field dependence of the 584Å scattering rate. In any case, the effects of the background are eliminated in the present experiment by subtracting the background count rate at each magnetic field point from the 2μ induced count rate. This gives the net 584Å fluorescence.

An estimate of the net fluorescence at zero field can be made by assuming negligible detector solid angle, ($\beta = \delta = 0°$), and uniform intensity from the light pipe over the solid angle determined by $\Theta_m$, ($\alpha = 33°$). With these angles and the field dependent amplitude from Fig. 6 in conjunction with Eq. (4), a value of 20 counts/sec is calculated for the net fluorescence at zero field. Considering the uncertainties in the solid angle estimates, this is good agreement with the observed value of 27 counts/sec.

Half-widths were determined from the data by means of a least squares fit to an equation of the form

$$R(H) = A\left[1 - \frac{(1-Bx)}{1+x^2}\right] + C \quad , \quad x = H/H_{\frac{1}{2}} \tag{7}$$

where the fitting parameters are A, the inverted Lorentzian

amplitude; B, a measure of the dispersive component in R(H); C, the scattering rate at zero field; and $H_{\frac{1}{2}}$, the half-width at half-maximum. The extent to which the solid angles of incident and detected radiation are not symmetric about perpendicular directions is measured by B. It has its origin in the third term of Eq. (2). Standard deviations on the fitting parameters were calculated by the usual techniques (Beers 1962). Fig. 7 shows an example of the 584Å count rate as a function of the magnetic field. The data for negative and positive fields are the scattering rates for opposite directions of the field. These data were normalized by subtracting the fitted parameter C and dividing by the fitted Lorentzian amplitude A.

The line shape is in good agreement with theory up to $H = \pm 2H_{\frac{1}{2}}$. However, at larger fields the experimental points always lie below the fitted curve. Anderson (1965) observed a similar effect in xenon and suggested that the deviation may be due to an effective decrease in the intensity of the incident light at the larger magnetic fields. This could occur because the frequencies for resonant absorption shift with field and move onto the shoulder of the Doppler broadened line from the lamp. The present experiment is particularly sensitive to such an effect. With a value of $5.7 \times 10^{-10}$ sec for the lifetime of the $2^1P$ state, the natural absorption breadth for 2μ light is

$$\Delta\lambda_N = \frac{\lambda^2}{2\pi c\tau} = 0.037\text{Å}.$$

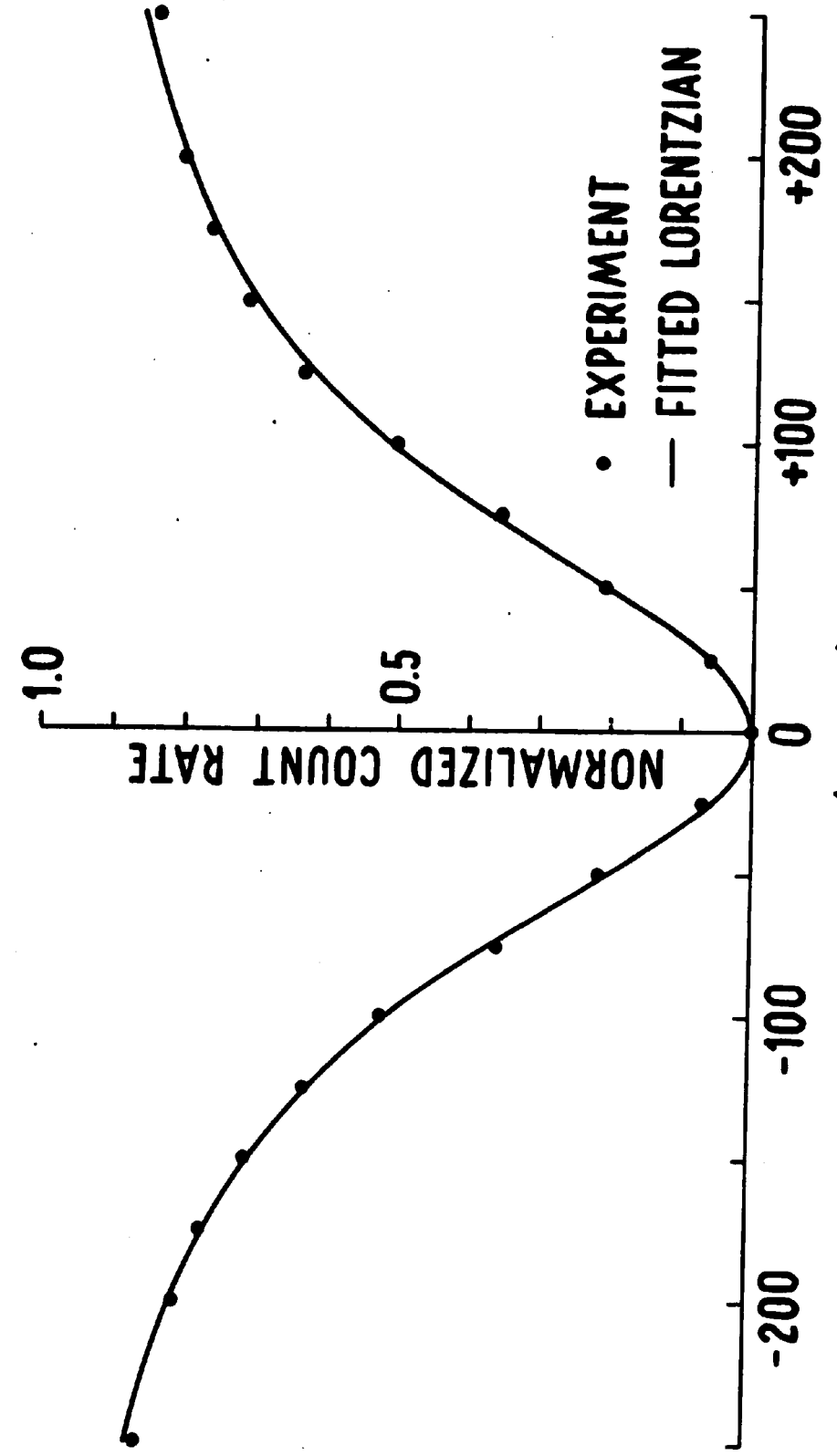



Fig. 7. Hanle effect signal from He($2^1$P). Dependence of the 584Å counting rate on the magnetic field for both directions of field (+ and -).

The fractional intensity of a Doppler broadened line at a wavelength shifted by $\Delta\lambda$ from the central wavelength is given for the case of the $2\mu$ helium line by

$$\frac{I}{I_o} = e^{-5.1 \times 10^4 (\Delta\lambda)^2/T} \quad ,$$

where $\Delta\lambda$ is in Å and T is the absolute temperature. If it is assumed that the atom temperature in the lamp is 800° K, then the fractional intensity at two natural linewidths, $2\Delta\lambda_N$, from the central wavelength is

$$\frac{I}{I_o} = 0.71 \quad .$$

Hence, the incident $2\mu$ intensity would be down by 29% at two natural linewidths from the center, and deviations in the inverted Lorentzian at $H = \pm 2H_{\frac{1}{2}}$ would be expected. However, since the deviations at $|H| = 2H_{\frac{1}{2}}$ are so small, the width of the lamp line is apparently further increased by mechanisms such as pressure broadening or current broadening. This is consistent with the broadening of helium lamp profiles observed by Fred et al. (1951).

Both the electron gun and the Channeltron detector were shielded with mu-metal. The Helmholtz field was then found to have no observable effect on the Channeltron counting rates and produced less than a 1% effect on the magnetic field in the electron gun. The effect of the Helmholtz field on lamp intensity was also <1%.

Changing the lamp intensity by 50% had no perceptible effect on line width. Finally, the asymmetry in the line

shape, as given by the least squares parameter B, was typically 0.5%.

The result for $H_{\frac{1}{2}}$ is

$$H_{\frac{1}{2}} = (100 \pm 4)\ G \quad .$$

The uncertainty is more than twice the standard deviation obtained from the least squares fit. It includes the uncertainties due to field measurement, asymmetry effects, and the deviation in the wings of the Lorentzian.

If the atom density in the scattering region is high enough, it is possible for resonance radiation of polarization corresponding to a level crossing to be reabsorbed and give rise to the same pair of coherent states. This effectively increases the time of coherence and leads to a narrowing of the Lorentzian width. The effect has been investigated theoretically (Barrat 1959a,b,c) and experimentally (Anderson 1965; Lurio and Novick 1964). In the present experiment the effect would be observed if the density of ground state helium atoms in the scattering region was sufficiently high. No pressure dependence of $H_{\frac{1}{2}}$ is observed within experimental error over a range of pressures in the scattering region of $3 \times 10^{-6}$ to $2 \times 10^{-5}$ Torr.

The result for the mean lifetime calculated from Eq. (6) is

$$\tau(2^1P) = (5.69 \pm 0.23) \times 10^{-10} \text{ sec},$$

where it is assumed $g_J = 1.0$.

## V. DISCUSSION

The total transition rate for an electric dipole transition from a state n to a state n′ of lower energy is given by (Bethe and Salpeter 1957),

$$A_{n',n} = \frac{32\pi^3 e^2}{3h\lambda_{n',n}^3} |\vec{r}_{n',n}|^2 \quad , \tag{8}$$

where $\lambda_{n',n}$ and $|\vec{r}_{n',n}|$ are respectively the wavelength and dipole matrix element for the transition. This can be rewritten

$$A_{n',n} = \frac{8\pi^2 e^2}{mc} \frac{g_{n'}}{g_n} \frac{f_{n,n'}}{\lambda_{n',n}^2} \quad , \tag{9}$$

where $g_{n'}$ and $g_n$ are the statistical weights of the respective states and $f_{n,n'}$ is the absorption oscillator strength for the transition n′ to n. The reciprocal of the mean lifetime of the state n is given by

$$\frac{1}{\tau_n} = \sum_{E_{n'}<E_n} A_{n',n} \quad . \tag{10}$$

If $f_{2^1P,2^1S} \approx f_{2^1P,1^1S}$ (the theoretical values quoted by Schiff and Pekeris (1964) are 0.376 and 0.276 respectively), then it can be shown from Eq. (9) that

$$\frac{A_{2^1S,2^1P}}{A_{1^1S,2^1P}} \approx 10^{-3} \quad .$$

Therefore, the contribution to $\tau(2^1P)$ from the $2^1P$-$2^1S$ transition is negligible within the present experimental accuracy. Now using Eqs. (9) and (10), the absorption oscillator strength, $f_{2^1P,1^1S}$, can be related to $\tau(2^1P)$ by

$$f\tau = \frac{mc}{8\pi^2 e^2} \frac{g_{2^1P}}{g_{1^1S}} \lambda^2 = 1.53 \times 10^{-10} \text{ sec.} \qquad (11)$$

The resulting oscillator strength for the $1^1S$-$2^1P$ transition with the present value of $\tau(2^1P)$ is

$$f = 0.270 \pm 0.011 \quad .$$

This agrees well with the theoretical result obtained by Schiff and Pekeris (1964), f = 0.276. Fig. 8 shows the comparison of the present result with this theoretical result and with the following experimental results.

(1) Kuhn and Vaughan (1964) performed interferometric profile analyses of helium lines terminating in the $2^1P$ state. These lines were obtained from a gas discharge. They found $f = 0.37 \pm 0.03$. The discrepancy between this value and the theoretical result was resolved within the next two years (Vaughan 1966a,b) by considering resonance broadening effects. In fact, their data provide a beautiful demonstration of this effect.

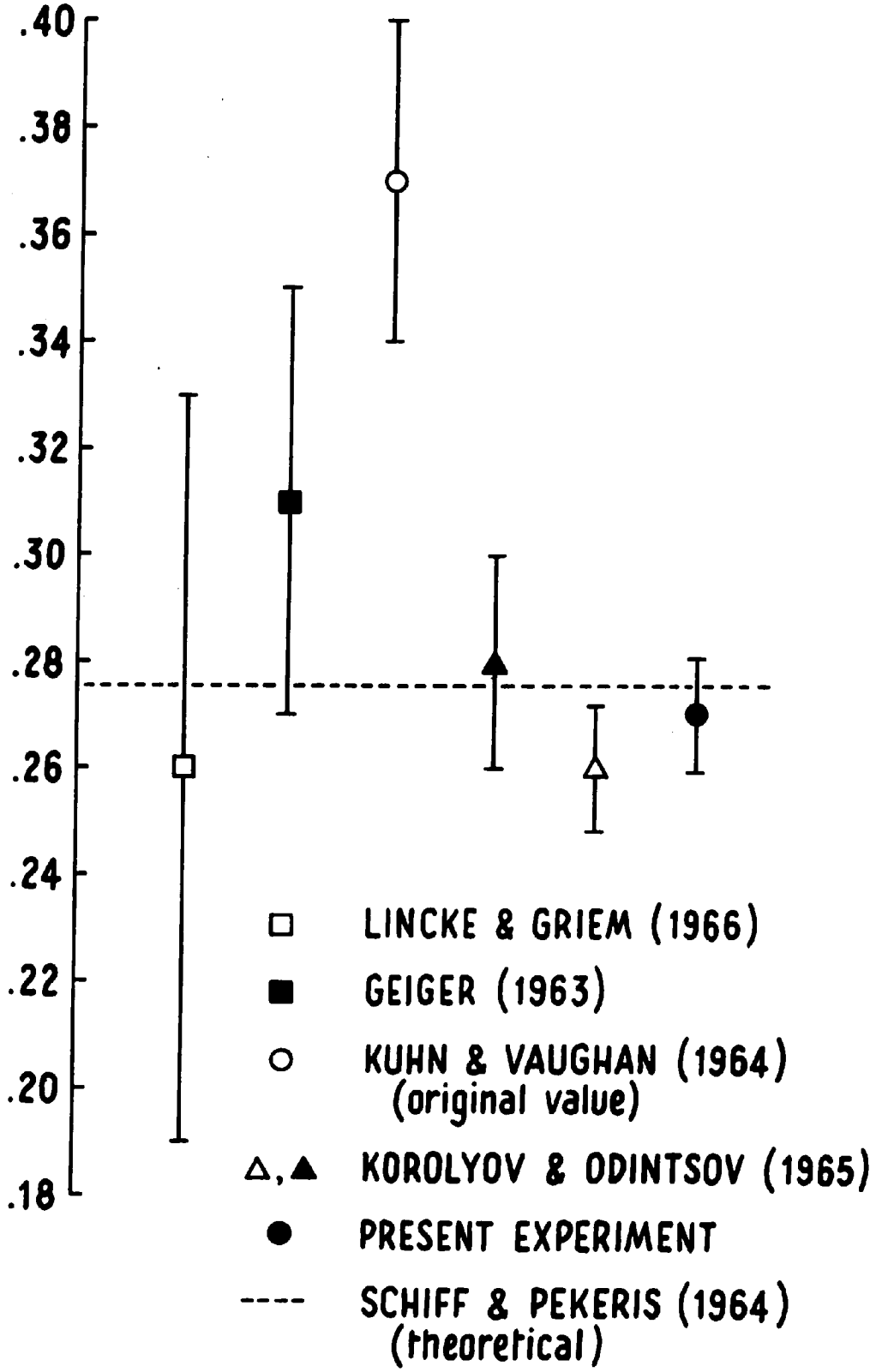



Fig. 8. Experimental f values for the $1^1S$- $2^1P$ transition in $^4He$.

By using the theoretical f value in the analysis of their data, they were able to obtain a value for the resonance broadening constant. This experimental value for the resonance broadening constant was in agreement with theory.

(2) Korolyov and Odintsov (1965) also performed interferometric profile analyses of helium lines terminating in the $2^1P$ state. These lines were obtained from a light source produced by electron bombardment of an atomic beam. They had considerable Doppler widths owing to the inelastic collisions with the exciting electrons. For the 6678Å ($3^1D$-$2^1P$) line where the conditions for determining the natural width were most favorable, they found $f = 0.26 \pm 0.012$. However, the results from other lines studied gave the average value, $f = 0.28 \pm 0.02$.

(3) Lincke and Griem (1966) studied the Stark broadened emission profile of the resonance line itself and found $f = 0.26 \pm 0.07$.

(4) Geiger (1963) measured the scattering cross section of 25 keV electrons from helium and obtained $f = 0.31 \pm 0.04$.

The present experiment yields a more precise f value for the $1^1S$-$2^1P$ transition in helium than was previously available. The result agrees with the theoretical f value for this transition. However, the result does not distinguish

between the theoretical f value and the best of the values obtained by Korolyov and Odintsov. For this purpose a 1% measurement is required. The present method is capable of such an accuracy if the deviations in the wings of the Lorentzian line can be completely understood.

This experiment also demonstrates a new technique which can be used to measure the lifetime of certain atomic states. The technique is particularly useful when the strong radiative transitions from these states are in the far ultraviolet. The inherent requirement is the presence of a metastable state lower in energy than the state whose lifetime is to be measured.

Finally, it has been shown that the inclusion of solid angle contributions in a level crossing experiment can reduce the ratio of field dependent to field independent signal from the optimum ratio.

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