The Nuclear Moment of Barium as Determined from the Hyperfine Structure of the Ba II Lines*

By P. GERALD KRUGER, R. C. GIBBS AND R. C. WILLIAMS**

Cornell University and the University of Illinois

(Received June 13, 1932)

The hyperfine structure of the Ba II lines λ4934A and λ4554A has been observed. The relative intensities of the observed components of λ4554A have been measured. From these data it was possible to determine the value of the nuclear moment of $Ba^{135,137}$, if it is assumed that the barium isotopes 136 and 138 have no nuclear spin. The most probable value obtained for i is 5/2. The separation of the hyperfine levels of $6s\,^2S_{1/2}$ is 0.272 cm^{-1}, of $6p\,^2P_{1/2}$ is 0.039 cm^{-1}, and of $6p\,^2P_{3/2}$ is approximately 0.033 cm^{-1}. In all other terms the hyperfine splitting is very small. There is some evidence that there is an isotopic shift of the center of gravity of the levels of the odd isotopes with respect to the even isotopes, and it has a probable value of 0.022 cm^{-1} for the $^2P_{1/2}$ state, and 0.017 cm^{-1} for the $^2P_{3/2}$ state.

Introduction

McLENNAN and Allin,[1] S. Frisch,[2] Gibbs and Kruger,[3] and Ritschl and Sawyer,[4] have previously examined the resonance lines of Ba II for hyperfine structure. The results in the first three reports were highly discordant, but the last two agreed in all essential details. However, none of the data was complete enough to determine the value of the nuclear moment for barium.

Experimental

The Ba II lines were strongly excited in a metal liquid air cooled Schüler lamp. The current used varied from 1 amp. to 1.4 amp. and the He gas pressure in the lamp varied from 4 mm to 10 mm. A Fabry-Perot interferometer was used in a Zeiss triple prism spectrograph to photograph the lines. Quartz etalon plates, whose silvered surfaces at various times during the work had reflection coefficients ranging from 60 percent to 94 percent, were spaced by etalon rings 1, 3, 5, 8, 10, 13, 15, 18, 20, 21, 25, and 30 mm in thickness. The times of exposure varied from thirty seconds to three hours.

Nichols and Merritt,[5] have shown that the intensity of light coming through a slit from a continuous source is proportional to the slit width, if

* The investigations upon which this article is based were supported by grants from the Heckscher Foundation for the Advancement of Research, established at Cornell University by August Heckscher. Acknowledgment is also made of the use of spectroscopic apparatus which was in part purchased by a grant from the National Research Council.

** R. C. Gibbs and R. C. Williams, Physical Laboratory, Cornell University; P. Gerald Kruger, Department of Physics, University of Illinois.

[1] McLennan and Allen, Phil. Mag. **8,** 515 (1929).

[2] S. Frisch, Zeits. f. Physik **68,** 758 (1931).

[3] Gibbs and Kruger, Phys. Rev. **38,** 1921 (1931).

[4] Ritschl and Sawyer, Zeits. f. Physik **72,** 36 (1931).

[5] Nichols and Merritt, Phys. Rev. [I] **31,** 502 (1910).

the slit is wider than 0.06 mm. This principle was used to put intensity marks on the plates so that the intensity of the components of the lines could be compared.

A dull white cardboard was placed 10 inches in front of the slit, and was uniformly illuminated by two frosted bulb lamps, which were placed two feet away, one on each side of the collimator. Slit widths of 0.8 mm, 1.0 mm, 1.2 mm, 1.4 mm, and 1.6 mm were used.

The intensity marks were photographed on the same plate as the line and its components without removing the plate from the spectrograph, so as to take account of the variation of plate sensitivity with wave-length. The time of exposure was 60 seconds. Later the plate was microphotometered and the intensity marks recorded at wave-length of the line.

Results

Table I gives the results obtained for the Ba II lines studied, and includes for the sake of comparison the data of McLennan and Allin and of Ritschl and Sawyer. Frisch found no components to these lines so his data are omitted. The intensities of the components are given in aribitrary units, and show

TABLE I. *Hyperfine structure of Ba II lines.*

λ air	Classification	Int.	$\Delta\lambda$ of components in A	$\Delta\nu$ of components in cm^{-1}	Total line width in cm^{-1}	Ritschl and Sawyer's data	McLennan and Allin's data
		5	+0.0279	−0.115		+0.027A	
		5	+0.0185	−0.076			+0.043A
4934.10	$6s\ ^2S_{1/2}-6p\ ^2P_{1/2}$	75	0.0000	0.0000		0.000	0.000
		5	−0.0477	+0.196		−0.045	−0.037
4899.97	$6p\ ^2P_{3/2}-7s\ ^2S_{1/2}$		sharp		0.057		0.000
							−0.060
4554.04	$6s\ ^2S_{1/2}-6p\ ^2P_{3/2}$	7	+0.0177	−0.085		+0.018	0.000
		75	0.0000	0.000		0.000	−0.051
		5	−0.0340	+0.164		−0.034	−0.085
4524.95	$6p\ ^2P_{1/2}-7s\ ^2S_{1/2}$		sharp		0.051		
4166.02	$6p\ ^2P_{3/2}-7d\ ^2D_{3/2}$		sharp		0.062		
4130.68	$6p\ ^2P_{3/2}-7d\ ^2D_{5/2}$		sharp		0.060		

the intensity ratio between components. The estimated intensity values given the strong parent line are not accurately determined with respect to those of the components, but are given merely to indicate that the parent line is very much stronger than the components.

Fig. 1 shows the hyperfine structure term schene for λ4934 $6s\ ^2S_{1/2}-6p\ ^2p_{1/2}$, and for λ4554 $6s\ ^2S_{1/2}-6p\ ^2P_{3/2}$.

Discussion

Two of the writers published a preliminary report[3] on the structure of the barium lines, and on the basis of estimated intensity ratios between the parent line and the satellites predicted a ratio of even to odd isotopes for barium of about ten to one. About the same time Aston reported isotopes 135, 136, 137 and 138, and has since then[6] reported the respective percentage ratios to be 5.9, 8.9, 11.1 and 74.2. This makes the even to odd ratio of isotopes about five to one.

At the time the preliminary report was made the two components +0.0279A and +0.0185A of λ4934 had only been suspected because of a gradual shading in intensity on the long wave-length side of the parent line. The presence of these new components increases the intensity ratio between parent line and the satellites so that it is of the right order of magnitude to agree with Aston's work.

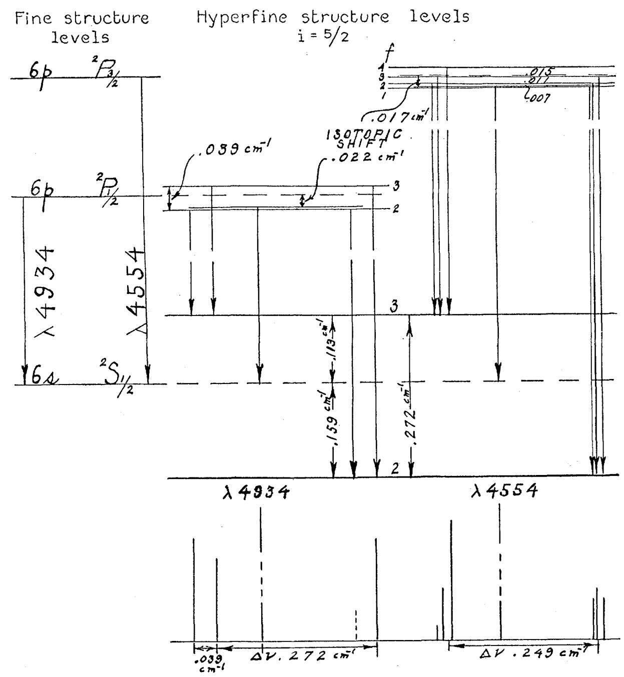

Fig. 1. Hyperfine structure energy level diagram of barium resonance lines, Ba II.

It was possible to observe these components only when using etalon spacings (25 mm), such that the −0.048A component fell on the next chief interference maximum; and (30 mm), such that −0.048A and +0.0279A fell very close to a higher order chief maximum, one on each side. This enabled accurate Δλ measurements to be made on these components, but prevented intensity measurements being made, since all the components could not be resolved on the same plate. Thus the intensities given for these components in Table I are estimated intensities. That they are all of about the same intensity can be seen from Fig. 2 which shows a microphotometer curve of λ4934. The components are unresolved, (due to the fact that the plate was taken with a 13 mm etalon separation) but are drawn in their relative positions.

Fig. 3 shows a simlar microphotometer curve for λ4554. The two com-

[6] Aston, Proc. Roy. Soc. **134**, 571 (1932).

ponents of this line are clearly resolved on the original plate but unfortunately the microphotometer does not show this. Therefore the intensity ratio of these two components was obtained in the following way. The center of the parent line was determined by bisecting the peak of the curve. Then the left side of the parent line was drawn, making it symmetrical about the center line. The right side of the -0.0340A component was projected in the same way, thus giving the shape and position of that component. The ordinates of the

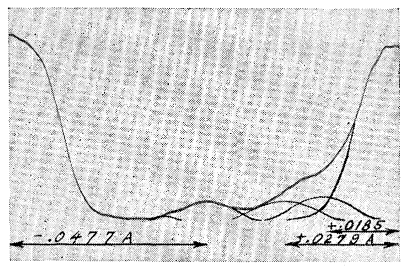

Fig. 2. Microphotometer curve of λ4934.

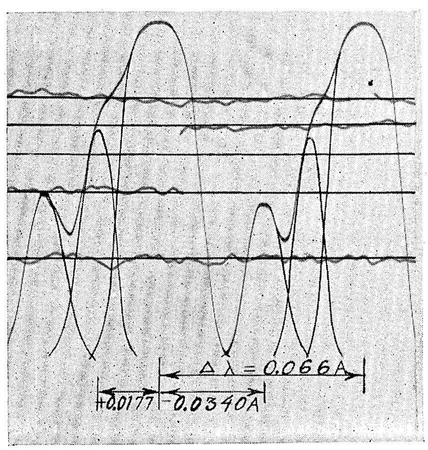

Fig. 3. Microphotometer curve of λ4554.

-0.0340A component and parent line were subtracted from the microphotometer curve to give the form and position of the $+0.0177$A component. When its position had been determined the $\Delta\lambda$ separation from the parent line was computed from measurements taken from the graph and found to agree with the measurements made on the original plate. This gives assurance that the components are correctly drawn in Fig. 3. The position of the peaks of the components may now be compared with the intensity marks (horizontal lines in Fig. 3) which were put on as described above and the intensity ratio obtained in this way. Such a calculation gives the value 1.41 to 1 for the intensity ratio of the components $+0.0177$A to -0.0340A.

A calculation of the theoretical intensities for the hyperfine components under consideration gives the following results for $i=5/2$.

	$^2P_{1/2}$	
f	3	2
$^2S_{1/2}$ 3	28	35
2	35	10

	$^2P_{3/2}$			
f	4	3	2	1
3	81	35	10	
2		28	35	27

Thus, since the $^2P_{3/2}$ hyperfine levels separations are very small, the theoretical ratio for the components +0.0177A to −0.0340A is 1.40 to 1. This fits the above data and i has, therefore, been chosen as 5/2.

Two difficulties arise from this choice. The fourth component to λ4934A is missing. But its theoretical intensity has only a ratio of 1 to 3.5 with respect to the other components, and it is, therefore, too weak to observe. Component +0.0185A has a theoretical ratio to +0.0275A of 4 to 5, and the curves show the two about equal in intensity. This may be due to the fact that the components were unresolved on the plate from which the curve in Fig. 2 was made. It may also be added that visually, component +0.0279A appears more intense than component +0.0185 on plates taken with a 25 mm etalon separation.

If i were 7/2 the theoretical intensity ratio of components +0.0275A and +0.0185A would be about 3 to 2 and such a ratio would not fit the curve in Fig. 2. Since this ratio increases as i increases it must be concluded that i is probably less than 7/2. On the other hand, even though the experimental intensity ratio of the components of λ4554 (1:41 to 1) indicate that i is 5/2, it must be admitted that the errors involved in the method of synthesizing the curves in Fig. 3 do not eliminate entirely the possibility that i may be 2 or 3. Thus, while the data give the most probable value of i as 5/2, it may be that $3/2 \leq i < 7/2$.

The hyperfine energy level diagram shown in Fig. 1 shows the theoretical hyperfine structure multiplets at the bottom. The observed $\Delta\nu$ separations are given. For λ4554 the two groups of three components each are unresolved and the observed $\Delta\nu$ is between the centers of gravity of the two groups. The energy level scheme has been built up from these data. The separation for the hyperfine levels of $^2S_{1/2}$ is 0.272 cm^{-1}. The unsplit $^2S_{1/2}$ level for the even isotopes, where $i=0$, has been conveniently placed at the center of gravity of the hyperfine levels. The $^2P_{1/2}$ hyperfine levels are separated by 0.039 cm^{-1}. This indicates a relative isotopic shift between the unsplit ^2P and ^2S levels for even isotopes and the center of gravity of the hyperfine levels of the odd isotopes of about 0.022 cm^{-1}.

The total widths of the hyperfine levels of $^2P_{3/2}$ is about 0.033 cm^{-1}. Here also, there is an indicated isotopic shift of about 0.017 cm^{-1}.

Other lines given in Table I were examined but no structure was found. This must mean that the hyperfine splitting in $7s^2S_{1/2}$ is very small.

All of the above mentioned etalon separations and times of exposure were used in order to make an exhaustive search for the components reported by McLennan and Allin but none were found.

The authors wish to express their appreciation for various helpful suggestions which Professor R. A. Sawyer has given them during the course of this investigation.

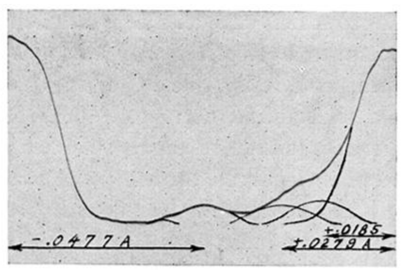

Fig. 2. Microphotometer curve of λ4934.

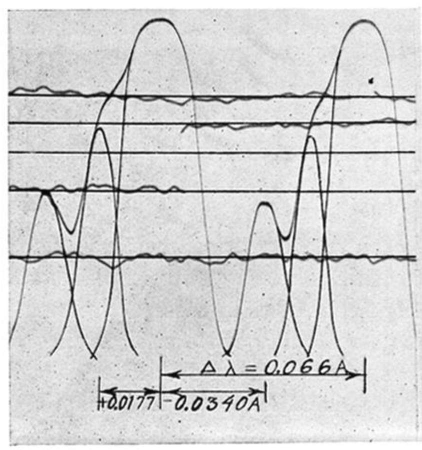

Fig. 3. Microphotometer curve of λ4554.