II. Atomic Beam Spectra

Application of Atomic Beams in Spectroscopy

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I. INTRODUCTION

THE solution of many problems in modern spectroscopy concerning fine structure, hyperfine structure (h.f.s.), Zeeman effect of h.f.s., and Stark effect depends upon the possibility of resolving very close line structures. For successful resolution we need on the one hand spectroscopes of sufficiently high resolving power, and on the other hand emission and absorption sources which produce lines of such a small half-width that the single components of a line group do not overlap.

By the application of a Fabry-Perot interferometer it is not difficult to obtain a resolving power of several millions if only a sufficiently high reflectivity of the metal films of the interferometer plates and sufficiently large plate separations are applied. It is possible to obtain an apparatus width which is comparable with the natural width of a line. The disadvantage of decreasing spectral range with increasing plate separations can be avoided by using Houston's compound interferometer, consisting of two Fabry-Perot interferometers of different thicknesses in series, whereby the plate separation of the thicker interferometer is a small multiple of the thinner one. In this case, the resolving power of the combined instruments is practically that of the thicker instrument whereas the spectral range is that of the thinner etalon.

Thus, the only problem is the production of a proper light source. In the usual light sources the main reason for the broadening of the spectral lines is the Doppler broadening due to the random motion of the emitting atoms or molecules. The Doppler half-width of a spectral line is given by

$$\Delta\nu = 2(2R \ln 2)^{\frac{1}{2}} \nu c^{-1} (T/M)^{\frac{1}{2}} \text{ cm}^{-1}$$

(R, the universal gas constant, c, light speed; T, absolute temperature; M, molecular weight). For sodium at 300°K, e.g., the half-width will be $\Delta\nu = 4.3 \times 10^{-2}$ cm^{-1}. In order to obtain a half-width ten times smaller, which is necessary in order to resolve the h.f.s. of the $3\,^2P_{1/2}$ term of Na, we would have to use a light source operating at less than 5°K. Even a Schueler lamp cooled with liquid hydrogen could not produce such sharp lines.

By means of an atomic beam, however, it is possible to reduce the width of spectral lines without the application of low temperatures. An atomic beam, as investigated and described first by L. Dunoyer,[1] consists of a stream of atoms moving in about the same direction. The density of the stream is supposed to be so small that, at least for a short part of the beam, there are no collisions between the atoms.

The principle of producing an atomic beam of a metal vapor is briefly the following. The metal is melted in an oven tightly closed by a cover which has a small opening, the "oven aperture" consisting of a round hole or a slit. If the vapor pressure in the oven is not too high, the atoms will effuse from the oven aperture in straight paths forming a diverging bundle of atomic rays. By attaching a so-called collimator chamber to the outfit, it is possible to select a narrow beam out of the diverging rays. In the case of metal vapors which can easily be condensed at cooled walls, the collimator chamber consists of a metal vessel, the cover plate of which is situated opposite to the oven aperture and is provided with an aperture called the collimator or image aperture. Only atoms having the direction towards the image aperture will emerge from the collimator and form a beam of atoms. The direction of the motion will differ only by small angles from that of the central connecting line oven aperture—image aperture, the axis of the beam.

If the atoms are excited (by radiation or electron impact) and if the emission is observed by means of a spectroscope, the collimator axis of which is perpendicular to the axis of the beam, the Doppler width will be decreased since the

components of the velocities of the emitting atoms in the direction of the line of view will be decreased. The amount of the increase of sharpness depends upon the special set-up. An approximate estimation can be obtained by the following consideration.

Let o and i be the linear dimensions of the oven and image aperture determined by the intersection of the aperture profiles with a plane containing the axis of the beam and the mean line of view (axis of the spectroscope collimator). Then the largest deviation of the atom paths from the axis of the beam is given by the angle $\alpha=(o+i)/2h$, where h is the distance between the apertures. The reciprocal of α is sometimes called the "collimation of the beam," C. The component of the atom velocity v in a direction perpendicular to the axis of the beam will have the maximal value $v \sin \alpha$ or approximately v/C and can easily be made ten to thirty times smaller than v.

In several investigations circular apertures were applied; in this case o and i are the diameters of the apertures. In many other investigations the apertures were formed by slits which were oriented parallel to each other, their widths being small compared with their lengths s. If the line of view is parallel to the extension of the slits, the collimation angle α is determined by $\alpha=(s_o+s_i)/2h$, where s_o and s_i are the lengths of oven and image slit, respectively. For the special case $s_o=s_i=s$ we get $\alpha=1/C=s/h$.

From these rough considerations we can only conclude that the Doppler width Δ_B observed with the beam will be about Δ_o/C, where Δ_o is the line width which would be observed with the gas in the oven.

Introducing the "effective temperature" T_e of the beam we can describe the reduction of the line width in another way. T_e may be defined as the temperature of a source which would produce lines of the same width as the atomic beam. As the velocities are proportional to $\sqrt{T}$ we have the relation $T_e=T_o/C^2$, where T_o is the oven temperature and C the collimation. The same reasoning can obviously be applied to the case of an absorbing beam.

These considerations concerning the width of the lines in an atomic beam are only rough and give extremal values. The correct treatment of the problem is given by Minkowski and Bruck[2] who calculated the intensity distribution observed with an atomic beam in a general way. Their results are important for investigations concerning intensity distribution of spectral lines derived from atomic beam experiments. Since we shall not deal with those questions in the following, we shall not go into details. It may only be mentioned that the form of the intensity distribution in the beam is different from the distribution in the oven, and that the distribution changes with the size and form of oven and image aperture and their distance.

An approximate expression for the sharpening effect of the beam emission in comparison with the oven emission was derived for the case $h/s>1$, where s is the length of image and oven slit and h their distance apart. The ratio of the half-width in the beam Δ_B to that of the vapor in the oven Δ_o is approximately given by

$$\Delta_B/\Delta_o=0.41s/h;$$

that means that the width in the beam is about 2.5 times smaller than the rough estimation given.

In these considerations the influence of the aperture of the spectrograph collimator has been neglected. Usually the corresponding correction is small, as relative apertures of $f:20$ are applied.

Although it was foreseen by Dunoyer that atomic beams could be very useful for spectrographic work, only a few attempts were made in this direction. Dunoyer himself showed that the excitation of a Na beam by resonance is possible. Bogros[3] investigated the fine structure of the Li resonance line 6708A in this way, and furthermore Dobrezov and Terenin[4] made a qualitative investigation of the hyperfine structure of the Na resonance line by means of the resonance fluorescence of a sodium beam. The application of a mercury beam in absorption was used also by Schein[5] and later by Brazdziunas[6] but a systematic development of the method has been undertaken only since 1934. Jackson and Kuhn[7–13] used preferably the absorption method whereas the excitation of the beam by electron impact was developed by Minkowski and Bruck[14] and by Meissner and Luft[15] independently. Bogros and Esclangon[16,17] and R. A. Fisher[18] excited the beam by a high frequency discharge in the

presence of argon at low pressure which, however, prevents the development of an undisturbed atomic beam.

II. CONSTRUCTION OF ATOMIC BEAM APPARATUS

(1) Absorption Method

Different types of atomic beam arrangements for use in spectroscopy have been described. The simplest are the outfits for the investigation of

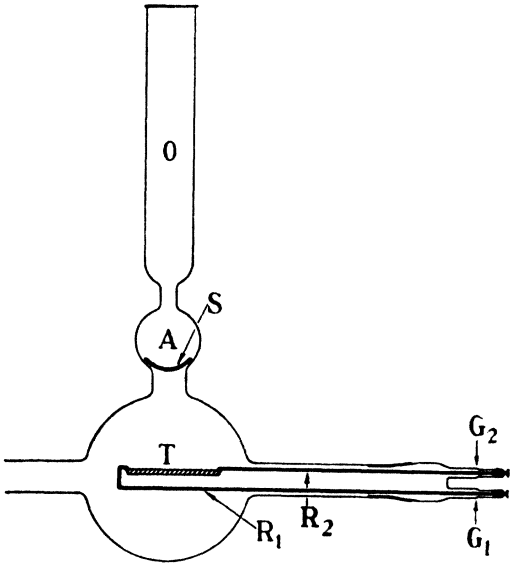

FIG. 1. Apparatus of Jackson and Kuhn for aluminum atomic beams.

easily condensing vapors of metals of low melting points. Jackson and Kuhn[7] describe such a simple apparatus in their first work about K and Na. It consisted of a glass tube of 35-cm length and 15-mm diameter, the upper part of which was attached to an observation chamber fitted with four windows at right angles. A side tube connected the apparatus to a mercury vapor pump. The lower part contained the carefully distilled metal, and was immersed to a depth of approximately 4 cm in an electrically heated bath of Wood's metal. A closely fitting sheet of asbestos prevented exaggerated heating of the upper part of the tube, where all the atoms not moving within the range of collimation were condensed. Oven and image aperture were formed by the tube itself, the collimation being about 24 : 1. For the investigation of the spectral lines light of a proper light source furnishing the background for the absorption lines had to pass through the observation chamber perpendicularly to the beam.

A similar arrangement made of fused silica was also used for the investigation of silver beams.[9] For metals with high melting points or for metals attacking glass or silica another form has to be employed. For the investigation of aluminum, Jackson and Kuhn[10] developed the apparatus shown in Fig. 1. A sphere of Pyrex glass of 10-cm diameter was provided with three side tubes. Through one of these was introduced a small tantalum container T which could be electrically heated. The container was made of tantalum sheet of 0.3-mm thickness, and was 5 cm long; the cross section was V-shaped, each side being 5 mm. The opening at the top was 4 mm wide. The image slit S, parallel to the length of the container, was at a distance of 7 cm. The slit was cut into a nickel plate which entirely separated the sphere from the observation chamber A. The collimation could be changed from 7 : 1 to 20 : 1. The container could hold four pieces of aluminum 15 mm long and 2 mm in diameter, enough in order to produce an atomic beam for 90 sec. with a heating current of 90 amperes. As one photograph took only 10 sec., the capacity of the container was sufficient. Through a side tube connected to A (perpendicular to the plane of drawing), the observations were made.

For general use, especially for metals of high melting points, the arrangements described in II (3) can also be used for absorption experiments. A very convenient outfit for absorption and fluorescence investigations has been described by Bogros in his thesis, "Propriétés physiques de la vapeur de Lithium."[3]

(2) Fluorescence Method

For the excitation of atomic beams by resonance-fluorescence the same arrangements as described in II (1) can be used provided that the observation chamber is furnished with a window through which the exciting radiation can be concentrated on the atomic beam.

In order to get sufficient resonance-fluorescence intensity it is necessary that the exciting light source produces sharp lines, as free as possible from reversal. For this purpose, a Schueler lamp

or an electrodeless high frequency discharge tube are the most convenient light sources.

(3) Electron Impact Method

The construction of atomic beam apparatus which allows the excitation of the beam by electron impact is much more complicated than that of the beam apparatus used in the absorption method.

The apparatus developed by Minkowski and Bruck[14] is shown in Fig. 2. The arrangement for producing the atomic beam was attached to the removable cover plate of a cylindrical brass vessel of 30-cm height and 18-cm diameter. The electrodes for the bombardment of the beam were introduced through ground joints attached to the wall of the vessel, which was also provided with two windows situated at 90° with respect to the ground joints mentioned above. These windows enabled one to observe the atomic beam perpendicular to the beam axis.

The tube R_1, fitted into a ground joint 1, carried the adjustable oven O which was surrounded by two concentric cylinders in order to diminish radiation losses. The upper part of the oven was provided with an adjustable oven slit of 1-cm length and a width of usually 0.2 mm. The ground joint *2* carried a German silver tube R_2 to which the circular disks P_1 and P_2 were attached, their distance being 5 cm. The lower disk was provided with image slits of 1-cm length and 0.2-cm width. By turning the disk, the different slits could be brought into position. During the exposure different slits had to be employed since by condensation of the vapor the slits grow together. In order to condense the vapor coming through the oven slit in inclined directions, the oven was surrounded by a copper cylinder R_4.

The direction of observation was parallel to oven and image slit. Perpendicular to the axis of the beam and to the direction of view the beam was bombarded by electrons which were produced by an oxide coated wire of zig zag shape and of 15-cm length covering an area of 1.3×1.3 cm^2. A molybdenum grid of area 1.6×1.6 cm^2 was attached in front of the filament. The total emission was 500 ma, the grid voltage 200 volts, the plate current exciting the beam was 200 ma. A mercury diffusion pump (20 liter/sec.) produced a vacuum better than 10^{-6} mm Hg.

The apparatus developed by Meissner and Luft was in principle of similar kind. The filament was a coated platinum sheet of effective area 20×20 mm^2, the grid consisted of six nickel tubes through which water circulated. Also the copper anode was water cooled. Filament and grid were arranged as concentric cylinders of about 2.0-cm radius, the grid being in a distance of about 2 mm from the filament. This arrangement secured a satisfactory focusing of the electrons. The grid potential was about 500 volts, the plate potential slightly higher. The

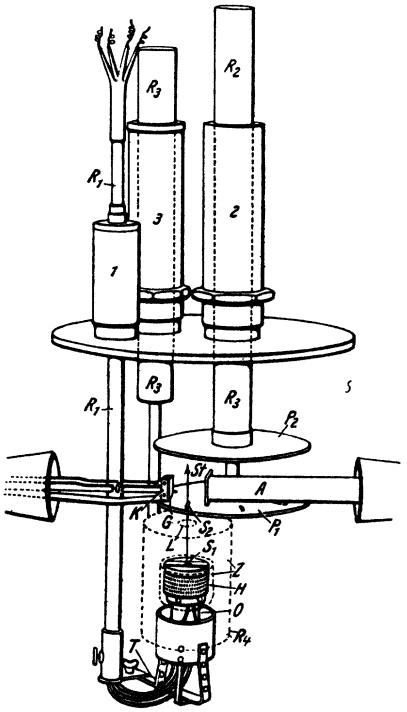

FIG. 2. Apparatus developed by Minkowski and Bruck for producing an atomic beam.

total emission current was at its maximum 600 ma, the excitation current about 300 ma. The top of the apparatus carried a German silver container which was cooled with liquid air

A newer construction developed by W. Paul[19] for beams of materials with high melting points is shown in Fig. 3. The oven O consisted of a molybdenum cylinder of 15-mm diameter and 50-mm height bearing tungsten wire of 0.4-mm diameter and 220-cm length for heating. For the

insulation Be and Al oxides were used. Fitted into this cylinder was a cylindrical molybdenum container, the cover of which carried the variable oven slit S_1 of 8-mm length and maximal width 2 mm. The capacity was 3.5 cm³. The oven was carried by Steatite tubes and an iron ring. The oven was surrounded by a nickel cylinder Z which diminished radiation losses. A doubly walled cylinder, cooled by circulating water, surrounded the oven part. The cover plate contained the image slit S_2, the length of which was 8 mm; the width could be changed between 1 and 6 mm. The ground plate was attached to a hard glass tube of 200-mm diameter, which was covered at the upper part by a plate carrying a container filled with liquid air where the atomic beam was condensed. Two side tubes carried the plate and the electron source for the excitation of the beam.

The cathode was a nickel disk of 2.5-cm diameter coated with earth alkali oxides. Indirect heating was applied. Immediately in front of the cathode there was a space charge grid G_1 of tungsten. By means of a second grid G_2 the proper speed of the electrons could be obtained. A cylinder L played the role of a focusing electron lens. The anode attached to the opposite side tube was water cooled.

The total emission current was 2.2 amp. By a proper choice of grid voltage, the grid current could be diminished to such an extent that the current available for excitation was 1.3 amp. This high exciting current, however, could be applied only for one to two hours. Therefore, usually only an exciting current of 0.5 amp. was used, the plate voltage being 500 volts. For smaller voltages, which would be advantageous since the maximum of the excitation function is usually smaller, such a high current could not be obtained.

III. APPLICATIONS OF THE ATOMIC BEAM METHOD

(1) Intensity Distribution in Lines

Minkowski and Bruck[14] applied the atomic beam method for the investigation of the red cadmium line 6438A. The spectral apparatus employed was a Fabry-Perot interferometer in connection with a prism spectrograph. The focal

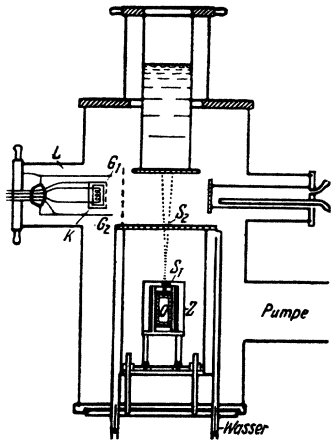

FIG. 3. Paul's apparatus for materials with high melting point.

length of the camera was 50 cm. The etalon spacer was 11 cm long; the resolving power, corresponding to a reflectivity of 81 percent, was 5×10^6.

The photometry of the interference patterns by means of a microphotometer and intensity marks, obtained by a rotating sector or a step wedge, furnished the intensity distribution.

It has been found that the intensity distribution is asymmetric, the slope towards lower frequencies being appreciably smaller. The half-width of the intensity curve was found to be 1.89×10^{-2} cm^{-1} when the beam was excited with slow electrons (grid-cathode 40 volts, anode-cathode 50 volts) and 1.94×10^{-2} cm^{-1} when excited with faster electrons (grid-cathode 180 volts, anode-cathode 445 volts). This half-width is essentially greater than the expected one which can be calculated from the apparatus half-width (4.55×10^{-3} cm^{-1}) and Doppler width (3.75×10^{-3} cm^{-1}) as 0.75×10^{-2} cm^{-1}.

The greater half-width of the line and the observed intensity asymmetry of the line can be explained by isotopic shifts. Cadmium consists of 78 percent of the even isotopes Cd 110, 112, 114, and 116 and of 22 percent of the odd isotopes 111 and 113. As the resolution of the pattern is impossible, one can make only rough estimations. Considering the total area of the intensity curve as composed of the areas of the separated isotopes, Minkowski and Bruck estimate that the shift of the even isotopes may be within the limits of 3.5×10^{-3} to 7×10^{-3} cm^{-1}.

The investigation was repeated by Meissner and Luft (unpublished) with a Fabry-Perot interferometer of 18-cm plate separation. The asymmetry of the intensity distribution could be confirmed and also the value of the half-width was found to be 1.9×10^{-2} cm^{-1}.

(2) Fine Structures

Although it seemed in the beginning of the experiments with excited beams that the small intensity would allow only the investigation of the strongest lines of a spectrum, it was finally possible to increase the exciting current to such an amount that weaker lines could be investigated. This is important since there are many cases in which even the multiplet fine structure could not be resolved with the usual light sources. Two examples may be given:

(a) *Fine Structure of the $^2D_{3/2,\,5/2}$ Terms of Sodium*

Applying somewhat longer slits and thereby admitting a somewhat greater width of the lines, Meissner and Luft[20] were able to excite several members of the subordinate series and to measure the absolute wave-lengths and splittings of the series lines.

The results were the following:

The ^2D terms 3^2D and 4^2D could be resolved, the ^2D splittings of the two following terms could be calculated from the distance of the strong components and the ^2P splitting. All resolved structures show inverted term order, the lower J value corresponding to the higher energy level. Exact absolute values of the $3^2P_{1/2,\,3/2}$ terms were obtained by calculation of the limits of the subordinate series.

(b) *Fine Structure of the 3^2D Term of* Mg I

A second case where the investigation of a multiplet by means of an atomic beam furnished a surprising result[21] is the first member of the first subordinate series of magnesium $\nu=3sp\ ^3P_{012}-3sd\ ^3D_{123}$ at 3832A, the D structures of which could not be resolved by means of the usual light sources, as the splitting is only a few thousandths A. The result of the analysis of the line was that the 3^3D term is a partially inverted term; the lowest being the $3D_2$, the highest the $3D_1$ term. Only the weakest line of the completed triplet $^3P_2-{}^3D_1$ could not be observed because its intensity is only about 1 percent of the strongest neighboring line. The partial inversion and the surprisingly small splittings have been explained by Pincherle.[22]

(3) Hyperfine Structure

The greatest progress has been made in the investigation of the hyperfine structure of lines for which the splitting was too small to be resolved in the spectra of the usual light sources. The absorption method as well as the emission method has been applied successfully.

(a) *Absorption Method*

The absorption method can be employed only for resonance lines. Jackson and Kuhn investigated in this way the h.f.s. of the resonance lines of the elements Li, K, Na, Mg, Ag, and Al. In their first paper[7] which contains also a description of the method, potassium and sodium were treated. Since the results obtained in this investigation have been improved in later investigations[11,12] it is not necessary to give details.

In a second paper[8] the isotopic shift in the resonance lines of Mg were investigated, a subject which will be treated by Mr. R. A. Fisher in the present issue. A third paper of Jackson and Kuhn[9] concerns the h.f.s. of the silver resonance lines at 3281A and 3383A. Each line was found to consist of four components; the position, intensity, and attribution to the isotopes Ag (107) and Ag (109) are given below.

	Ag (109)	Ag (107)	Ag (107)	Ag (109)
$5^2S_{1/2}-5^2P_{3/2}$, 3281A	0.000	−0.013	−0.052	−0.077 cm^{-1}
$5^2S_{1/2}-5^2P_{1/2}$, 3383A	0.000	−0.013	−0.058	−0.084 cm^{-1}

The most probable value for the nuclear spin I was found to be $\frac{1}{2}h/2\pi$, a value which was confirmed by the investigation of the Zeeman effect (III, 4). By means of Goudsmit's formula also the values for the nuclear magnetic moments could be derived, −0.10 n.m. for Ag (107) and −0.19 n.m. for Ag (109).

Furthermore we mention the paper about the h.f.s. of aluminum[10] in which the structure of the resonance lines $3^2P_{3/2,\,1/2}-4S_{1/2}$ at 3962A and 3944A and $3^2P_{3/2,\,1/2}-3^2D_{5/2,\,3/2}$ at 3092.7; 3092.8 and 3082A have been described. This paper contains extended measurements of the intensity ratios of the lines involved. The line $3^2P_{1/2}$

$-4^2S_{1/2}$ (3944A) has three components of nearly equal intensity, with relative positions

$$-0.048 \quad 0.000 \quad +0.048 \text{ cm}^{-1},$$

showing that the two levels involved are split into two levels of separation 0.048 cm^{-1}. The line $3^2P_{1/2}-3^2D_{3/2}$ shows two components of separation 0.0666 cm^{-1}, the intensity ratio of longer λ to shorter λ being 1.21 : 1. The observed splitting of this line is mainly due to the splitting of the $3^2P_{1/2}$ term and to a small unresolved structure of $3^2D_{3/2}$; thus the splitting is slightly larger than that observed in the line 3944A.

From the intensity measurements a spin of 9/2 for the Al^{27} nucleus was deduced by Jackson and Kuhn. This high value is not in accordance with the value of 5/2 obtained by Heyden and Ritschl[23] who applied the interval rule to the h.f.s. of Al II lines. In the meantime, Millman and Kusch[24] applied the molecular beam magnetic resonance method and confirmed the value 5/2. This example shows that even careful intensity measurements may furnish doubtful results.

(*b*) *Emission Method*

The emission method was used by Bogros and Esclangon[16, 17] for the investigation of Cd and Li and by R. A. Fisher[18] for Mg. These authors used the excitation by high frequency discharge in the presence of argon.

The excitation of a beam by electron impact was applied by Meissner and Luft for the investigation of the sodium[15] and potassium[23] resonance lines. In the work on sodium not only the h.f.s. splitting of the $^2S_{1/2}$ term, detected first by H. Schueler[25] could be measured very accurately but also the splitting of the $^2P_{1/2}$ term could be resolved. The splitting of the $^2S_{1/2}$ term was found to be 0.0594 ± 0.0003 cm^{-1}, that of the $^2P_{1/2}$ term 0.0058 ± 0.0003 cm^{-1}. The total splitting of the $^2P_{3/2}$ term could be calculated as 0.0053 cm^{-1}, but the resolution of the lines involved could not be performed. The values have been confirmed by Jackson and Kuhn.[12]

The value of the nuclear moment $i=\frac{3}{2}(h/2\pi)$, established by magnetic measurements of Rabi and by spectroscopic intensity measurements, allowed one to calculate the magnetic moment of the nucleus according to the formulae of Fermi and Segrè, and Goudsmit. The S splitting furnished the value 2.08 n.m., the P splitting, 1.96 n.m.

The development of "radiofrequency spectroscopy" furnishes the $^2S_{1/2}$ splitting with a much higher accuracy. The investigation of P. Kusch and S. Millman[26] gave for Na^{23} the value $\Delta\,^2S_{1/2}=0.059103$ cm^{-1}. On the other hand, the molecular beam magnetic method yields $g(i)$ factors immediately with high precision and gives with known i values the magnetic moment of the nucleus without other considerations. For Na^{23} $\mu=2.215$ n.m. was found.[27]

The second investigation of Meissner and Luft[28] dealt with the investigation of the resonance lines of K^{39}. This investigation was undertaken because the results of Jackson and Kuhn with the absorption method were not in accordance with the results of Rabi and his coworkers with respect to the sign of the magnetic nuclear moment. Jackson and Kuhn found from intensity observations (strong component towards shorter wave-lengths) that the fine levels show inverted term order and that, therefore, the magnetic moment of the nucleus is negative. The result obtained by Meissner and Luft was in accordance with Rabi's result. They found regular hyperfine term order. Later, Jackson and Kuhn also confirmed this result.[11] The splitting of the lines was found to be:

$$7699\text{A} \quad \Delta\nu_1=0.0163 \text{ cm}^{-1};$$
$$7665\text{A} \quad \Delta\nu_2=0.0141 \text{ cm}^{-1}.$$

The difference of both values shows that the splittings are due to the nuclear spin splittings of the ^2S and ^2P levels. With the value $\frac{3}{2}$ for the nuclear spin it is possible to calculate from the center of gravity of the observed patterns the splitting of the terms themselves. It was found $\Delta\,^2S_{1/2}=0.0152$ cm^{-1} and $\Delta\,^2P_{1/2}=0.0033$ cm^{-1}, corresponding to 0.40 n.m. and 0.30 n.m., respectively. (The value of $\Delta\,^2S_{1/2}$, known from radiofrequency spectroscopy, is 0.015403 cm^{-1}, whereas Jackson and Kuhn[11] found 0.0153 cm^{-1}.)

One of the newest investigations of h.f.s. with atomic excited beams is that of W. Paul[19] about the resonance line of Be II (3130A). All investigators of the Be spectrum could not find any trace of splitting or asymmetries since in all

these investigations the light source was a Schueler tube with liquid-air-cooled hollow cathode. Because of the Doppler effect we have, therefore, to deal with a half-width of approximately 0.1 cm^{-1} at 3130A. With the Be I line λ2349A, Mrozowski[29] obtained a width of 0.21 cm^{-1} at 3130A. The lines investigated by Mrozowski were unsplit and symmetric.

The line width obtained by Paul was very much smaller. Corresponding to an oven temperature of 1500°K and a collimation 7.5 : 1 the expected Doppler width should be 0.015 cm^{-1} to which the apparatus width 0.008 cm^{-1} has to be added so that the total width of 0.023 cm^{-1} is about seven times smaller than obtained by Mrozowski with the Schueler tube.

Despite this small width, Paul did not succeed in detecting a splitting of the lines. By applying an interferometer of 40-mm interval he could state only that the stronger fine structure line of the resonance doublet showed a distinct dissymmetry towards smaller ν. By estimating the width of the observed lines and comparing it with the calculated width of the beam it is possible to obtain the limits of splitting $\delta\nu$.

$$0.020 < \delta\nu < 0.040 \text{ cm}^{-1}.$$

According to Goudsmit[30] it is possible to calculate the $\delta\nu$ of the $^2S_{1/2}$ term. For $i=\frac{3}{2}$ it should be $\delta\nu = 0.050 g(i)$ where $g(i)$ is the Landé factor for the nucleus. The splittings of the ^2P terms are too small to be observed.

Each fine structure component will be split into two h.f.-components possessing an intensity ratio of 5 : 3. According to theoretical reasoning the nuclear magnetic moment of Be is supposed to be negative, so that the term order of the F terms will be inverted. Accordingly we have to expect that the weak component will be situated towards shorter wave-lengths.

With this theoretical feature the observed asymmetry is in accordance. Furthermore, the estimated limits of $\delta\nu$ allow one to give the limits of the g values of the nuclear moments

$$-0.4 > g(i) > -0.8$$

and the limits of the nuclear moments

$$-0.6 > \mu > -1.2 \text{ n.m.}$$

These values are in accordance with the value $g(i) = -0.783$ which was found with the resonance method.[31] If we assume this g value as granted, the value $i=5/2$ can be excluded because in this case the h.f.s. would have been separated; $i=\frac{1}{2}$ cannot be quite excluded, but $i=\frac{3}{2}$ is the most probable value.

The last paper concerning h.f.s. is the investigation of the isotopic shift of magnesium lines which the writer performed in 1937.[32] By means of an excited beam and etalons of 36; 42; and 60-mm separation, it was possible to resolve the patterns of the series $3^1P - m^1D$, $m=3, 4, 5$ into three nearly equally spaced lines which according to the intensities could be attributed to Mg (24), (25), (26). Also, one member of the sharp singlet series $3^1P - 5^1S$ could be resolved. The theory has been worked out by Vinti.[33]

4. Zeeman Effect of Hyperfine Structure

The Zeeman effect of the hyperfine structure is very important for the determination of the nuclear moment. In weak fields each fine level is split into $(2f+1)$ components; in strong fields, however, each component of the anomalous Zeeman effect of the fine structure consists of $(2i+1)$ hyperfine components (Back-Goudsmit-effect) of fairly uniform spacings and intensities. As soon as it is possible to resolve this hyperfine structure so that the number of components can be clearly counted, it is possible to establish the value i of the nuclear spin with certainty. This is a great advantage over the method which uses intensity ratios.

The method was several times applied in cases where the separations were not great enough in order to give resolved components with usual light sources. Experiments with atomic beams were carried out by Jackson and Kuhn for Li, Na, and K. They used the absorption method and employed as a resolving instrument a compound interferometer. In the case of potassium,[11] they were able to separate the h.f.s. of K^{39} and K^{41}. The collimation was very high, namely, 35 : 1. In order to get sufficient absorption, 3 atomic beams in series were employed. The Zeeman effect of K^{39} was studied with a single beam and collimation 25 : 1. The intensity ratios found for K^{39} in the two resonance lines 7664A and 7694A were found to be 1.44 and 1.45, respectively. With this

ratio the value $i=\frac{3}{2}$ is in accordance, the calculated values being 1.40. As the stronger h.f.s.-components have longer wave-lengths, the term order is regular in accordance with the experiments of Rabi, and Meissner and Luft (III, 3, *b*).

In order to establish the value $\frac{3}{2}$ with certainty the Zeeman effect of the π components were studied for K^{39} at a field of 730 gauss. Each of the two π components was found to consist of four lines, the positions being -0.0172 -0.0136 -0.0100 -0.0063 $+0.0180$ $+0.0148$ $+0.0106$ $+0.0056$ cm^{-1}. The value of i for K^{41} could be found only by the intensity ratio as $i=\frac{3}{2}$. The magnetic moment can be calculated as $=0.22$ n.m. The ratio of the moments $\mu_{39}/\mu_{41}=1.77$ ± 0.05 was found with high accuracy.

In a further work,[12] Jackson and Kuhn investigated the Zeeman effect of the hyperfine structure of Na in a wide range of field strength employing a compound interferometer consisting of two etalons of 2-cm and 8-cm spacing in series. The spectral range was 0.25 cm^{-1} and two lines with a separation of 0.003 cm^{-1} could be resolved. The D_1 line was observed at 11 different field strengths ranging from 790 to 2090 gauss, the D_2 line from 1060 to 3060 gauss. Only the π components were investigated.

The observations were in agreement with the theory (Heisenberg and Jordan 1926, Darwin 1927, Goudsmit and Bacher 1930).

Figure 4 shows the splitting of the h.f.s. levels according to the theory; Fig. 5 (Figs. 1, 2, and 3 of reference 12) shows the reproduction of interference patterns obtained with different field

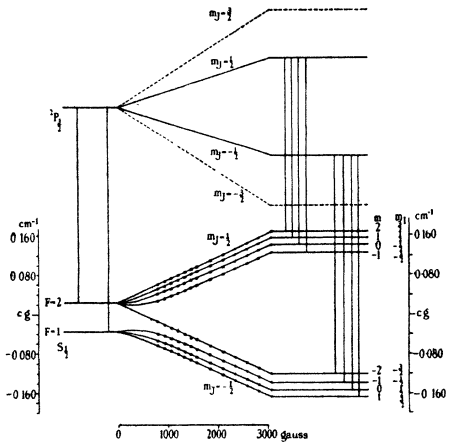

FIG. 4. Term diagram of the Zeeman effect of the line $3^2S_{1/2}-3^2P_{3/2}$ of sodium (Fig. 5 of reference 12).

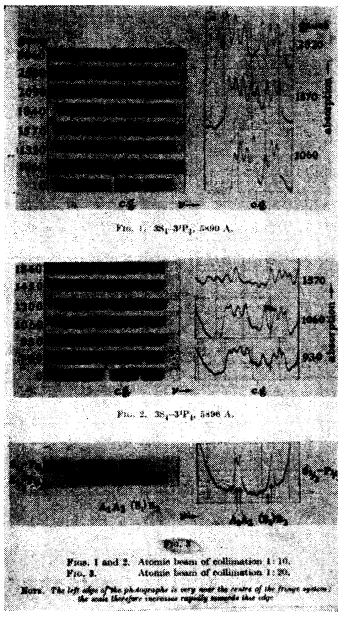

FIG. 5. Interference patterns for sodium lines (Figs. 1, 2 and 3, reference 12).

strengths. The beautiful photographs show clearly the development of the splitting and yield immediately the value $i=\frac{3}{2}$, since with sufficiently high field strength each hyperfine component possesses four lines.

The last paper of Jackson and Kuhn we have to mention deals with the h.f.s. and Zeeman effect of the resonance line of lithium.[13] This investigation was carried out with a multiple atomic beam and a collimation of 1/30 to 1/40 giving absorption lines between thirty and forty times narrower than the normal Doppler width. A compound interferometer (5-mm and 5-cm etalon in series) gave a spectral range of 1 cm^{-1} and resolution of about 0.004 cm^{-1}. The separation between adjacent emission lines, which formed the background for the absorption lines, was about $\frac{1}{3}$ order of the 5-mm etalon. The Zeeman effect investigation furnished the value of $i=\frac{3}{2}$. The two Zeeman π components were found to consist of four just resolved lines, the separation being about 0.005 cm^{-1}. With the knowledge of i it is possible to calculate the hyperfine splitting of the ^2S and ^2P terms involved. The measured values of the line splittings are

$2^2S_{1/2}-2^2P_{3/2}$ $\Delta\nu_1=0.0270\pm 0.0001$ cm^{-1},
$2^2S_{1/2}-2^2P_{1/2}$ $\Delta\nu_2=0.0280\pm 0.0002$ cm^{-1}.

The hyperfine splittings of the S and $P_{1/2}$-term are calculated as:

$$\Delta S_{1/2}=\tfrac{1}{2}(\Delta\nu_1+\Delta\nu_2)=0.0275\pm0.0003\ \text{cm}^{-1},$$
$$\Delta P_{1/2}=\tfrac{3}{2}(\Delta\nu_2-\Delta\nu_1)=0.0015\pm0.0009\ \text{cm}^{-1}.$$

The value of $\Delta S_{1/2}$ is in close agreement with the value found by Fox and Rabi,[34] $\Delta S_{1/2}=0.0267\pm0.0003\ \text{cm}^{-1}$.

The nuclear magnetic moment could be calculated from the ^2S splitting as $\mu=3.25$ n.m. This is the same value (3.250 n.m.) as found directly by the molecular beam magnetic resonance method.[35]

5. Application of the Atomic Beam Method for the Investigation of the Inverse Stark Effect

The atomic beam method is very convenient for the investigation of the inverse Stark effect which was first studied on the sodium D lines by R. Ladenburg.[38] The high vacuum, necessary for the production of an atomic beam, is very favorable for the maintenance of a strong electric field.

The method was developed by Kopfermann and his co-workers.[36, 37, 19] The arrangement used by Paul[19] was the apparatus described in II 3. The arrangement for the excitation of the beam by electron impact was removed and replaced by a condensator consisting of two plane plates, their separation being 1 mm (Fig. 6). The polished nickel plates (15×20 mm^2 area) were attached to amber plates. One of them was fitted to the cover plate which was provided with the image slit of the atomic beam apparatus. Four screws L_1 allowed parallel adjustment of the plates. By means of the screws L_2 which clamped one amber plate to the image slit plate a shift in the horizontal direction was possible. The adjustment could be performed from the outside.

With a similar apparatus Jenckel and Kopfermann[36] investigated singlet lines and were able to measure very small Stark-effect shifts. Paul[19] investigated the Cr resonance multiplet $^7S_3-{}^7P_{2,3,4}$(λ4254; 4275; 4290A). The continuous background for the production of the absorption lines was produced by means of a water-cooled hollow cathode fitted with a chromium cylinder.

With field strengths of 206, 234, and 275 kv/cm, red shifts of the lines could be observed in the order of 2×10^{-3}A, the shifts being proportional to the square of the field strength. Also a very weak broadening could be observed.

Since it was not possible for the writer to obtain the papers of references 36 and 37 it is not possible to give details of the results of these new investigations. We have, therefore, to restrict ourselves to the mere reference to these papers.

6. Further Possible Applications of the Beam Method

It is obvious that the beam method is applicable also for the investigation of band spectra. However, in order to obtain satisfying intensity or absorption it may be necessary to apply a number of molecular beams in series. In this way, an increase in the thickness of the absorbing or emitting medium will be accomplished without decrease of the width of the lines.

Furthermore, it may be mentioned that the beam light source may be very useful for precision intensity measurements of spectral lines. This source enables one to eliminate the effects of self-absorption by the application of different depths of the beam which can easily be accomplished by the proper choice of the length of the image slit.

Very important is the development of an atomic beam apparatus for studying the spectra

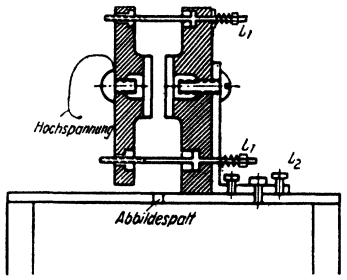

FIG. 6. Apparatus for observing Stark effect.

of gases for which the condensation method is not applicable. The papers of W. E. Williams and J. E. Mack in the present issue deal with this problem.

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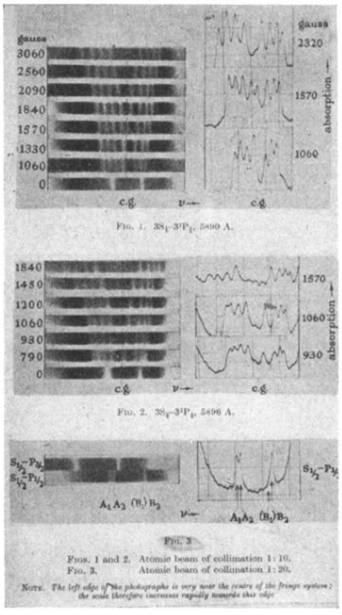

FIG. 5. Interference patterns for sodium lines (Figs. 1, 2 and 3, reference 12).