A Direct Experimental Test of the Principle of Spectroscopic Stability

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The spectroscopic stability required by quantum mechanics is subjected to a direct test, and it is demonstrated that the atoms of saturated thallium vapor exhibit no double refraction due to spatial quantization in a magnetic field up to 1200 gauss. The accuracy of the measurement permits of the assertion that if present at all the phase-difference between the component of the electric vector at right angles and that parallel to the field, is less than 10^{-5} of the wave-length employed. At the pressures employed this establishes a constancy of atomic refractivity to one part in 10^4.

I. Statement of Problem

ACCORDING to the old Bohr theory one expects hydrogenic atoms to exhibit spatial quantization in magnetic fields however weak. This spatial quantization has been directly demonstrated by deflection experiments in an inhomogeneous magnetic field and Stern[1] surmised that it should also become observable by the occurrence of double refraction in a magnetic field. The essential feature of this double refraction effect should be found in the fact that it would occur even at a very small value of the field strength and would be substantially independent of its magnitude. Various attempts at demonstrating the effect have been undertaken by a number of authors, but with negative results in every case. R. Fraser[2] and W. Schuetz[3] observed the variation of the index of refraction for various gases in a longitudinal and in a transverse magnetic field. The work of W. Schuetz is notable for the high degree of sensitivity achieved. It should have permitted the observation of a phase difference of 10^{-4} of the wave-length, but no sign of anisotropic behavior could be ascertained.[4]

The result to be expected from the point of view of the new theory of quantum mechanics is fundamentally different from that to be expected on the basis of the old Bohr theory. The principle of spectroscopic stability, introduced originally with the help of the correspondence principle, is derivable from the fundamental equations of quantum mechanics. The negative result of these tests is therefore, in the light of the new theory, entirely to be expected, although in the particular case of Na and the other gases tested the experiments cannot be considered as testing spectroscopic stability since the orbital properties of S terms are spherically symmetrical.

The matter takes on a different aspect for atoms having no S term in the normal state. In this case according to the picture given by the old theory of quantum mechanics optical anisotropy is to be expected, while according to the new theory the principle of spectroscopic stability implies the absence of double refraction.

In the experiments described here Tl-atoms in $6p_{\frac{1}{2}}$ states were used. The atomic refractivity was found to be constant to within 1 part in 10^4 in fields as high as 1200 gauss. These experiments may be regarded as proving the validity of spectroscopic stability directly because the orbital wave functions have an angular dependence.

II. Arrangement of the Apparatus

In its normal state $6p_{\frac{1}{2}}$ Tl absorbs the lines of the sharp and the diffuse series which lie in the ultraviolet. This fact is very favorable to the investigation of double refraction remote from the points of anomalous dispersion. In the visible range the known green thallium line 5350.46A appears only at higher temperatures, when sufficient atoms have been brought to the somewhat higher state $^2p_{\frac{3}{2}}$. By the employment

[1] O. Stern, Zeits. f. Physik **7**, 249 (1921).
[2] R. Fraser, Phil. Mag. **1**, 885 (1926).
[3] W. Schuetz, Zeits. f. Physik **38**, 853 (1926).
[4] For analogous tests in the field of gas kinetics, which are likewise negative in result, cf. for instance A. Sommerfeld, *Wave Mechanics*.

of a suitable light filter in the visible range it becomes readily possible to separate the phenomena attendant on anomalous dispersion in the magnetic field from the double refraction sought for.

For the purpose of the present tests a commercial preparation (Kahlbaum) was employed. The only impurities were slight traces of lead. The material was degassed by repeated heating in a high vacuum, but no further purification was carried out.

The arrangement of the apparatus is shown in Fig. 1. The first observations were taken with

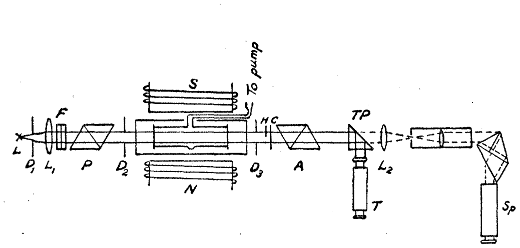

FIG. 1. L = source of light; D_1, D_2, D_3 iris diaphragms; L_1, L_2 lenses; F, filter; P, polarizer; N, S poles of magnet; H, half-shadow plate; C, compensator plate; A, analyzer; TP, totally-reflecting prism; T, telescope; Sp, spectrograph.

monochromatic light. The source of light employed was a quartz bulb mercury vapor point-light lamp of high intrinsic brilliancy the light from which was made monochromatic by a Zeiss filter. This filter lets through 80 percent of the green Hg line while it absorbs all but 0.003 percent and 0.1 percent, respectively, of the blue and yellow lines. The pencil rays emitted by the lamp are rendered parallel by a lens of great focal length, and limited by a number of iris diaphragms arranged in series.

In the experiments two absorption chambers of transparent quartz having plane-parallel windows fused on without strains were employed. Both quartz tubes were 1 cm in diameter; the one used at the start was 20 cm, the other 15 cm long. They were connected with the pumping device by means of ground joints. In this manner the diffusion of the thallium vapor from the absorption vessel was prevented.

In order to be able to produce any desired pressure of the saturated thallium vapor, the absorption tube was inserted in a two-part electric furnace consisting of a fire-brick tube about which a nickel-chromium strip was non-inductively wound; this eliminated the influence of longitudinal magnetic fields. Since the furnace was twice as long as the absorption vessels and was, moreover, well insulated against loss of heat, the temperature could be maintained fairly constant through the length of the vessels. The measurements were made at temperatures from 600°C to 950°C as measured by means of a thermocouple. This range of temperature corresponds to a variation in the vapor pressure of thallium from 0.05 to 10.5 mm Hg.

For the detection of double refraction there was employed a highly sensitive Brace half-shadow compensator constructed by the writers following Szivessy.[5] Since the principle of this apparatus has been amply described elsewhere, it is sufficient to refer briefly to the peculiarities of the half-shadow compensator here employed. The half-shadow and the compensator plates were each connected to a vernier and could be rotated independently in their respective planes. The accuracy of reading amounted to 1/3 minute. The compensator plate was made up of two mica leaves which were cemented between two plates of glass. Its retardation for Na light was 0.045λ. The half-shadow plate was composed as follows: A thin sheet of mica with a retardation of 0.020λ for Na light, was used to cover one-half of the field of vision of 10 mm diameter; the necessary weak double refraction was produced by means of a rectangular cover glass plate of 0.1 mm thickness which could be pressed parallel to two edges. In this manner any desired double refraction of the cover glass plate could be produced, and the sensitivity of the apparatus could be increased to some three times that obtainable with the use of the mica half-shadow plate. The adjustment of the apparatus was made as follows. The two nicols were first crossed, the direction of oscillation of the polarizer being inclined 45° to the horizontal magnetic field. The half-shadow plate was then inserted, and its direction of oscillation likewise turned to 45° with reference to the zero azimuth of the analyzer. This could be approximately done by turning the half-shadow plate in its plane until the two halves of the field of vision

[5] G. Szivessy, Zeits. f. Physik 6, 311 (1931).

showed the strongest contrast in brightness. The more accurate adjustment could then be carried out after the insertion of the compensator plate. If this latter be rotated through 360° in its plane, the whole field of vision is darkened four times. For the angle of rotation of the compensator from the zero azimuth the following relation is valid:[5]

$$2\alpha = \pi/2 - (p_2 - p_1) = (p_3 - p_2) - \pi/2$$
$$= \pi/2 - (p_4 - p_3) = (p_1 - p_4) - \pi/2,$$

in which p_1, p_2, p_3, p_4 represent the readings on the arc of the compensator in the four half-shadow positions. The equality of the angle 2α, as calculated from the four readings, is a criterion for the correct setting of the half-shadow plate.

The beam of light emerging from the analyzer fell, as can be seen from Fig. 1, on a totally reflecting prism, and was here deflected into a telescope mounted at right angles to the direction of the beam, and accurately focussed on the limiting edge of the half-shadow plate. It was possible, by rotation of the totally reflecting prism, to throw the beam of light on the slit of a spectrograph. In this manner it was possible to keep a check on the composition of the light traversing the absorption chamber, and more particularly to detect the occurrence of any absorption lines. The spectrograph with a direct wave-length scale employed for this purpose was a Hilger instrument which separated the *D*-lines by about 1 mm.

The magnetic field was produced by a magnet built in the laboratory with poles of circular cross section 20 cm in diameter. The spacing of the poles had to be increased to 4.6 cm in order to accommodate the electric furnace, for which reason the maximum field strength obtainable was 1200 gauss. The poles of the magnet were fixed at this distance from each other by means of brass spacers since it was found that otherwise the poles approached each other by a few millimeters when the current was switched on. In spite of the wide spacing of the poles, the homogeneity of the field except for small distances from the edge was maintained by the large superficial area of the poles.

A vacuum of 10^{-5} mm Hg was maintained during the experiments by means of a rotary oil pump in series with a mercury vapor pump.

III. Experimental Results

In order to ascertain empirically the sensitivity of the half-shadow arrangement for the detection of double refraction, the Cotton-Mouton effect was observed with benzene. For this purpose benzene (specially refined for molecular weight determination) was placed between the poles of the magnet in a 15 cm tube with plane-parallel windows. The double refraction in the transverse magnetic field corresponded to a rotation of the compensator plate through 7 minutes. From the relation $\Delta = (\sin \varphi / \sin 2\beta)(\sin 2\alpha' - \sin 2\alpha)$ there resulted for the phase-difference of movement of the components of the electric vector oscillating at right angles to and parallel to the magnetic field, respectively, the value $5.9 \times 10^{-5}\lambda$ ($\lambda = 5461$A), or for the difference $n_1 - n_2$ in the refractive indices the value 2.2×10^{-10}. In the formula just given φ denotes the retardation of the compensator plate, β the azimuth of the half-shadow plate (in the present instance $\beta = \pi/4$), α and α' the azimuths of the compensator plate without and with the magnetic field. Since, as above mentioned, the readings of the arc were accurate to 1/3 minute, the error in the above value is presumably about 5 percent. Now in the calibration just performed the difference in intensity between the two halves of the field of vision was so great that a much smaller double refraction could have been detected with certainty. Thus a phase-difference of $1 \times 10^{-5}\lambda$ would be easily observable.

The saturated thallium vapor was first tested in monochromatic light of wave-length 5461A at temperatures varying between 600° and 800°C. Up to this latter temperature the thallium atoms are in the normal state; at all events the number of excited atoms present is negligibly small. The above-mentioned range of temperature corresponds to a pressure interval of the saturated thallium vapor of from 0.05 to 1.5 mm Hg. The absorption spectrum of thallium shows, at the temperatures mentioned, the lines of both subordinate series, starting from the lowest level $^2P_{\frac{1}{2}}$, and all lying in the ultraviolet. No absorption line appears in the visible range, up to about 800°C.

As proved by repeated measurements under the described conditions, *no double refraction of the thallium vapor could be ascertained within the given limits of sensitivity up to 800°C.* It should be noted that in the above experiments the magnetic field was varied through a wide range. Thus the effect of space quantization could not have been accidentally masked by effects due to a small longitudinal component of the magnetic field since this effect varies with the field while the double refraction looked for is independent of it.

As a check on the proper functioning of the apparatus we observed the magneto-optic effect in the neighborhood of 5350A. The effect was largest at about 850°C corresponding to a vapor pressure of about 4 mm Hg. It should be emphasized that this effect is not in contradiction to the principle of spectroscopic stability being just another form of anomalous dispersion.

Electron Scattering by Atomic Electrons

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The velocity distributions of electrons scattered by helium atoms, at angles ranging from 10° to 60°, have been measured for electrons having energies of 800, 1000, and 1200 volts. The curves have a well-defined narrow maximum where the scattered electrons have the same velocity as the primary electrons, this being the well-known elastic scattering. In addition, for each angle of scattering, a single broad peak is superposed on the continuous distribution of velocities ranging from the maximum down to zero. This represents the inelastically scattered electrons. The position of each peak is such that the velocity corresponding to it, is given approximately by $v=u\cos\theta$, where u is the velocity of the electron before impact and θ the angle of scattering. This is the formula for the velocity of an electron when scattered through θ, by a free electron initially at rest. The inference is that we may associate these inelastic peaks with collisions between the incident electrons and the atomic electrons when the binding energy is small in comparison with the energy transfers during the collision. Jauncey's theory of the breadth of the modified line in the Compton effect is discussed in relation to the breadth of the inelastic peak, on replacing the photon by the incident electron.

INTRODUCTION

When an electron is moving with a velocity u towards another electron, initially at rest, application of the principles of conservation of energy and momentum lead to the conclusion that if the first electron is deviated through an angle θ, its velocity will be given by $v_1=u\cos\theta$, while that of the second electron will be given by $v_2=u\sin\theta$, a result which implies that the two paths after collision are necessarily at right angles.[1] It is not possible to make a direct test of this result because of the difficulty of securing a sufficient density of free electrons. However, a close approximation to the ideal case is realized when a beam of beta-rays is passed through matter of low atomic number, a condition which insures that the binding energy of the atomic electrons may be neglected in comparison with the energy transfer involved during a collision. Experiments show that the beta-ray tracks in a Wilson cloud chamber are frequently forked and that the angle between the tracks is close to 90°.[2] This implies that the fork results from a collision between the beta-ray and an atomic electron, the nucleus playing no part. The beta-ray, because of its high speed, has to pass so close either to an atomic electron, or to the nucleus, in order to suffer an appreciable deflection, that the observed deflection can be attributed to a

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[1] This follows easily from Eqs. (3) and (4) (given later) on omitting the binding energy.

[2] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 238 (Macmillan).