Isotope Shift in Mg I

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The lines of the Mg I spectrum, lying in the visible and in the photographic infrared regions, have been examined and some of them found to show structure. It is pointed out that the structure should be attributed to isotope shift, which, in the case of the $3s3p\,{}^1P-3s3d\,{}^1D$ series, owes its origin to the fact that the $smd\,{}^1D$ terms, perturbed by the $p^2\,{}^1D$ term, have passed on to this term some of their isotope separation, which, in the unperturbed case, would have been the same as that of $3s3p\,{}^1P$ and thus unobservable. This perturbation is discussed in connection with the observed shifts, and it is found possible to correlate the observed shifts with the calculated displacements of the $3smd\,{}^1D$ energy levels produced by the $p^2\,{}^1D$ perturbation, with satisfactory agreement. Since the observed patterns show two components, they cannot be attributed to mass effect, which would give three nearly equally spaced components. Furthermore, the shift is in the wrong direction to be accounted for by the usual assumption that heavier isotopes have larger radii, and, consequently, looser binding of electrons than the lighter isotopes.

INTRODUCTION

IT is a well-known fact that very often the spectral lines of different isotopes of the same element have different wavelengths. The shift in wavelength, which is caused by a relative displacement of the initial and final energy states, has been attributed entirely, in the case of light elements, to the mass difference of the isotopes. For example, the mass difference of the isotopes has been shown by Hughes and Eckart[1] to account for the observed shift in Li, and, although the agreement with experiment is none too good, the observed separations in Ne have been attributed by Bartlett and Gibbons[2] to the mass difference alone. It seems, therefore, that for light elements, the mass effect is the most important factor. For the heavier elements, on the other hand, this factor is almost negligible, since the relative change in mass from one isotope to another is too small to account for the rather large displacements which have been observed. Consequently, the shift must be accounted for by some difference in the nuclei other than the difference of their masses, and the suggestion has been made that it is the external fields of the isotopes that are in some way different. It has been found[3] that if the same nuclear density is assumed, the change in radius, due to the increase in the number of particles, is sufficient to account for the observed displacements for heavy elements such as Hg, Tl and Pb. The elements mentioned above occur at either end of the periodic table; it was with the hope of obtaining some information about an "intermediate" element that the following study of Mg I was undertaken.[4]

EXPERIMENTAL

The Mg I spectrum was excited in a hollow cathode discharge tube, so constructed that the cathode was outside and could be cooled in water or liquid air, as the occasion demanded. The inside of the cathode was lined with magnesium foil. It was found, in general, that the sharpness of the lines was increased more by lowering the current than by cooling with liquid air. The spectrum was studied with a Fabry-Perot interferometer, used in conjunction with a glass spectrograph of the Littrow type. A variety of plate separations up to 29.5 mm was used. The lines investigated extended from λ4500 to λ8800, and various types of photographic plates were employed, sensitized Eastman I-P plates being very satisfactory for the far red.

RESULTS

Fig. 1 gives an energy level scheme of Mg I showing the lines which have been investigated.

[1] D. S. Hughes and C. Eckart, Phys. Rev. **36**, 694 (1930).
[2] J. H. Bartlett and J. J. Gibbons, Phys. Rev. **44**, 538 (1933).
[3] J. H. Bartlett, Nature **128**, 408 (1931); G. Racah, Nature **129**, 723 (1932); J. E. Rosenthal and G. Breit, Phys. Rev. **41**, 459 (1932); G. Breit, Phys. Rev. **42**, 348 (1932).
[4] Several of the lines of the Mg I spectrum (λλ5711, 4571, 5184, 5173 and 5167) have been examined previously and found to be single by Murakawa, Zeits. f. Physik **72**, 793 (1931).

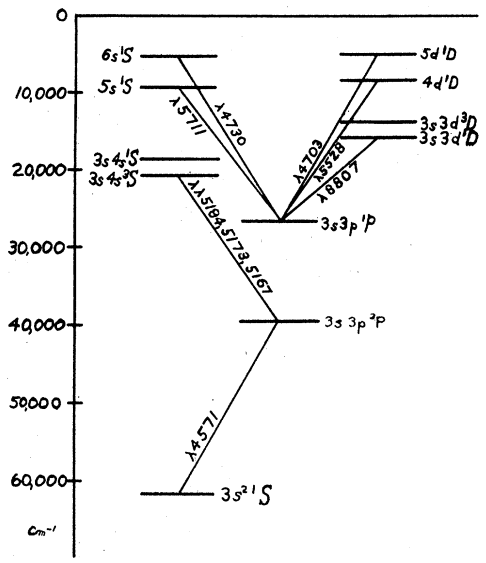

FIG. 1. Energy level scheme of Mg I showing lines which were studied.

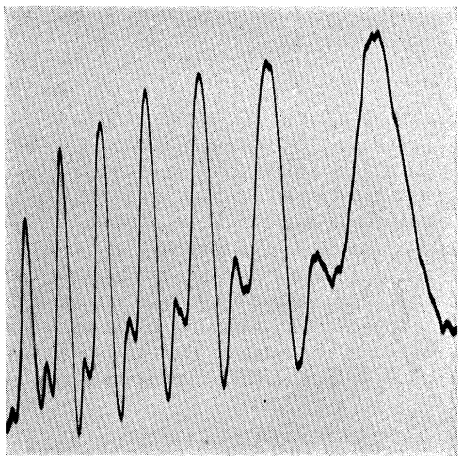

FIG. 2. Microphotometer trace of λ8807. Interferometer separation 29.5 mm. ν increases to the left.

λ4571 ($3s^2\,{}^1S-3s3p\,{}^3P_1$). This line is found to have two components, a strong one at say, $\Delta\nu=0$ and a very much weaker one at 0.083 cm^{-1}.

λλ5184, 5173, 5167 ($3s3p\,{}^3P_{012}-3s4s\,{}^3S$). These strong lines in the green show no structure under any of a variety of excitation conditions. With low currents and liquid-air cooling these lines become increasingly sharp.

λ8807 ($3s3p\,{}^1P-3s3d\,{}^1D$). This line has been investigated with several different plate separations. In general, it was necessary to use currents of 75 milliamperes or more through the discharge tube in order to obtain sufficient intensity. The line was found to consist of a strong central component with a weaker component on the high frequency side, at a separation of 0.082 cm^{-1}. Fig. 2 is a section of a microphotometer tracing of one of the photographs of this line showing the two components. It is estimated from the areas under the microphotometer curves that the two lines have intensities approximately in the ratio of 7 to 2.

λ5528 ($3s3p\,{}^1P-3s4d\,{}^1D$). This line shows a structure similar to λ8807 except that the separation is smaller, $\Delta\nu=0.065$ cm^{-1}, the weak component being on the high frequency side.

λ4703 ($3s3p\,{}^1P-3s5d\,{}^1D$). The fringes for this line show a definite asymmetry but the components are not sufficiently well separated to measure. The structure appears to be of the same type as that of λ8807 and λ5528, but with still smaller separation. On the basis of a measurement of the line width, an estimated upper limit for this separation is 0.061 cm^{-1}.

λ5711 ($3s3p\,{}^1P-3s5s\,{}^1S$). There is some asymmetry to the fringes for this line, which suggests that it may have structure. If so, it is definitely much narrower than λ5528.

λ4730. This line is faint, but its fringes seem to be sharper than those of λ4703.

DISCUSSION OF RESULTS

The most interesting lines which have been studied are those of the $3s3p\,{}^1P-3smd\,{}^1D$ series, all of which have structures of the sort that arises from isotope shift. In the case of these lines, moreover, it was found possible to show that, since they are not expected to show hyperfine structure, their structure can be attributed to isotope shift alone. Any hyperfine structure which the $3s3p\,{}^1P$ and $3smd\,{}^1D$ terms would possess would necessarily be due either to (a) deviation from Russell-Saunders coupling, (b) interaction of the outer electrons with the s electron, or (c) perturbation by another level. Of the above, (a) and (b) can be immediately eliminated: The first because the sd and sp configurations in Mg I are in very good Russell-

Saunders coupling, and under these circumstances it is known[5] that neither the ^1D's nor ^1P will have hyperfine structure; the second, because, since in both the initial and final states the s electron has a total quantum number which is the same as or smaller than the other outer electrons, it will be the most intimate with the nucleus and would be considered mainly responsible for hyperfine structure if any did exist.[6] As for (c), although the ^1D series is perturbed[7] by the $3p^2\,^1D$ to such an extent that the singlets all occur below their triplets, the $p^2\,^1D$ will have no hyperfine structure to pass along, since it contains no s electron outside the core. The conclusion is, therefore, that hyperfine structure in these lines would be negligible and that the observed structure should be attributed to isotope shift.

Magnesium is known, from the work of Dempster, to have three isotopes with mass number $M=24$, 25, 26, and abundances in the ratios 7 : 1 : 1. The appearance of only two components in the lines must mean, then, that the components from two of the isotopes fall together. Since Mg_{24} must certainly be in the strong component, possibly together with Mg_{25} or Mg_{26}, the weak component may correspondingly be either Mg_{25} or Mg_{26} or both together. A measurement of relative intensities should decide this point. For λ8807 an estimate of the relative intensities from the areas of the microphotometer traces gave 7 : 2. From this rough intensity estimate it would appear that Mg_{25} and Mg_{26} fall together in the weaker component. It is hoped to settle this point definitely by more exact intensity measurements.

Now if the isotope shift were due to mass effect alone, the line pattern would be three components nearly equally spaced, for both the "normal" effect and the "specific" effect are closely proportional[2] to $1/M$, and so the isotopes with $M=24$, 25 and 26 would be very nearly equally spaced. In the observed lines it is not possible, with the abundance ratios as they are, for the Mg_{25} to be midway between the other two components, as there is a definite minimum on the microphotometer curve between the two observed components. Thus it appears that the isotope shift cannot be accounted for entirely on the basis of mass effect.

It is rather difficult, since the isotopes form a set of levels which do not have intercombinations, to get from the observed lines to the possible level scheme. In general, since the isotopes probably differ most in the immediate neighborhood of their nuclei, it may be assumed that the largest isotope effect will be for those configurations with the most s electrons. On this basis, the $3s3p\,^1P-3smd\,^1D$ series should show no relative shift. But the ^1D terms are not pure, being perturbed by $p^2\,^1D$, and this perturbation does give a relative shift. Accordingly, a large isotope shift should be assigned to $3s3p\,^1P$ and smaller ones to the $3smd\,^1D$ series, the shift increasing for the higher members. If such assignments are made, however, it is necessary that either or both of the isotopes of mass 25 and 26 have their electrons more tightly bound than the isotope of mass 24 in order for the faint component to appear, as it does, on the high frequency side. If this tighter binding is to be accounted for by assuming different nuclear radii, Mg_{24} would necessarily have a larger radius[8] than the heavier isotopes, whereas it is ordinarily assumed that larger radii accompany larger number of particles. These isotope shifts can, of course, also easily be accounted for by postulating that the nuclei differ in other respects.

If it is true, as stated above, that the ^1D series shows structure in its combinations with $3s3p\,^1P$, because of the perturbation of $p^2\,^1D$, it should be possible to correlate this perturbation with the information which is available about the displacement of the energy states. It has previously been shown[7] that when wave functions extrapolated from Hartree functions by the

[5] S. Goudsmit and R. F. Bacher, Phys. Rev. **34**, 1501 (1929).

[6] From the work of Goudsmit (Phys. Rev. **43**, 636 (1933)) one can find that $a(3s)=0.050\ g(I)$; $a(3p_{\frac{1}{2}})=0.011\ g(I)$ and $a(3p_{1\frac{1}{2}})=0.002\ g(I)$ cm^{-1}. Using these values and taking $g(I)=1$ for example, one finds (Breit and Wills, (Phys. Rev. **44**, 470 (1933)) $A(sp\,^1P)=0.003$ cm^{-1} and $A(p^2\,^1D)=0.004$ cm^{-1} which would be negligible.

[7] R. F. Bacher, Phys. Rev. **43**, 264 (1933).

[8] In this respect the structure observed here is somewhat similar to several other elements, as Ne, Cu and Zn. See G. Hansen, Naturwiss. **15**, 163 (1927); R. Ritschl, Zeits. f. Physik **79**, 1 (1932); H. Schüler and H. Westmeyer, Zeits f. Physik **81**, 565 (1933). This difference between Cu and Zn and the heavier elements has been pointed out by Schüler and Westmeyer, Zeits. f. Physik **82**, 685 (1933).

Slater method are used, the nondiagonal matrix elements are sufficiently large to explain the presence of $3s3d\,{}^1D$ below ${}^3D$. The numerical agreement was rather poor, however, probably because the value of the $3d$ function which was used. In addition, this function also gave the unperturbed levels too widely separated. If a hydrogen function is used for $3d$, and the other wave functions are retained, the singlet-triplet separation, while diminished greatly by the perturbation, does not change sign. It is proposed here to fix the unperturbed levels arbitrarily some place between the position they occupied with the Hartree functions and the position they would occupy with a hydrogenic $3d$, and to fix the higher unperturbed levels by a series with constant quantum defect. The displacement δ_m due to the perturbation can then be determined from the observed levels. In terms of the two unperturbed terms $E_0(p^2\,{}^1D)$ and $E_0(smd\,{}^1D)$ and the nondiagonal matrix element of the electrostatic interaction we can now write

$$\delta_m=\frac{(p^2\,{}^1D|\,V|\,smd\,{}^1D)^2}{E_0(smd\,{}^1D)-E_0(p^2\,{}^1D)}.$$

If all the $smd\,{}^1D$'s have an isotope shift σ and we say that $p^2\,{}^1D$ has relatively no isotope shift, then the amount of shift which will be passed along[9] will be

$$\sigma_m'=\frac{(p^2\,{}^1D|\,V|\,smd\,{}^1D)^2\sigma}{[E_0(smd\,{}^1D)-E_0(p^2\,{}^1D)]^2}=\frac{\delta_m\sigma}{E_0(sd\,{}^1D)-E_0(p^2\,{}^1D)};$$

σ_m' is the observed separation in the $sp\,{}^1P-smd\,{}^1D$ series. Inserting the values of δ_m, the unperturbed states, and the observed separation, one should be able to obtain the same value of σ from each series member. They are indeed approximately the same (see Table I) and this agreement is not greatly affected by reasonable changes in the location of the unperturbed $sd\,{}^1D$ levels. This explanation of the origin of the isotope shift in these particular lines seems to be in accord, both qualitatively and quantitatively, with the position of the energy levels themselves. It is thus also apparent why the isotope shift in the $(3s3p\,{}^1P-3smd\,{}^1D)$ lines decreases more slowly than the displacement δ_m as one goes to higher series members, though their origin is the same.

TABLE I. *Absloute term values and energy displacements measured in cm*$^{-1}$.

m	$3smd\,{}^1D$ Unperturbed	$3smd\,{}^3D$ Observed	$3smd\,{}^1D$ Observed	δ_m	σ_m'	σ
3	~12000	13715	15269	3269	0.082	0.386
4	~ 6775	7480	8537	1762	0.065	0.375
5	~ 4350	4704	5364	1014	≤0.061	≤0.460

$p^2\,{}^1D=\sim-3400$ cm^{-1}.

The presence of structure in the $3s3p\,{}^1P-3sms\,{}^1S$ series, which has been observed but not resolved, is undoubtedly due to the same cause. It is smaller because the perturbing term $(p^2\,{}^1S)$ is much farther away and because the lowest member observed is for $m=5$.

The structure of the line λ4571 $(3s^2\,{}^1S-3s3p\,{}^3P_1)$ is probably due to isotope shift also, if one is to judge from its structure, though here the possibility of hyperfine structure in the initial state cannot be excluded.

The green lines λλ5184, 5173, 5167, $(3s3p\,{}^3P_{012}-3s4s\,{}^3S_1)$, which were found sharp, would be expected to show practically no isotope shift on the basis of *inner s* electrons, of which each state has one. There is, furthermore, no reason for believing that either the initial or final level is perturbed to any extent.

CONCLUSION

Structure has been observed in several of the Mg I lines and, in particular, in the $3s3p\,{}^1P-3s3d\,{}^1D$ series. The observed structure is attributed to isotope shift, since it is characteristic and since these lines are not expected to show hyperfine structure. The relative separations of the series members are in agreement with the idea that the structure arises because the $3s3d\,{}^1D$ terms have passed on to the $p^2\,{}^1D$

[9] This method of procedure is closely analogous to that used by Whitelaw, Phys. Rev. **44**, 544 (1933), in the study of multiplet separations which were due to perturbation. Here, however, the various levels have the same quantum number J.

some of their isotope separation which, in the unperturbed case, would have been the same as that of $3s3p\ ^1P$ and would thus not have been observed.

It has been concluded that the observed structure cannot be due to mass effect alone, since, in that case, three components, nearly equally spaced, would be expected. It is also pointed out that the shift is in the wrong direction to be accounted for by a difference in nuclear fields caused by the fact that the isotopes with larger number of particles have larger radii. It is possible, and even probable, that the change in the fields in the neighborhood of nuclei is due to other causes, as well, and it is suggested that a survey of isotope displacements may yield valuable information in this connection.

The experimental work reported here was done in 1933 in the Physics Laboratory of the University of Michigan.

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The Scattering of Protons on Protons

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A technique for obtaining large numbers of high energy proton-tracks in hydrogen with a Wilson cloud chamber is described. The recoil-particles from cellophane bombarded by polonium alpha-particles were used as a source of protons. The velocity distribution of a sample of 500 protons is given. Over 15,000 stereoscopic views containing above 200,000 tracks of protons in a 90 percent hydrogen-10 percent air mixture have been obtained. Of the thirty-three intimate proton-proton collisions two were within the region of anomalous scattering of alpha-particles by hydrogen. The closest distance of approach realized experimentally was 6.1×10^{-13} cm.

INTRODUCTION

THE recent interpretations of Heisenberg[1] and others of the structure of the heavier nuclei as composed of protons and neutrons in close combination make any experimental evidence about the interaction of protons at close distances of primary importance. With the technique developed in the present experiments it is entirely possible to obtain more detailed experimental information of the laws governing proton-proton interaction. In view of the time that will be required to take and to analyze the large numbers of photographs necessary for conclusive evidence about the proton-proton interaction, it is felt appropriate to give an account of the methods used and the results obtained thus far. These results will serve to delineate the usefulness of a cloud chamber in attacking this problem and will thus be of value in any future work using either radioactive or high voltage sources of high energy particles.

For central and glancing collisions of alpha-particles on He and H nuclei, the following critical distances have been found within which the Coulomb interaction was no longer valid:[2]

	On He	On H
Central collisions	3.5×10^{-13} cm	4×10^{-13} cm
Glancing "	14.0×10^{-13} cm	8×10^{-13} cm

Taylor[3] was able to show, by assuming an interaction energy of the kind applied by Gamow[4] to the radioactive nuclei, that the main features of the earlier experiments could be accounted for without departure from the conception of a spherically symmetric field for an alpha-particle. In the above-mentioned experiments the failure of the Coulomb interaction might be ascribed either to the structure of the He nucleus alone or to both the He and the H nuclei. Further information on this point can be

[1] Heisenberg, Zeits. f. Physik **77**, 1 (1932); **78**, 156 (1932).

[2] Rutherford, Phil. Mag. **37**, 537 (1919); Chadwick and Bieler, Phil. Mag. **42**, 823 (1921); Rutherford and Chadwick, Phil. Mag. **4**, 605 (1927).

[3] Taylor, Proc. Roy. Soc. **A136**, 605 (1932).

[4] Gamow, *Atomic Nuclei and Radioactivity*.

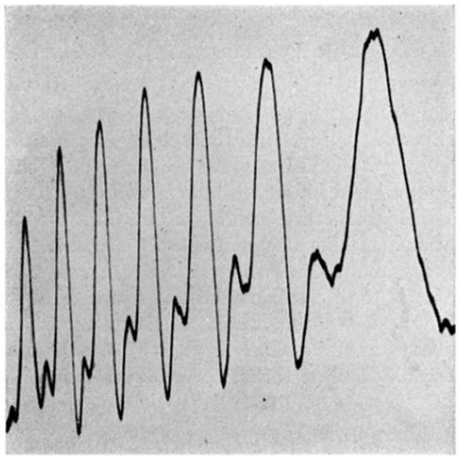

FIG. 2. Microphotometer trace of λ8807. Interferometer separation 29.5 mm. ν increases to the left.