

## $m_J$ Mixing in Oriented $4^2P_{1/2}$ Potassium Atoms, Induced by Collisions with Inert Gases\*

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(Received 2 June 1967)

A modified Zeeman scanning method was used to excite selectively the magnetic substates of the  $4^2P_{1/2}$  potassium atoms mixed with inert gases and placed in a strong magnetic field. The resulting potassium-inert-gas atomic collisions induced  $m_J$  mixing in potassium, which manifested itself by the depolarization of the potassium resonance fluorescence. The polarization measurements yielded the following disorientation cross sections: K-He: 46 Å<sup>2</sup>; K-Ne: 39 Å<sup>2</sup>; K-A: 52 Å<sup>2</sup>; K-Kr: 80 Å<sup>2</sup>; K-Xe: 107 Å<sup>2</sup>.

### 1. INTRODUCTION

RECENT investigations of collisional excitation transfer between the  $^2P_{1/2}$  and  $^2P_{3/2}$  resonance states in alkali atoms<sup>1</sup> have led to speculations about the possible existence of selection rules that might govern collisional transitions between Zeeman sublevels within a fine structure state and also between Zeeman sublevels of the two  $^2P$  states.<sup>2,3</sup> In order to probe further into these questions, a series of experiments was conceived in which, by exciting selected Zeeman sublevels of either the  $^2P_{1/2}$  or  $^2P_{3/2}$  resonance state in alkali atoms mixed with an inert gas and placed in a strong magnetic field (sufficient to produce complete Paschen-Back effect of the hyperfine structure), and monitoring fluorescence arising from both optically and collisionally populated Zeeman sublevels, it should be possible to determine the cross sections for transitions between the  $m_J$  states (disorientation cross sections) and to reach conclusions about the possible existence of selection rules. The present investigation deals specifically with collisional  $m_J$  mixing within the  $4^2P_{1/2}$  state of potassium.

### 2. THE PRINCIPLE OF MAGNETIC SCANNING

The optical excitation of the  $m_J$  sublevels proceeds as follows. A potassium spectral lamp is placed in a constant magnetic field of about 5 kG, and the emitted resonance radiation is made incident on potassium vapor at low pressure, contained in a fluorescence cell located in a parallel magnetic field which can be varied from one to 10 kG. Interference filters in the exciting beam transmit only the 7699 Å component of the resonance doublet. The light emitted parallel to the magnetic field surrounding the lamp may be separated into the  $\sigma^+$  and  $\sigma^-$  components by means of a circular polarizer which can also be used to change the polarization of the  $\sigma$  and  $\pi$  components in the light emitted perpendicularly to the field, from linear to circular. Thus optical excitation may proceed in two ways: by means of pure  $\sigma^+$  or  $\sigma^-$

components, according to the selection rules  $\Delta m_J = +1$  or  $-1$ , respectively, or by means of a circularly polarized mixture of  $\pi$  and  $\sigma$  light, with  $\Delta m_J = 0$  and  $\pm 1$ . In both cases the beam of exciting light is directed perpendicularly to the magnetic field surrounding the potassium vapor. As the latter field is increased, various coincidences arise between the Zeeman components in emission from the lamp and in absorption by the vapor in the cell, as is shown in Fig. 1, for the second mode of excitation. There are resonances not only between the corresponding  $\pi$  and  $\sigma$  components in emission and absorption which give rise to the central peak but, as long as the two magnetic fields are of the correct magnitudes, the  $\pi$  and  $\sigma$  components in fluorescence may also be excited by the  $\sigma$  and  $\pi$  components, respectively, emitted by the lamp. The results obtained using the first mode of excitation are illustrated in Fig. 2 which shows the fluorescence resulting from  $\sigma^-$  excitation. The presence of the  $\sigma^+$  component and of the small peak at about 2.5 kG, which corresponds to the first peak in Fig. 1, arises from a small  $\pi$  impurity in the exciting light. At very low potassium vapor pressures the polarization of the fluorescence is virtually complete.

If a small quantity of inert gas is admitted to the fluorescence cell, collisions between the excited potassium atoms in their  $m_J$  substates and the inert gas atoms will cause mixing between the Zeeman substates and a resulting depolarization of the resonance fluorescence. An experimental study of the depolarization, which manifests itself by an increase in the relative intensity of the  $\sigma^+$  component in Fig. 2, leads to the  $m_J$  mixing cross sections. The mixing may, in general, be induced by collisions with inert gas atoms, unexcited alkali atoms or molecules.

The technique of Zeeman scanning is not new and a comprehensive review of other experiments employing it has recently been given by Kessler.<sup>4</sup> Most of the investigators used the principle of Mrozowski's Zeeman filter<sup>5</sup> to produce a very narrow emission line which was then used to scan the hyperfine structure of the mercury resonance radiation.<sup>6,7</sup> The present investigation con-

\* Supported by the National Research Council of Canada and by the U. S. Air Force Office of Scientific Research under Grant No. AFOSR 361-67.

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<sup>1</sup> L. Krause, *Appl. Opt.* **5**, 1375 (1966).

<sup>2</sup> F. A. Franz and J. R. Franz, *Phys. Rev.* **148**, 82 (1966).

<sup>3</sup> W. Gough, *Proc. Phys. Soc. (London)* **90**, 287 (1967).

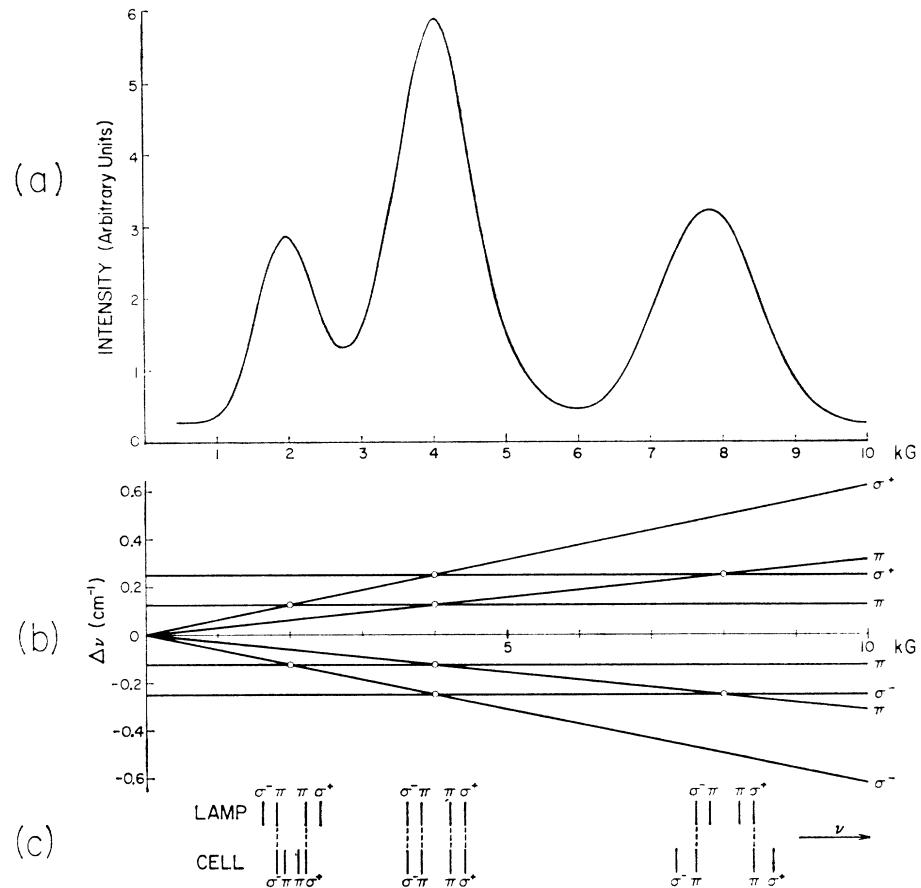
<sup>4</sup> K. G. Kessler, *Physica* **33**, 29 (1967).

<sup>5</sup> S. Mrozowski, *Bull. Acad. Polon. Sci.* **A9-10**, 464 (1930).

<sup>6</sup> O. Buhl, *Z. Physik* **109**, 180 (1938); **110**, 395 (1938).

<sup>7</sup> F. Bitter, S. Davis, B. Richter, and J. Young, *Phys. Rev.* **96**, 1531 (1954).

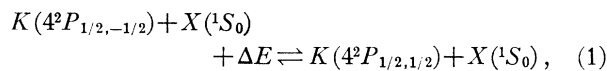
FIG. 1. The selective excitation of resonance fluorescence in the Zeeman components of the  $4^2P_{1/2}$  level in potassium. (a) The experimental intensity profile of the  $\sigma$  component (the  $\pi$  component appears identical). (b) The Zeeman splitting of the 7699 Å line in the lamp (constant at 4 kG) and in the cell (variable). (c) Resonances between Zeeman components in the lamp and fluorescence cell.



stitutes the first application<sup>8</sup> in which both the light source and the absorbing atomic vapor are placed in magnetic fields. The optically excited sublevels may be pinpointed by using light of both correct frequency and polarization and, together with analysis of the fluorescent light, the method provides a useful experimental tool for the investigation of collisional and relaxation processes.

### 3. THEORETICAL

The vapor-gas mixture may be assumed to exist in a steady state which involves continuous optical excitation with the  $\sigma^+$  and  $\sigma^-$  components of the 7699 Å resonance radiation, spontaneous decay, and inelastic collisions. The collisions induce transitions between the Zeeman sublevels, which proceed as follows:



where  $K(4^2P_{1/2,-1/2})$  is a potassium atom in its  $4^2P_{1/2}$  resonance state and  $m_J = -\frac{1}{2}$  substate,  $X(^1S_0)$  is an inert gas atom in its ground state, and  $\Delta E$  is the energy

<sup>8</sup> Some preliminary results dealing with the disorientation of  $4^2P_{3/2}$  potassium atoms by collisions with He, appear in the Proceedings of the XX Colloque Ampere (North Holland Publishing Company, to be published).

defect between the  $m_J = -\frac{1}{2}$  and  $m_J = +\frac{1}{2}$  substates, whose magnitude depends on the magnetic field strength, but is much smaller than  $kT$ .

The processes contributing to the steady state, which are depicted in Fig. 3, are represented by the following rate equations.

$$\begin{aligned} dn_{-1/2}/dt = & -(1/\tau)n_{-1/2} - Z_{-1/2,1/2}n_{-1/2} + Z_{1/2,-1/2}n_{1/2} \\ & - Z_{12}n_{-1/2} + \frac{1}{2}Z_{21}N_2 + S_{-1/2} = 0, \quad (2) \end{aligned}$$

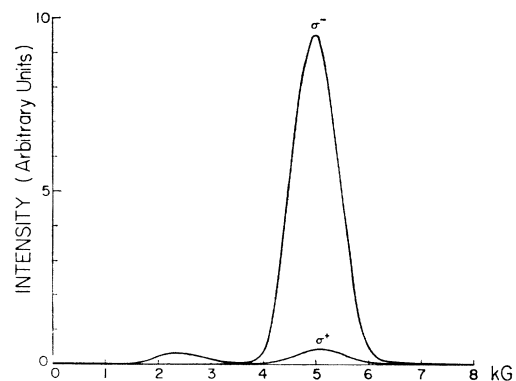


FIG. 2. Fluorescence from the  $4^2P_{1/2}$  level in pure K vapor excited with  $\sigma^-$  light. The peak at 2.5 kG and the  $\sigma^+$  component arise from a  $\pi$  impurity in the exciting radiation.

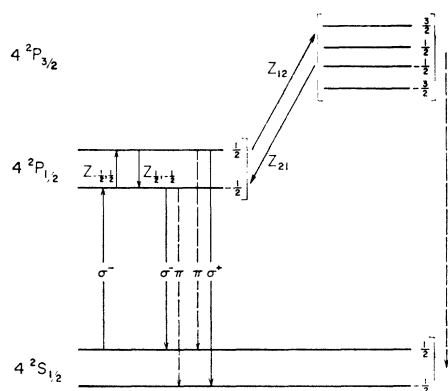


FIG. 3. Transitions between the Zeeman levels of the ground and resonance states. Broken lines indicate emissions not observed in the experiment.

$$\frac{dn_{1/2}}{dt} = -(1/\tau)n_{1/2} - Z_{1/2,-1/2}n_{1/2} + Z_{-1/2,1/2}n_{-1/2} - Z_{12}n_{1/2} + \frac{1}{2}Z_{21}N_2 + S_{1/2} = 0, \quad (3)$$

$$\frac{dN_2}{dt} = -(1/\tau)N_2 + Z_{12}(n_{-1/2} + n_{1/2}) - Z_{21}N_2 = 0, \quad (4)$$

where  $\tau = 2.7 \times 10^{-8}$  sec is the average lifetime of the  $4^2P_{1/2}$  and  $4^2P_{3/2}$  states,<sup>9</sup>  $N_1$  and  $N_2$  are the densities of atoms in these states, and  $Z_{12}$  and  $Z_{21}$  are the previously determined<sup>10</sup> collision numbers (numbers of collisions

per excited atom per second) corresponding to the  $^2P_{1/2} \rightarrow ^2P_{3/2}$  and  $^2P_{1/2} \leftarrow ^2P_{3/2}$  transitions, respectively;  $n_{-1/2}$  and  $n_{1/2}$  are the densities of atoms in the  $m_J = -\frac{1}{2}$  and  $m_J = \frac{1}{2}$  substates and  $Z_{-1/2,1/2}$  and  $Z_{1/2,-1/2}$  are the collision numbers corresponding to the  $-\frac{1}{2} \rightarrow +\frac{1}{2}$  and  $-\frac{1}{2} \leftarrow +\frac{1}{2}$  transitions, respectively, between the Zeeman substates of the  $4^2P_{1/2}$  state:  $S_{-1/2}$  and  $S_{1/2}$  are the densities of atoms excited optically per second to the  $m_J = -\frac{1}{2}$  and  $m_J = \frac{1}{2}$  states. It should be noted that the depolarization of the resonance radiation is caused not only by  $m_J$  mixing within the  $^2P_{1/2}$  state, but also by collisional transitions to the  $^2P_{3/2}$  state. Other effects such as stimulated emission or trapping of resonance radiation are assumed to be absent.<sup>10</sup>

The addition of Eqs. (2) and (3) yields

$$-(1/\tau)N_1 + Z_{21}N_2 - Z_{12}N_1 + S_{-1/2} + S_{1/2} = 0, \quad (5)$$

which, together with Eq. (4), represents the well-known process of sensitized fluorescence which is caused by collisional excitation transfer between the  $^2P_{1/2}$  and  $^2P_{3/2}$  resonance states.<sup>1</sup>

If the exciting radiation consists mainly of the  $\sigma^+$  or the  $\sigma^-$  component and thus one of the  $m_J$  sublevels is much more highly populated than the other, it is possible to obtain from Eqs. (2) and (3) the ratio of the atomic densities  $n_{1/2}$  and  $n_{-1/2}$ .

$$\frac{n_{1/2}}{n_{-1/2}} = \frac{(S_{1/2}/S_{-1/2})(1/\tau + Z_{-1/2,1/2} + Z_{12} - \frac{1}{2}Z_{21}\eta_2) + Z_{-1/2,1/2} + \frac{1}{2}Z_{21}\eta_2}{(S_{1/2}/S_{-1/2})(Z_{1/2,-1/2} + \frac{1}{2}Z_{21}\eta_2) + 1/\tau + Z_{1/2,-1/2} + Z_{12} - \frac{1}{2}Z_{21}\eta_2}, \quad (6)$$

where  $\eta_2 = N_2/N_1$ .

The degree of circular polarization is defined as follows in terms of the intensities  $I_{\sigma^-}$  and  $I_{\sigma^+}$  of the  $\sigma^-$  and  $\sigma^+$  components:

$$P = I_{\sigma^-} - I_{\sigma^+} / I_{\sigma^-} + I_{\sigma^+}. \quad (7)$$

In the absence of depolarizing collisions,  $P = P_0$ , where

$$P_0 = (S_{-1/2} - S_{1/2}) / (S_{-1/2} + S_{1/2}). \quad (8)$$

Since the transition probabilities for the  $\sigma^-$  and  $\sigma^+$  transitions are equal to one another,

$$I_{\sigma^-} = An_{-1/2}, \quad I_{\sigma^+} = An_{1/2}, \quad (9)$$

where  $A$  is the Einstein  $A$  coefficient. Substitution in Eq. (7) yields

$$P = \frac{1 - n_{1/2}/n_{-1/2}}{1 + n_{1/2}/n_{-1/2}}. \quad (10)$$

The substitution of Eq. (6) in Eq. (10) gives  $P$ , the degree of polarization of the fluorescence in a mixture of potassium vapor and an inert gas.

$$P = P_0(1 + \tau Z_{12} - \tau Z_{21}\eta_2) / (1 + \tau Z + \tau Z_{12}), \quad (11)$$

<sup>9</sup> G. Stephenson, Proc. Phys. Soc. (London) A64, 458 (1951).

<sup>10</sup> G. D. Chapman and L. Krause, Can. J. Phys. 44, 753 (1966).

where  $Z = Z_{-1/2,1/2} + Z_{1/2,-1/2}$ . In the absence of collisional transitions from  $^2P_{1/2}$  to  $^2P_{3/2}$  (at very low inert gas pressures), Eq. (11) reduces to the Stern-Volmer formula.<sup>11</sup> Equation (11) provides the connection between the experimental measurements of the degree of polarization,  $P$ , which may be obtained in relation to inert gas pressure, and the disorientation ( $m_J$  mixing) cross sections  $Q$  which are defined analogously with the gas-kinetic cross sections:

$$Z_{ab} = NQ_{ab}v_r, \quad (12)$$

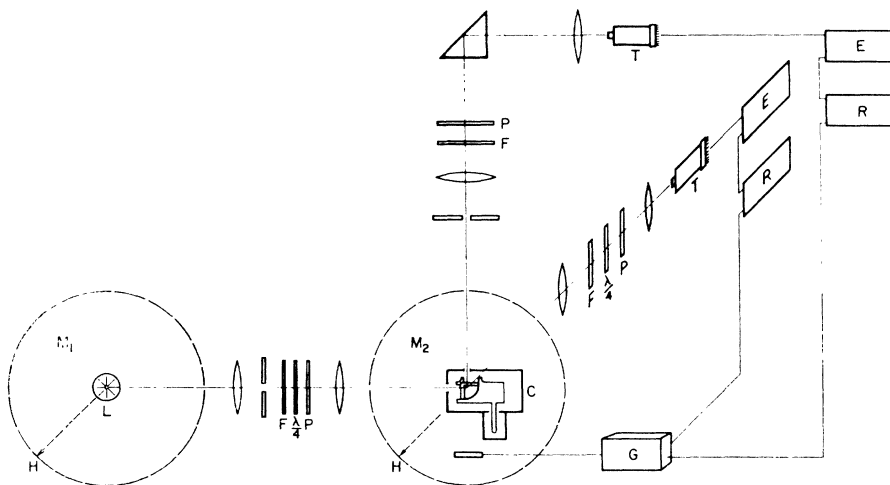
where  $N$  is the density of inert gas atoms and  $v_r$  is the average relative velocity of the colliding partners. In the present case  $Q_{-1/2,1/2} = Q_{1/2,-1/2}$  because the statistical weights of both  $m_J$  levels are equal to one another and  $\Delta E \ll kT$ .

#### 4. EXPERIMENTAL

The arrangement of the apparatus is shown in Fig. 4. Resonance radiation, consisting of Zeeman components, was emitted by the rf lamp placed in a steady magnetic field of 5 kG, and was brought to a focus inside the fluorescence tube which was mounted in a constant temperature oven and located in a magnetic field that

<sup>11</sup> D. Stern and M. Volmer, Physik. Z. 20, 183 (1919).

FIG. 4. Arrangement of the apparatus. L lamp;  $M_1$ ,  $M_2$  magnets; C fluorescence cell; G gaussmeter; T photomultipliers; E electrometers; R XY plotters; F interference filters; P polaroids.



could be varied continuously in the range 0–10 kG. The two magnetic fields were generated by 12 in. electromagnets and were oriented parallel (or antiparallel) to one another. Fluorescent light which could be observed along two directions perpendicular to the exciting light beam, was detected with liquid air-cooled I.T.T. FW 118 photomultiplier tubes whose outputs were amplified with Keithley Model 417 picoammeters and were applied to the Y axes of X-Y plotters, to whose X axes was connected the output of a Hall-effect magnetometer. Spectrolab interference filters which, when used in tandem, were capable of isolating the 7699 Å radiation with a spectral purity better than one part in  $10^6$ , as well as linear and circular polarizers, were placed as required in the exciting and fluorescent light beams to isolate the  $\sigma$  and  $\pi$  components. This arrangement permitted the observation of the  $\sigma^-$ ,  $\sigma^+$ , or  $\pi$  components of the fluorescence and the direct recording of the intensity profiles as functions of the magnetic field strengths.

The rf electrodeless discharge, especially developed for the present use, has been described elsewhere.<sup>12</sup> The discharge tube was mounted in the 4 in. gap of the electromagnet together with a totally reflecting prism. This arrangement provided either a light beam directed perpendicularly to the magnetic field and containing a mixture of  $\pi$  and  $\sigma$  radiation, or a beam emitted along the direction of the magnetic field consisting entirely of  $\sigma$  light, which could be separated into the  $\sigma^+$  and  $\sigma^-$  components by a circular analyzer. With a field of 5 kG the lamp emitted well-resolved Zeeman components of the 7699 Å resonance line, which, as expected, were of equal intensities.

The fluorescence cell is shown in Fig. 5. It consists of a cylindrical Pyrex tube in whose front-end three plane windows are set perpendicularly to each other, forming a rectangular corner. This arrangement permits the simultaneous observation of the fluorescence in two

directions perpendicular to the exciting light beam. The fluorescence was excited in the corner between the windows and, with all light paths in the vapor being kept very short, no trapping of resonance radiation took place. The tube, which was painted with "Aquadag" to eliminate scattered light, included a short sidearm which contained liquid potassium metal. The tube and sidearm were mounted in a small oven made of phenolite, which consisted of two compartments: one contained the fluorescence cell proper and the other, kept at a somewhat lower temperature, contained the side-arm whose temperature determined the potassium vapor pressure in the cell. The main part of the oven was heated using a noninductively wound heater rated at about 40 watt and the sidearm compartment by means of a copper coil in which oil was circulated from a Jena ultrathermostat. The temperature in the main oven was kept constant at 95°C for long periods of time by means of a proportional controller.<sup>13</sup> The sidearm temperature was held at about 80°C. The temperature as well as its uniformity throughout each compartment was monitored by means of several copper-constantan thermocouples attached to various parts of the fluorescence cell.

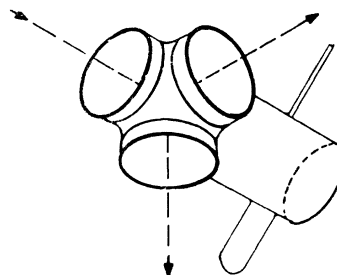


FIG. 5. Sketch of the fluorescence cell showing the location of the three mutually perpendicular windows, the sidearm, and capillary connection. The arrows indicate the directions of excitation and of observation.

<sup>12</sup> W. Berdowski, T. Shiner, and L. Krause, *Appl. Opt.* 6, 1683 (1967).

<sup>13</sup> G. D. Chapman, Ph.D. thesis, University of Windsor, 1966 (unpublished).

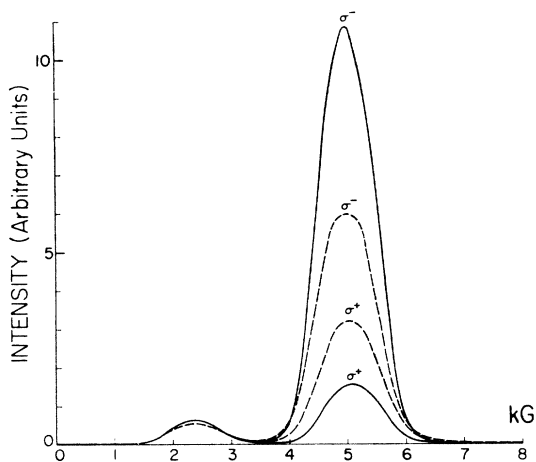


FIG. 6. Fluorescence from the  $4^2P_{1/2}$  level in potassium vapor mixed with argon, excited with  $\sigma^-$  light. The  $\sigma^+$  component arises from collisional  $m_J$  mixing. — 0.5 Torr; - - - 5.0 Torr.

The cell was connected by means of a 2 mm capillary tube to a vacuum and gas-filling system which was capable of providing an ultimate vacuum of  $6 \times 10^{-8}$  Torr in the cell and from which controlled quantities of inert gases could be admitted to the cell as required. Gas pressures were measured with a C.V.C. type GM-100A McLeod gauge. The cell, oven and vacuum system were mounted on a rolling stand which permitted the precise positioning of the tube and oven in a 4 in. gap of a 12 in. electromagnet. Its current-regulated power supply included a provision for linear sweeping of the magnetic field at a variety of speeds.

## 5. RESULTS AND DISCUSSION

The depolarization of the fluorescence was studied by making  $\sigma^-$  light emitted from the lamp in a direction antiparallel to the magnetic field, incident on the vapor-gas mixture placed in a field perpendicular to the direction of the exciting beam. The intensities of both the  $\sigma^-$  and  $\sigma^+$  components of the fluorescence were monitored in directions parallel and antiparallel to the magnetic field and were recorded during several scans of the field surrounding the fluorescence cell. All the inert gases were used at pressures ranging from 0 to 10 Torr and typical profiles resulting from such scans are shown in Fig. 6. The  $\sigma^-$  and  $\sigma^+$  fluorescent components were obtained by reversing the direction of the variable magnetic field. The reversal of the steady magnetic field surrounding the lamp, which led to excitation of the fluorescence by means of the  $\sigma^+$  rather than  $\sigma^-$  component, introduced no change in the experimental results. It was important to orient properly the polaroid which was combined with the quarter-wave plate in the exciting beam in order to select the linearly polarized component with its  $\mathbf{E}$  vector perpendicular (and not parallel) to the field surrounding the fluorescence cell.

The relative intensities of the  $\sigma^-$  and  $\sigma^+$  fluorescent components were substituted in Eq. (7) which yielded

values for the degrees of polarization,  $P$ , that are plotted in Fig. 7 against the inert gas pressures. It may be seen that, in the absence of inert gas, the polarization  $P_0$  is nearly but not exactly equal to unity. The actual magnitude of  $P_0$  which depends on the purity of the Zeeman components emitted by the lamp<sup>12</sup> and on the efficiency of the circular analyzers, might be regarded as a measure of the success with which both exciting and fluorescent light has been filtered with respect to wavelength separation and to polarization. The values of  $P_0$  corresponding to the two sets of depolarization curves are not exactly equal to one another because different lamps were used in the two sets of measurements. It was found that the departure of  $P_0$  from the theoretically predicted value of unity, was due almost entirely to stray scattered light in the lamp. The circular polarizers which worked quite efficiently contributed very little to this effect. Collisions with cell walls also appeared to have no significant influence on the atomic orientation.<sup>12</sup>

The values of  $P$  corresponding to the experimental points were substituted in Eq. (11) to obtain the collision numbers  $Z_{-1/2,1/2}$  or  $Z_{1/2,-1/2}$  which are plotted in Fig. 8 against inert gas pressures. According to Eq. (12), the slopes of the resulting straight lines are proportional to the cross sections  $Q_{-1/2,1/2}$  or  $Q_{1/2,-1/2}$ . The cross sections were actually obtained by the substitution of the experimental data for each point in Eq. (12) and by taking the arithmetic average of the resulting cross sections for the particular inert gas, all of which agreed within  $\pm 5\%$ . It should be noted that Eq. (11) makes provision for collisional transfer from  $4^2P_{1/2}$  to  $4^2P_{3/2}$ , for which experimental cross sections are available.<sup>10,13</sup> If it is assumed that this process is negligible and that

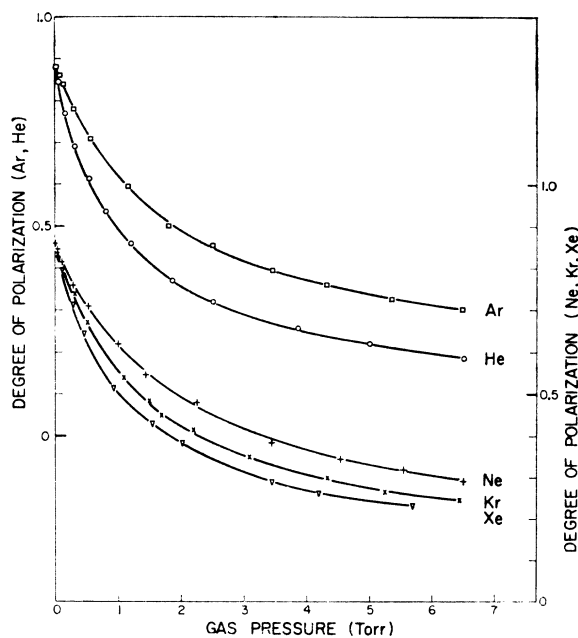


FIG. 7. The degrees of polarization of the 7699 Å resonance fluorescence, plotted as functions of inert gas pressures.

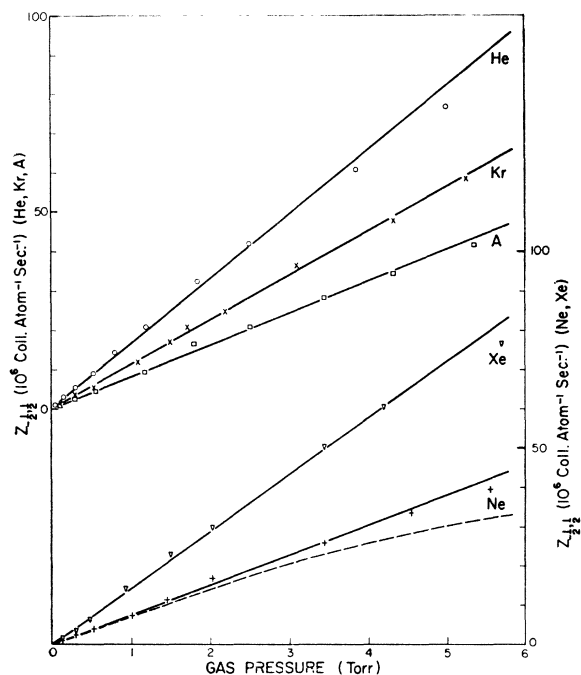


FIG. 8. Plots of collision numbers against the pressures of the inert gases. The broken curve results from a treatment which neglects  $^2P_{1/2}$ - $^2P_{3/2}$  mixing.

depolarization is produced exclusively by mixing within the  $4^2P_{1/2}$  state, Eq. (11) reduces to the Stern-Volmer form<sup>11</sup> and gives rise to the broken curve which is obviously less correct as it does not yield a constant value for the disorientation cross section.

The resulting total cross sections are summarized in Table I. Although the values are estimated to be correct

TABLE I. Collision cross section for  $(m_J = -\frac{1}{2})-(m_J = +\frac{1}{2})$  mixing in the  $4^2P_{1/2}$  state of potassium.

Collision partners	$Q_{-1/2, 1/2}$ or $Q_{1/2, -1/2}$ ( $\text{\AA}^2$ )
K-He	46
K-Ne	39
K-Ar	52
K-Kr	80
K-Xe	107

within  $\pm 5\%$ , this error is largely statistical in origin, and we believe the systematic error not to be as large. The values are of the same order of magnitude as recently determined alignment depolarization cross sections for the lowest  $^3P_1$  level of cadmium<sup>14</sup> and the  $^2P_{1/2}$  levels of rubidium and cesium<sup>15</sup> perturbed by inert gases. A comparison between the individual cross sections might also be of interest. Figure 9 shows a plot of the cross sections against the atomic numbers of the inert gases, which serve as a convenient index. The figure also contains a similar plot of the elastic scattering cross sections for collisions between electrons and the inert gas atoms.<sup>16</sup> The disorientation cross sections are larger by one order of magnitude, but the sequence of the cross sections appears to be the same in both cases. A similar effect has been observed in the cases of  $^2P_{1/2}$ - $^2P_{3/2}$  mixing collisions between potassium, rubidium, or cesium and inert gas atoms.<sup>1</sup> The cadmium results<sup>14</sup> show similar properties with a larger than expected He-Cd cross section, though the dip from He to Ne is not resolved. It has been suggested that the collisional interactions leading to  $^2P_{1/2} \leftrightarrow ^2P_{3/2}$  excitation transfer, take place between the inert gas atoms and the  $^2P$  alkali electron behaving as a quasifree particle with a possibility of

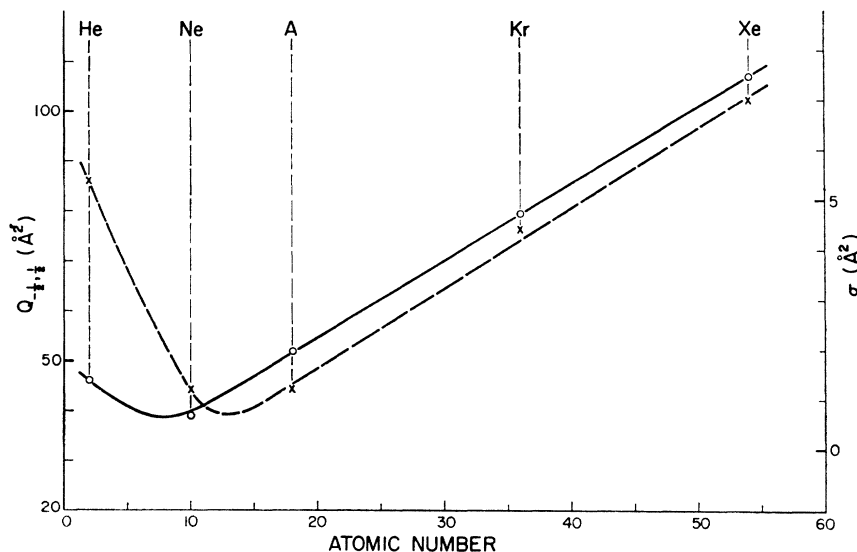


FIG. 9. A comparison of the disorientation cross sections  $Q_{-1/2, 1/2}$  for potassium-inert gas collisions with the elastic electron scattering cross sections  $\sigma$  ( $\circ$ ,  $Q_{-1/2, 1/2}$ ;  $\times$ ,  $\sigma$ ). No physical dependence of the cross sections on the atomic number is implied.

<sup>14</sup> R. L. Barger, Phys. Rev. **154**, 94 (1967).

<sup>15</sup> A. Gallagher, Phys. Rev. **157**, 68 (1967).

<sup>16</sup> H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford University Press, London, 1952).

overlap forces coming into play in the case of helium, because of its small size.<sup>1</sup> It is hoped that these results may provide some stimulus for further theoretical investigation of the mechanism involved in the collisional interactions.

## 6. CONCLUSION

The modified Zeeman scanning technique has been used to excite selectively the Zeeman sublevels of the  $4^2P_{1/2}$  level in potassium. The resulting  $m_J$  mixing cross sections for collisions with inert gas atoms do not lead, by themselves, to  $\Delta m_J$  selection rules which are now being investigated in an  $m_J$  mixing experiment involving the Zeeman sublevels of the  $4^2P_{3/2}$  level.

## APPENDIX: THE WIDTHS OF THE SPECTRAL LINES

The collisional broadening of the spectral lines at inert gas pressures ranging from 0 to 5 Torr is very

slight, as may be seen from a comparison of the profiles in Fig. 2, obtained with pure potassium vapor, with those in Fig. 6, obtained at two different inert gas pressures.

The profiles shown in Figs. 2 and 6 do not represent the shapes of the lines emitted in fluorescence, as they result from superpositions of both exciting and fluorescent lines. If, however, fluorescence is excited with lines of constant shape, it is possible to obtain from the profile of the fluorescent spectrum, the relative half widths of the  $\sigma$  and  $\pi$  fluorescent components. Such a mode of excitation, which is depicted in Fig. 10, was brought about as follows. The polarization of the exciting light (7699 Å) emitted by the lamp in the direction parallel to the magnetic field, was changed by a quarter wave plate from circular to linear, to make the planes of polarization of the  $\sigma^-$  and  $\sigma^+$  components mutually perpendicular. A magnetic field scan of the fluorescing pure potassium vapor produced two intensity peaks, of which the first at 4 kG corresponds to a resonance between the  $\sigma^-$  component in the exciting

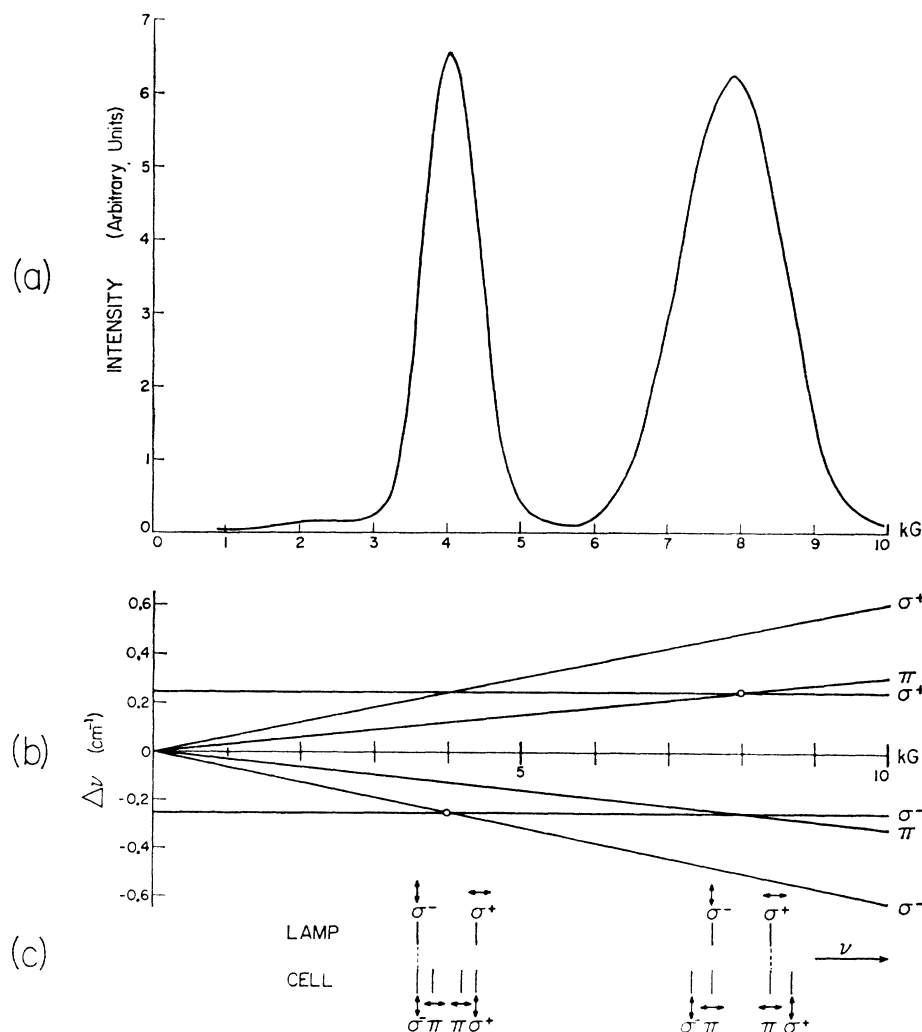


FIG. 10. The selective excitation of resonance fluorescence in the Zeeman components of the  $4^2P_{1/2}$  level in potassium, by means of  $\sigma^-$  and  $\sigma^+$  components linearly polarized in mutually perpendicular planes. (a) The experimental intensity profile of the  $\sigma$  and  $\pi$  fluorescent components. (b) The Zeeman splitting of the 7699 Å line in the lamp (constant at 4 kG) and in the cell (variable), showing points of resonance. (c) Resonances between Zeeman components in the lamp and fluorescence cell. The arrows over the symbols  $\sigma$  and  $\pi$  give the directions of the E vector. Resonance occurs when the appropriate frequencies are equal and planes of polarization parallel.

light and the  $\sigma^-$  component in absorption. The second peak at 8 kG arises from the resonance between the  $\sigma^+$  component in the exciting light and the  $\pi$  component in absorption. The shapes of the  $\sigma^-$  and  $\sigma^+$  components in the exciting light are identical and thus the observed differences in the profiles of the peaks in Fig. 10(a) should arise from the differences in the rates of increase in  $\Delta\gamma$  with magnetic field for the  $\sigma$  and  $\pi$  components, as shown in Fig. 10(b). These rates are in the ratio  $\frac{4}{3}:\frac{2}{3}$  and, consequently, the half-width of the second peak is

twice that of the first peak. This relation has been shown experimentally not to depend on the magnitude of the magnetic field.

#### ACKNOWLEDGMENT

The authors express their appreciation to Master Glassblower Wolfgang Eberhart who constructed the fluorescence cell and thus contributed significantly to the success of the investigation.

### S-Wave Cross Section for $D(p, \gamma)He^3$

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(Received 10 August 1967)

Nonadiabatic theory has been applied to calculate an accurate wave function for the  $p\mu d$  muonic molecule. The value of the wave function describing the nuclear motion evaluated at an internuclear distance equal to zero yields a cross section for the  $D(p, \gamma)He^3$  reaction in agreement with the experimental value.

#### I. INTRODUCTION

FROM the total fusion rate of a proton and deuteron bound in an  $S$  state by a muon, one can get,<sup>1,2</sup> under certain assumptions, the radiative fusion rate  $\lambda_r$ , which can be expressed as

$$\frac{1}{3}\lambda_r = R|G(0)|^2, \quad (1)$$

where  $R$  denotes the reaction constant, the  $\frac{1}{3}$  factor is the probability that the  $p d$  system is in the doublet state, and  $G(0)$  is the value of the wave function describing the nuclear motion in the muonic molecule  $p\mu d$ , evaluated with the internuclear distance equal to zero. On the other hand, the low-energy  $S$ -wave cross section for the  $D(p, \gamma)He^3$  reaction is<sup>1</sup>

$$\sigma_s = 2\pi\eta[\exp(2\pi\eta) - 1]^{-1}R/v, \quad (2)$$

where  $v$  denotes the velocity of the nuclei at infinity, and  $\eta = e^2/hv$ . Assuming the same rate constant  $R$  in (1) and (2), one can eliminate it from the above equations thus getting a relationship between  $\lambda_r$ ,  $\sigma_s$ , and  $G(0)$ . Usually the experimental value of  $\lambda_r$  and the theoretical value of  $G(0)$  are used to evaluate  $\sigma_s$ , and

the result is compared with the experimental cross section. However, previous theoretical values of  $G(0)$  yielded the cross section  $\sigma_s$ , differing from the experimental value by a factor of 10 or more.<sup>3</sup> Recently, Carter<sup>2</sup> reported for  $\sigma_s$  a more accurate value which, however, was still about 2.5 times smaller than the experimental one. To clarify this matter, extensive computations on the  $p\mu d$  system have been carried out. The method of computation is briefly sketched in Sec. II, and the results are presented and discussed in Sec. III.

#### II. METHOD

The  $p\mu d$  system is similar to the  $HD^+$  molecular ion, the only difference being in the mass of the light particle. However, since the muon is almost 207 times heavier than the electron, the adiabatic approximation, successful in molecular calculations, breaks down, and the muonic molecule must be treated as a three-particle system. Previous nonadiabatic calculations<sup>4-9</sup> for muonic molecules have usually been limited to symmetric systems, as, e.g.,  $p\mu p$  or  $d\mu d$ . For  $p\mu d$ , however,

\* The research reported in this publication was supported by the Advanced Research Projects Agency through the U. S. Army Research Office (Durham) under Contract No. DA-31-124-ARO-D-447, ARPA Order 368, and by a grant from the National Science Foundation, GP-6445.

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