Isotope Effects in the Hyperfine Structure of the Resonance Lines of Gallium I

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The hyperfine structure of the lines 4033 and 4172 A of gallium I has been investigated by means of the absorption of a multiple atomic beam of high collimation. From the measurements of the structure of the line 4033 A are derived: the hfs intervals of the terms $4\,^2P_{\frac{1}{2}}$ and $5\,S_{\frac{1}{2}}$ for Ga^{69} and Ga^{71}, the ratio of the nuclear magnetic moments, and the isotope shift; and from the line 4172 A, the hfs intervals of the term $4\,^2P_{\frac{3}{2}}$ of Ga^{69} and Ga^{71}, and hence an approximate value for the quadrupole moment coupling factors for the two isotopes.

THE hyperfine structure of the two resonance lines of the arc spectrum of gallium, in the visible ($4\,^2P_{\frac{1}{2}}-5\,S_{\frac{1}{2}}$, 4033 A and $4\,^2P_{\frac{3}{2}}-5\,S_{\frac{1}{2}}$, 4172 A) has been investigated by means of the absorption of a multiple (9-fold) atomic beam. The background in which the absorption was observed was provided by a water-cooled hollow cathode. The instrument, of high resolving power, was a double etalon with plate separations of 1.67 and 5.0085 cm with plates coated respectively with 5-fold and 7-fold dielectric multilayers of zinc sulfide and cryolite; the spectral range was 299.49 mK and the limit of resolution between 2 and 3 mK (1 mK$\equiv$1 millikayser$\equiv 10^{-3}$ cm^{-1}). The combined instrumental and Doppler width of simple components was between 4 and 5 mK.

The structure of the line 4033 A is shown in Fig. 1, a microphotometer recording of an interferogram of the absorption of the atomic beam. Intensity of illumination decreases, and absorption increases towards the top of the tracing. The six minima *a*, *A*, *bB*, *Cc*, *D*, and *d* are the hfs components; but the minima *x*, *x'* and *X* appear in photographs made in the absence of absorption, *x* and *x'* being gaps between the three wide hfs components emitted by the hollow cathode, and *X* being a gap between adjacent spectral orders. The components *A* and *D* are ascribed to the isotope Ga^{69} and *a* and *d* to Ga^{71}; while *bB* and *Cc* are each blends of two unresolved components, one due to each isotope.

On account of their narrowness, it was possible to measure the positions of the six components with a high degree of accuracy. Random errors were minimized by measuring a large number of plates; and systematic errors which might be caused by the nonlinear dispersion of the etalon fringe system, were avoided by altering the disposition of the six components in the fringe system by changing the pressure of the air in the air-tight containers which housed the two etalons (necessary for phasing the double etalon). The results of the measurements are given in the following table:

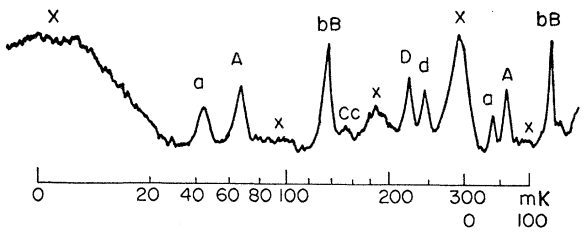

FIG. 1. Hyperfine structure of the 4033 A line of gallium. The hfs components are *a*, *A*, *bB*, *Cc*, *D*, and *d*.

Component	*a*	*A*	*bB*	*Cc*	*D*	*d*
Wave number (mK)	0.0_0	22.2_7	92.3_2	112.0_2	183.1_3	204.9_9
Mean deviation (mK)	...	1.0	1.1	1.0	1.0	1.0
Intensity	4	6	10	2	6	4

Since 68 independent measurements of the structure were made, the probable error is of the order of ± 0.1 mK. The intensities were estimated from the microphotometer traces; they confirm the allocation of the hfs components to the two isotopes, being in agreement with the theoretical values for the spin $\frac{3}{2}$ ($A:B:C:D = 5:5:1:5$) and the abundance ratio $Ga^{69}:Ga^{71}=60:40$.

The isotope shift is $\frac{1}{2}(A-a)-\frac{1}{2}(d-D)$ and is thus equal to $0.5_6\pm 0.07$ mK the lines of Ga^{71} being shifted to the red. The ratio of the nuclear magnetic moments of the two isotopes, derived from the sum of the hfs splitting of the terms $4\,^2P_{\frac{1}{2}}$ and $5\,S_{\frac{1}{2}}$, is simply the ratio $(d-a):(D-A)$, and thus $Ga^{71}:Ga^{69}=(1.270_0\pm 0.0008):1$.

The difference between the splitting of the term $4\,^2P_{\frac{1}{2}}$ and that of the term $5\,S_{\frac{1}{2}}$ can be found either from the separation between the blends *bB* and *Cc*, or from the position of *bB* or of *Cc* in conjunction with the above value of the isotope shift. (The position of the blend *bB*, in which the absorption is very strong, is taken as the simple mean of the positions of *b* and *B*; but for *Cc*, in which the absorption is weak, *C* and *c* are weighted in the ratio 60:40.) The three values thus obtained for this difference are 17.8, 17.6, and 17.2 mK, mean 17.5_3 mK for the isotope Ga^{69}; and the mean value for Ga^{71} is 22.2_6 mK; the differences in the splittings of the terms for the two isotopes are assumed to be in the same ratio as the sums of the splittings. These values for the differences in the splittings combined with the values of the sums, $D-A$ and $d-a$, give the following values for the hfs splittings of the terms:

Ga^{69}	$4\,^2P_{\frac{1}{2}}$	$5\,S_{\frac{1}{2}}$	Ga^{71}	$4\,^2P_{\frac{1}{2}}$	$5\,S_{\frac{1}{2}}$	
	89.2	71.7		113.3	91.0	± 0.1 mK.

The structure of the line 4172 A is shown in Fig. 2. The resolution is less satisfactory than in the case of the line 4033 A; only six components appear, whereas if the resolution were complete there would be twelve components, of which, however, three are too weak to give an observable absorption. As will be shown below, only three of the observed components are simple, the others being blends. The results of 10 measurements of the structure are given in the following table:

Component	*A*	*B*	*C*	*D*	*E*	*F*
Wave number (mK)	0.0	13.8	24.7	64.2	84.0	91.4
Mean deviation (mK)	...	1.5	1.5	1.0	1.4	1.4
Intensity	$1\frac{1}{2}$	4	4	10	2	$1\frac{1}{2}$.

Since ten measurements were made, the probable error estimated from the mean deviation is of the order of 0.5 mK. It would not be possible to make a significant improvement in this accuracy by making more measurements since the small separations can introduce systematic errors, and also the three strongest lines are blends.

In spite of the incomplete resolution of this line, the spacings of the hfs levels of the term $4\,{}^2P_{\frac{3}{2}}$ of both isotopes can be derived with an accuracy of the order of 1 mK, provided the theoretical intensity ratios are assumed, since the structure of the term $5\,S_{\frac{1}{2}}$ is known from the line 4033 A, and also the total width of the blends cannot exceed about 4 mK. The following levels for the term $4\,{}^2P_{\frac{3}{2}}$, combined with the values for the term $5\,S_{\frac{1}{2}}$ given above, yield a structure which agrees very closely with the measurements:

Ga^{69}:	*F*	0	1	2	3		Ga^{71}:	*F*	0	1	2	3	
		4	7	18	39	mK,			0	7	21	46	mK

The wave numbers and intensities of the six components given by the six transitions for the two isotopes are:

Transition $5\,S_{\frac{1}{2}}$: *F*		1	1	1	2	2	2
$4\,{}^2P_{\frac{3}{2}}$: *F*		2	1	0	3	2	1
Ga^{69}: Wave number (mK)		13.5	23.5	26.5	63.5	84.5	95.5
Intensity		9	9	4	25	9	2
Ga^{71}: Wave number (mK)		0	14	21	66	91	109
Intensity		6	6	2	17	6	1.

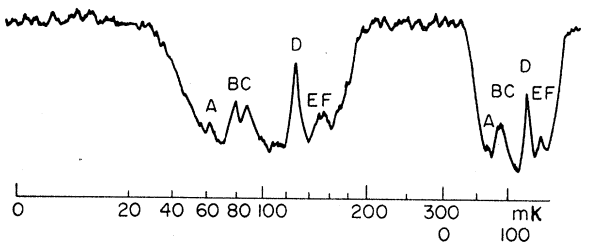

FIG. 2. Hyperfine structure of the 4172 A line of gallium. The hfs components are *A*, *B*, *C*, *D*, *E*, and *F*.

The isotope shift in the line 4172 A is assumed to be equal to that in 4033 A, and consequently the components of Ga^{71} have been displaced -0.5 mK (to the red) from the positions required by the above term levels. If it is assumed that components separated by less than 4 mK are not resolved, the above 12 components are reduced by blending to the following 8 components:

Wave number (mK)	0.0	13.7	24.0	64.5	84.5	91.0	95.5	109.0 mK
Intensity	$1\frac{1}{2}$	4	4	10	2	$1\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$

(The intensities have been reduced to the scale used in the measurements, the strongest blend 25+17 being reduced to 10, and the others reduced in the same ratio.) This calculated structure is in excellent agreement with the measured structure both with regard to position and intensity of the components and blends, the components calculated at 95.5 and 109.0 mK being too weak to give an observable absorption. It can therefore be assumed that any errors in the above hfs levels of the term $4\,{}^2P_{\frac{3}{2}}$ are not likely to exceed 1 mK.

The values of the hfs splitting factor, *A*, and of the quadrupole moment coupling factor, *B*, calculated from the above levels are:

$$Ga^{69}: \quad A=6.4\pm0.3; \quad B=1.8\pm0.7,$$
$$Ga^{71}: \quad A=7.8\pm0.3; \quad B=1.6\pm0.7.$$

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