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THE HYPERFINE STRUCTURE SEPARATIONS AND MAGNETIC MOMENTS OF Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84}

J. C. Hubbs, W. A. Nierenberg, H. A. Shugart,
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ABSTRACT

Measured by an atomic-beam magnetic resonance method, the hyperfine-structure separations and magnetic moments of four neutron-deficient isotopes are found to be

Rb^{81}, $\Delta\nu = 5097 \pm 13$ Mc, $\mu_I = +2.05 \pm 0.02$ n.m.;

Rb^{82}, $\Delta\nu = 3094.1 \pm 2.4$ Mc, $\mu_I = +1.50 \pm 0.02$ n.m.;

Rb^{83}, $\Delta\nu = 3183.3 \pm 5.8$ Mc, $\mu_I = +1.42 \pm 0.02$ n.m.;

Rb^{84}, $\Delta\nu = 3077.5 \pm 5.1$ Mc, $\mu_I = -1.32 \pm 0.02$ n.m.

THE HYPERFINE STRUCTURE SEPARATIONS AND MAGNETIC MOMENTS OF Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84} *

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I. INTRODUCTION

In several previous papers,[1, 2, 3] accounts have been given of the measurements of the spins of four neutron-deficient isotopes of rubidium and a metastable state of one of these isotopes. Also, the hyperfine structure and magnetic moment of Rb^{81} have been measured by the zero-moment atomic-beam method.[1] In this paper, report is made of the measurement of the atomic hyperfine structures (hfs) of Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84} by use of the atomic-beam magnetic resonance method and radioactive detection. A different method of preparing the radioisotope Rb^{84} for atomic-beam purposes is discussed in some detail, because the low intensities used in the previous work had to be augmented to obtain sufficient sensitivity to determine the sign as well as the absolute value of the hfs. Because of the small numbers of atoms produced in the Berkeley 60-inch cyclotron, special procedures were employed in the search for resonance lines to minimize the amount of material required. No attempt was made to determine the hfs any more accurately than was necessary to determine the sign of the moment.

*This work was done under the auspices of the U. S. Atomic Energy Commission and the Office of Naval Research.

II. ISOTOPE PREPARATION

For most of these experiments, the radioisotopes were produced by alpha particles on natural Br^{79} and Br^{81}. The chemical extraction and beam preparation have been described in Reference 2. However, in order to increase the signal-to-noise ratio, absorber foils were used to select the particular (α, kn) reaction desired. In a general way this procedure improved matters except for Rb^{84}, for which the (α, n) reaction yield is very poor. Although several curves were run using this reaction, it was decided to use (p, n) reactions on Kr in an attempt to increase the Rb^{84} yield. Fortunately Kr^{84} is 57% abundant, compared with 12% for Kr^{83}, so that production of Rb^{84} is favored over that of Rb^{83}. The improvement in signal-to-noise ratio over the Br bombardments was about 4 to 1. In addition, runs using the Kr^{84} (p, n)Rb^{84} reaction provided an independent assignment of spin 2 for Rb^{84}.

In practice approximately 2 liters of krypton at atmospheric pressure is contained in a water-cooled, rectangular tube of cast aluminum with a 1-mil aluminum window at one end for the 12-Mev proton beam. Following suitable exposure to a proton beam of approximately 25 microamperes, the assembly is allowed to stand for several days to permit the short-lived activities to decay. After the krypton is frozen out and replaced with air, the entire assembly is washed with several hundred ml of water containing controlled amounts (~20 mg) of RbBr carrier. This is boiled away to a few drops of RbBr solution, and the concentrate is transferred to an iron cup and dried thoroughly. Calcium is then added and the beam produced as described in Reference 2. As was expected, the krypton bombardment proved more efficient than the $BaBr_2$ production scheme. Overheated $BaBr_2$ in an alpha beam often distilled and redistributed itself away from the intense parts of the beam, thus limiting the useful production rate. Moreover, in the Kr bombardments the degradation of the beam by Ba was eliminated.

III. METHOD OF MEASUREMENT

The hyperfine line observed was the flop-in line corresponding to a change of $\Delta m_J = \pm 1$ in the regions of the focusing fields.[4] For small C-field values (i.e., $\frac{|g_J \mu_0 H|}{h} << \Delta\nu$), the Breit-Rabi formula[5] may be expanded to second order in H, with the result that the frequency of the transition

$$m_F = -I - \frac{1}{2} \qquad -I + \frac{1}{2} \qquad \text{is given by}$$

$$\nu \cong \nu_0 + \frac{2I\nu_0^2}{\Delta\nu}, \qquad \nu_0 \cong -\frac{1}{2I+1}\,\frac{g_J \mu_0 H}{h}, \qquad g_J = \frac{\mu_J}{J}, \qquad (1)$$

where $\Delta\nu$ is the hfs constant, ν is the observed resonance frequency, ν_0 is the Zeeman frequency for the upper hfs level corresponding to $F = I + 1/2$, g_I is neglected, and $g_J \cong -2$. The transition indicated is an example for $\Delta\nu > 0$. The line width in these experiments varied between 0.1 and 0.5 Mc, depending on the magnitude and previous history of the C field and on the amplitude of the radio-frequency transition field. The width of the line determined the method of search. To illustrate, consider Rb^{81}(4.7 hr). The spin is 3/2 for this isotope and one can safely assume that the hfs lies somewhere between 2000 and 8000 Mc. Since experience has shown that it is reasonable to obtain approximately 50 beam exposures during a run with good statistics, it is advisable to take a small number of these, about 10, for a crude estimate of the hfs. The line width may be on the order of 0.1 Mc, and therefore 10 points may be used to cover a 1-Mc interval. Examination of Eq. (1) indicates that for $I = 3/2$ and $\nu \sim 30$ Mc the line will shift by 1 Mc for a variation in $\Delta\nu$ from 2000 to 8000 Mc. Since at least one of the exposures should have an indication of hfs, this will represent a measurement of the hfs to the order of 10 %. If the hfs turns out to be, say, 5100 ± 500 Mc, then 10 more exposures can be assigned to the next order of accuracy. At $\nu_0 = 125$ Mc the variation of ± 500 Mc in $\Delta\nu$ corresponds to a variation of 1 Mc in ν, and again the resonance will show on at least one exposure. Thus, the $\Delta\nu$ is known to approximately 1%. Now the hfs is determined to about 0.2% by carefully taking a full resonance curve at the best resolution available and at the highest frequency available (200 Mc). Finally, an attempt is

made to see the resonance at some suitably low value of the field that will show the greatest sensitivity to the effect of the sign of g_I in the Hamiltonian. This field is determined by the resolution, I, the magnitude of g_I, and the magnitude of $\Delta\nu$. Fortunately, despite the poor resolution of the apparatus used, the magnitudes of the nuclear moments and the hfs constants are just sufficient to determine the signs.

The value of the magnetic field was measured by use of the carrier Rb^{85} and Rb^{87} in the beam. The carrier beam is also used to monitor the beam intensity. The carrier line was monitored in frequency and magnitude before and after each radioactive exposure. The frequency was used for the calculation of the magnetic field, and the magnitude of the carrier resonance served to normalize the activity collected during the exposure.

IV. DATA REDUCTION

In order to treat the data systematically, the normalized data points obtained for each resonance were fitted by a bell-shaped curve by a least-squares procedure. To be more precise, the reciprocals of the resonance heights were fitted by a weighted least-squares parabola. This technique gives high weights to points near the peak of the curve, and relatively little weight to the tails; therefore departures from the assumed line shape have little effect. A good fit is shown in Fig. 1.

By use of the resonance of the stable Rb^{85} or Rb^{87} to obtain a value of the magnetic field, the hyperfine structure constant $\Delta\nu$ can then be computed from[6]

$$\Delta\nu = \frac{\left(\nu + \frac{g_I \mu_0 H}{h}\right)\left(\frac{-g_J \mu_0 H}{h} - \nu\right)}{\nu + \frac{g_J \mu_0 H}{(2I+1)h} + \frac{2I}{2I+1}\,\frac{g_I \mu_0 H}{h}} , \qquad (2)$$

where $g_I = \frac{\mu_I}{I}$,

if g_I is known. In this particular case g_I is not known. It could be obtained in principle from simultaneous solution of Eq. (2) for two values of the field; in practice, however, the available resolution is not adequate, and the magnitude of g_I is obtained by simultaneous solution of Eq. (2) and the Fermi-Segrè relation[7]

$$\left| g_I \right| = \left| g_I' \right| \frac{2I'+1}{2I+1}\,\frac{\Delta\nu}{\Delta\nu'} , \qquad (3)$$

where the primed quantities are known values for a stable isotope of the same element. This method yields two values of $\Delta\nu$ depending on the assumed sign of g_I. The correct sign gives consistent results as the field is varied; the incorrect sign gives a systematic variation in apparent values of $\Delta\nu$. The constants used in these calculations are:[1, 2, 8, 9]

Rb^{85}, $g_J = -2.00238$, $\Delta\nu = 3035.735$ Mc, $\mu_I = +1.35268$ n.m., $I = 5/2$;

Rb^{87}, $g_J = -2.00238$, $\Delta\nu = 6834.7005$ Mc, $\mu_I = +2.750529$ n.m., $I = 3/2$.

Assumed value for Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84}, $g_J = -2.00238$;

Rb^{81}, $I = 3/2$; Rb^{82}, $I = 5$; Rb^{83}, $I = 5/2$; Rb^{84}, $I = 2$;

$\mu_0 = +0.92732 \times 10^{-20}$ erg/gauss, $h = 6.6252 \times 10^{-27}$ erg sec.;

$\frac{M}{m} = 1836.13$.

The following uncertainties enter the $\Delta\nu$ calculation:

(a) The uncertainty in H as determined from the carrier resonance. The largest contribution to this was usually the variation in the C field during a run. Steady drifts could be corrected for, but appreciable uncertainty remained.

(b) The uncertainty in the frequency of the radioactive peak as a consequence of dependence on the uncertainties in the input data to the least-squares procedure. It was usually quite small.

(c) The uncertainty in the frequency of the radioactive peak arising from fitting a symmetric curve to a possibly asymmetric line. This is hard to evaluate. The internal consistency of the results indicates a probable error of about one-tenth the half width of the resonances. This value has been assumed in drawing Figs. 2 through 5. The somewhat more conservative value of one-quarter the half width has been used in Table I.

V. RESULTS

Each isotope is discussed in terms of three to five resonance curves obtained during the course of a total of nine runs. Figures 2 through 5 present graphically the calculated values of $\Delta\nu$ when the moment is assumed negative and positive. In each case it is seen that for one of the assumed signs the calculated values of $\Delta\nu$ scatter about a constant value, while for the other assumed sign some of the $\Delta\nu$ values lie well outside their stated probable errors. That sign for which the hfs remains constant is the correct sign of the nuclear moment.

To illustrate the smooth variation in the calculated hfs constant when the incorrect sign of the moment is assumed, a curve in each figure shows the theoretical variation of the calculated hfs with magnetic field for the best known values of $\Delta\nu$ and g_I. In all cases the experimental points fall along the theoretical curves.

From the consistency of the calculated values of $\Delta\nu$ as shown in Figs. 2 through 5, a positive moment is assigned to Rb^{81}, Rb^{82}, and Rb^{83}; and a negative one to Rb^{84}. The final values of $\Delta\nu$ given in Table II result from an average of the data from Table I weighted by the reciprocal of the square of the stated error. This analysis preserves to a large extent the highest field values, by virture of their small errors. The final errors are equivalent to those of the highest field resonance, and arise principally from the uncertainty of one-quarter the half width, which is placed on the frequency of the radioactive resonances. Experiments using the stable Rb^{85} and Rb^{87} demonstrate that the apparatus is free from any appreciable systematic errors in the magnetic field and radio-frequency regions covered in this experiment.

CONCLUSIONS

Some results of rather general interest have come from the rubidium research. The moment table for the odd-odd isotopes (Table III) indicates that the neutron configuration of Rb^{82} is perhaps the same as that of Se^{79}, which also contains 45 neutrons. This neutron system, generally considered to be $(g_{9/2})^7\ (7/2)^+$, is anomalous in the sense of the simple shell picture and would not necessarily be expected to persist with the addition of three protons.

The moment table indicates that the proton configuration for Rb^{82} is $p_{3/2}$, while that of Rb^{84} is $f_{5/2}$. Bellamy et al. have concluded that the proton configuration in Rb^{86} is also likely $f_{5/2}$.[10] Thus the favored odd-proton configuration for neutron number between 46 and 49 is evidently $f_{5/2}$, while $p_{3/2}$ is similarly favored at either end of the range. Considering the large quadrupole moments of selenium nuclei, one is tempted to ascribe the phenomenon to nuclear deformability effects. There is a Rb isotope of $A < 81$. A measurement of its spin or of the quadrupole moment of Rb^{83} or Rb^{84} would be significant in this respect, but is not feasible at the present stage of our experimental technique.

A third result of greater interest is best shown by the graph of Fig. 6, wherein is plotted the magnetic moment of all $p_{3/2}$ odd-proton nuclei near rubidium as a function of neutron number. Neutron shell closings as obtained from the Klinkenberg scheme[11] are indicated. It would appear that the filling of neutron shells is in large measure responsible for the magnetic-moment fine structure. Indeed, for the $g_{9/2}$ neutron shell, Rb and Br moments may be fitted by a single straight line to within a very few percent. A survey of known magnetic moments shows that this effect is very common, and appears to be in such a direction as to indicate an increase in the intrinsic magnetic moment of the proton system as neutrons are added to a shell. There are, however, no clear-cut cases suggested by Fig. 6 in which one sees the large drop in moment at a neutron shell closing for a given element. An investigation of the spins and magnetic moments of copper and gallium isotopes is now under way, and should yield significant support or contradiction to these discussions.

One would expect in this region that the shell model is a reasonable first approximation. Quite generally the absolute value of the effect of one neutron

should be nearly that of 2j neutrons if the shell-model nomenclature and assumptions are at all valid. Further, configuration mixing within a proton shell is of no help, if for no other reason than that the observed level schemes in the rubidium series do not show a systematic monotonic trend in low-lying levels. The effect might be ascribed to a quenching of the proton moment by partially filled neutron shells, in a manner analogous to the self-quenching discussed by Bloch.[12] Since the number of unfilled levels decreases linearly with the number of neutrons in a shell, this effect might be expected to give results of the observed form. One further explanation is not implausible, namely, that the reduced-mass effect of Johnson and Teller[13] is coming into play as a result of a change in the relative radii of neutron and proton shells, or in the distance from the odd proton to the well edge, and thus the effective velocity-dependent potential that is seen. Two facts argue against this conclusion, however. The total effect of this phenomenon should be at most a small fraction of a nuclear magneton, since it is said that the mass of a nucleon at the center of the nuclear well is about half that of a free nucleon. In addition, the sign of the effect should be the same for all odd-proton nuclei, and experimentally it is not.

ACKNOWLEDGMENTS

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Figure Captions

Fig. 1. A good least-squares fit to a resonance of Rb^{81}.

Fig. 2. Calculated values of the hyperfine-structure separation for Rb^{81}. (a) Moment assumed positive. (b) Moment assumed negative.

Fig. 3. Calculated values of the hyperfine-structure separation for Rb^{82}. (a) Moment assumed positive. (b) Moment assumed negative.

Fig. 4. Calculated values of the hyperfine-structure separation for Rb^{83}. (a) Moment assumed positive. (b) Moment assumed negative.

Fig. 5. Calculated values of the hyperfine-structure separation for Rb^{84}. (a) Moment assumed positive. (b) Moment assumed negative.

Fig. 6. The magnetic moments of $p_{3/2}$ odd-proton nuclei near rubidium.

Table I. The radioactive and stable isotope resonance frequencies and calculated hyperfine-structure separations for Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84}.

Reference frequency (Mc)/sec	Reference isotope	Radioactive frequency (Mc)/sec	hfs (assumed positive moment) (Mc)/sec	hfs (assumed negative momen (Mc)/sec
Rubidium 81				
46.207 ± .010	87	46.572 ± .110	4981 ± 460	5409 ± 460
55.462 ± .002	87	55.904 ± .045	5195 ± 141	5592 ± 141
79.648 ± .002	87	80.598 ± .052	5119 ± 75	5368 ± 75
85.973 ± .016	85	121.165 ± .074	5119 ± 49	5276 ± 49
47.795 ± .025	85	200.268 ± .045	5094 ± 13	5183 ± 13
		weighted average	5097 ± 13	
Rubidium 82				
46.207 ± .010	87	17.400 ± .035	3108 ± 115	3198 ± 115
85.973 ± .016	85	47.410 ± .084	3107 ± 38	3137 ± 38
55.153 ± .004	85	30.312 ± .035	3077 ± 37	3124 ± 37
81.270 ± .006	85	101.681 ± .024	3094.1 ± 2.4	3105.9 ± 2.4
		weighted average	3094.1 ± 2.4	
Rubidium 83				
53.579 ± .006	85	53.340 ± .089	3203 ± 67	3260 ± 67
24.973 ± .005	85	123.884 ± .033	3183.2 ± 4.8	3204.7 ± 4.8
24.998 ± .015	85	123.908 ± .038	3183.3 ± 5.8	3204.8 ± 5.8
		weighted average	3183.3 ± 5.8	
Rubidium 84				
32.387 ± .005	85	38.805 ± .033	2997 ± 53	3077 ± 53
40.592 ± .009	85	48.587 ± .053	3024 ± 55	3088 ± 55
04.651 ± .005	85	124.531 ± .027	3051.3 ± 4.6	3074.6 ± 4.6
51.140 ± .005	85	178.942 ± .061	3066.1 ± 5.1	3081.6 ± 5.1
			weighted average	3077.5 ± 5.1

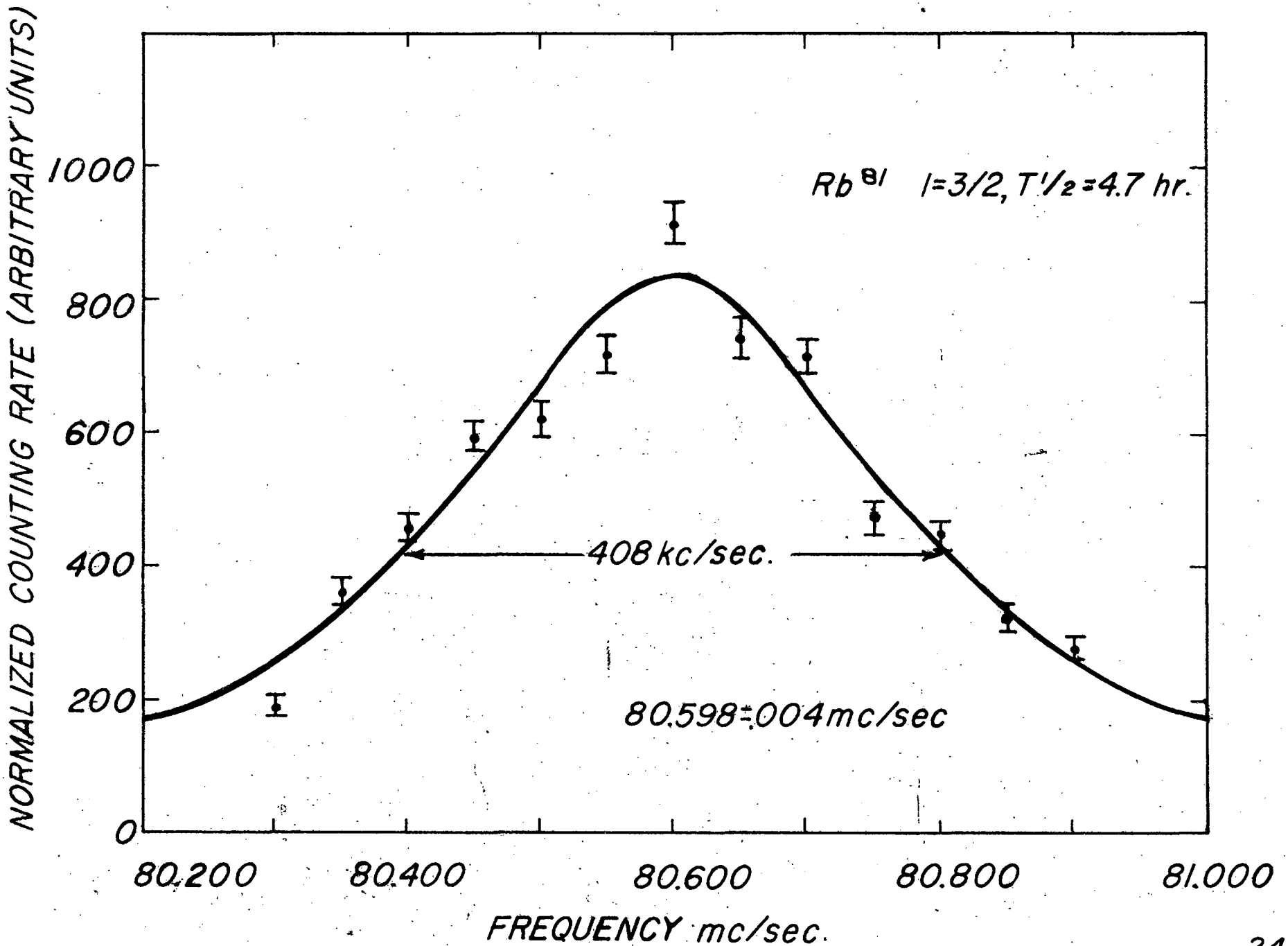
Table II. The weighted average values for the hyperfine-structure separations and the nuclear magnetic moments of Rb^{81}, Rb^{82}, Rb^{83}, and Rb^{84}.

Isotope	Half life	Hyperfine-structure separation (Mc)	Nuclear Magnetic Moment (nuclear magnetons, nm)
Rb^{81}	4.7 h	$\Delta\nu = 5097 \pm 13$	$\mu_I = +2.05 \pm .02$[a]
Rb^{82}	6.3 h	$\Delta\nu = 3094.1 \pm 2.4$	$\mu_I = +1.50 \pm .02$
Rb^{83}	83 d	$\Delta\nu = 3183.3 \pm 5.8$	$\mu_I = +1.42 \pm .02$
Rb^{84}	33 d	$\Delta\nu = 3077.5 \pm 5.1$	$\mu_I = -1.32 \pm .02$

[a]The stated errors are meant to include any diamagnetic shielding corrections and the hyperfine-structure anomolies.

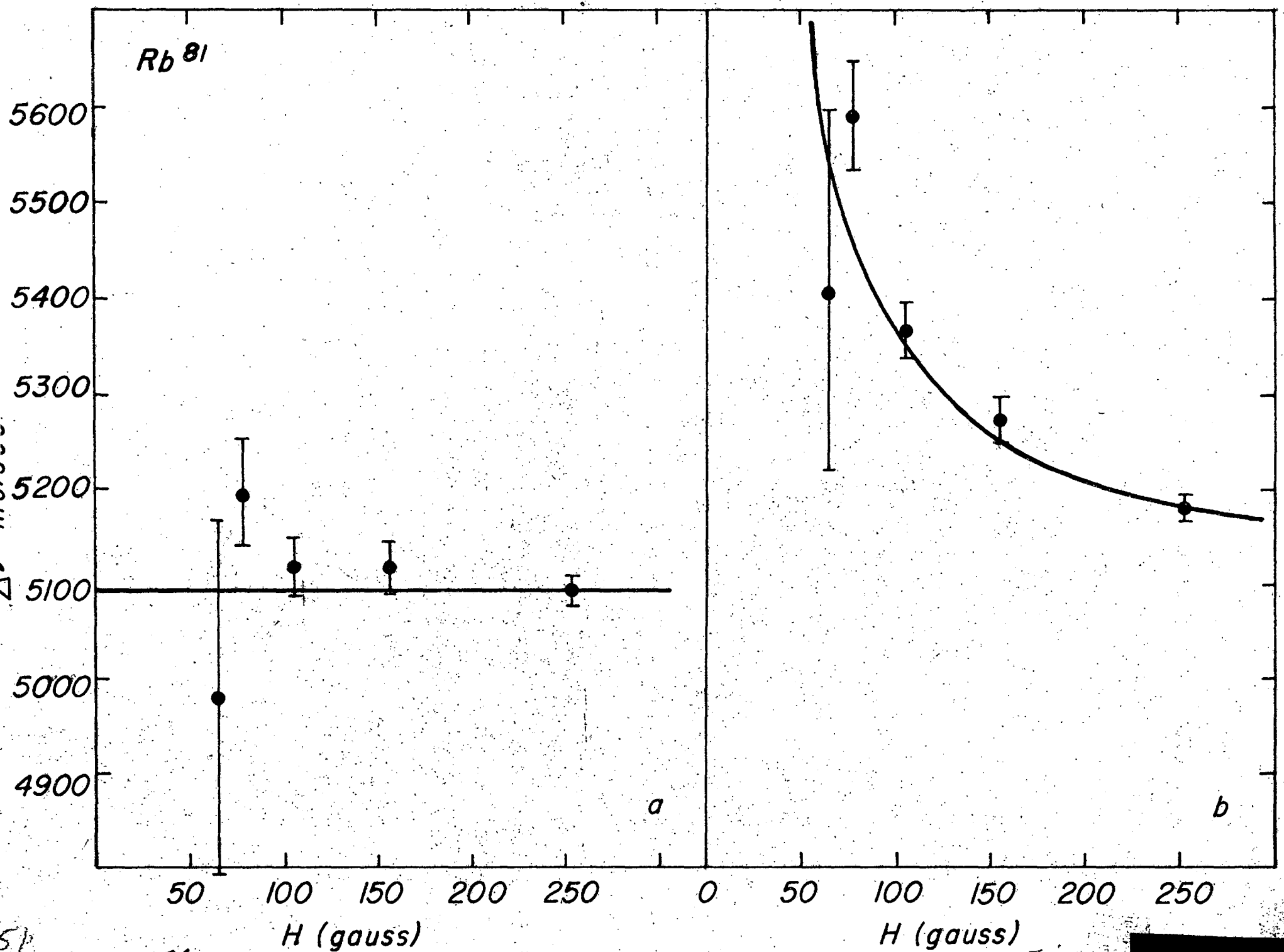
Table III. Comparison of the magnetic moments of Rb^{82} and Rb^{84} with predictions from different shell model configurations. The five $g_{9/2}$ neutrons, $(g_{9/2})^5$, are coupled to an angular momentum of 7/2 as for Se^{79}. Experimental values in making these estimates were derived from $\mu\ Se^{79} = -1.018$ and this is the moment associated with the $(g_{9/2})^5$ subconfiguration; $\mu\ Kr^{83} = -0.969$ and this is the moment associated with the $g_{9/2}$ neutron system; $\bar{\mu}\ p_{3/2} = 2.4$ is obtained from the average of the magnetic moments of Rb^{81} and Rb^{87}. $\bar{\mu} f_{5/2} = 1.4$ is obtained from the average of the magnetic moments of Rb^{83} and Rb^{85}.

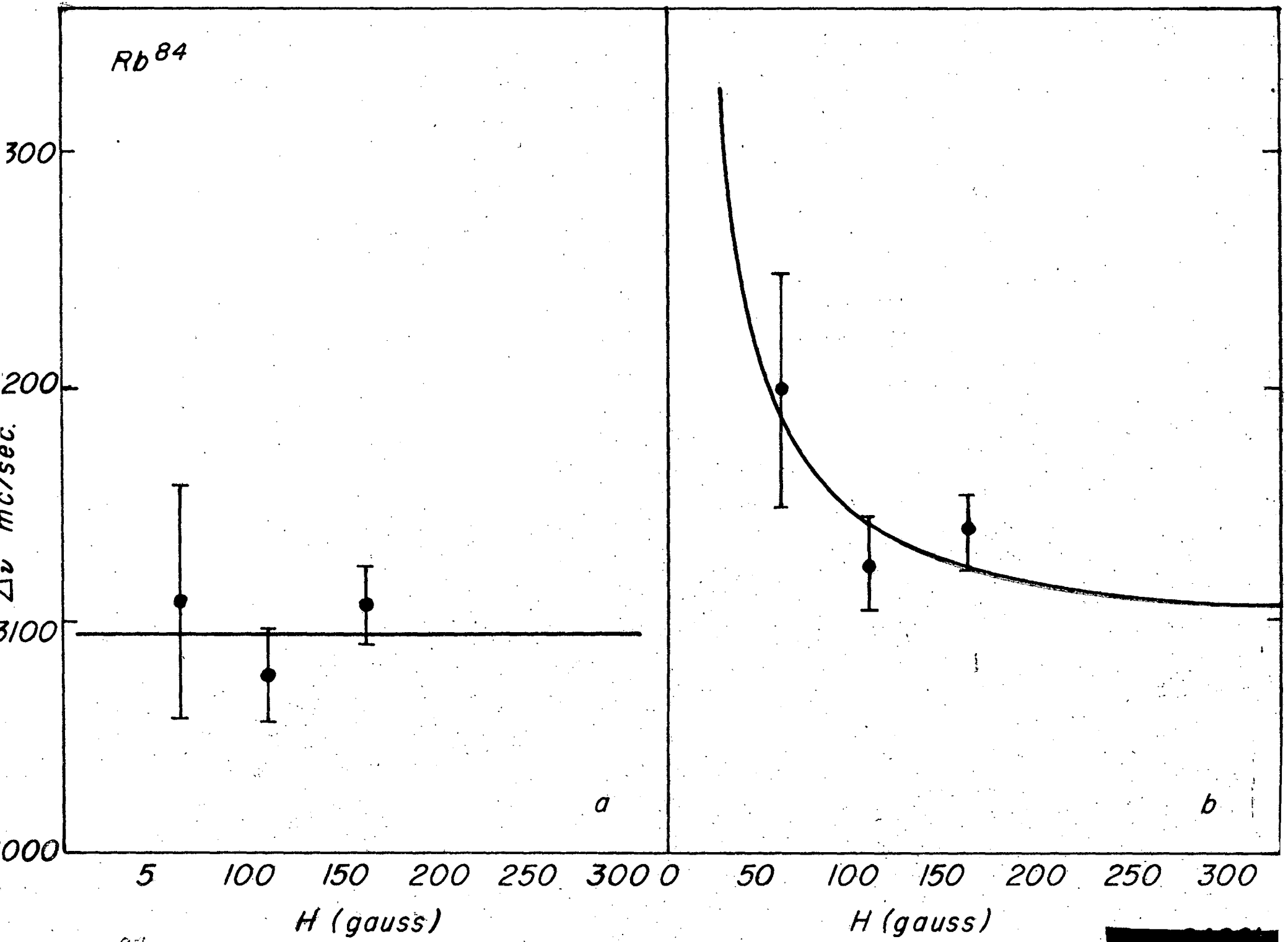
Experimental Values			Calculated magnetic moments for Experimental Spins.		
Isotope	I	μ	$p_{3/2} \cdot g_{9/2}$	$p_{3/2}(g_{9/2})^5$	$f_{5/2} g_{9/2}$
Rb^{82}	5	1.50	0.3	1.4	-.17
Rb^{84}	2	-1.32	----	-2.5	-1.7


NORMALIZED COUNTING RATE (ARBITRARY UNITS)
1000
800
600
400
200
0
Rb 81 I=3/2, T1/2=4.7 hr.
408 kc/sec.
80.598±.004mc/sec
80.200
80.400
80.600
80.800
81.000
FREQUENCY mc/sec.

24859-1

Fig 1


Rb 81
5600
5500
5400
5300
5200
5100
5000
4900
a
b
50
100
150
200
250
0
50
100
150
200
250
H (gauss)
H (gauss)


Rb 84
300
200
3100
000
Δν mc/sec.
5
100
150
200
250
300
H (gauss)
a
0
50
100
150
200
250
300
H (gauss)
b

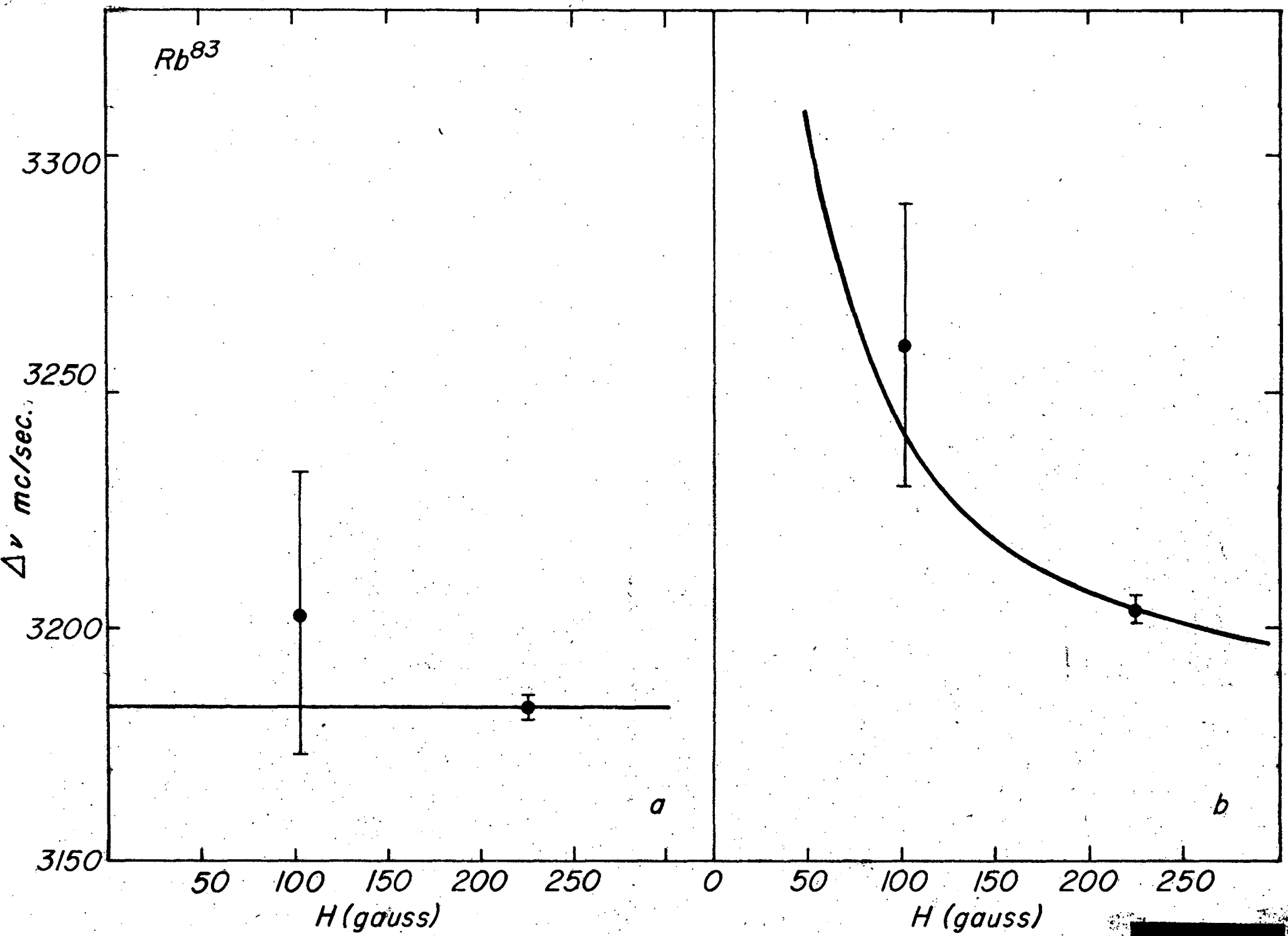


Fig 4

[redacted]

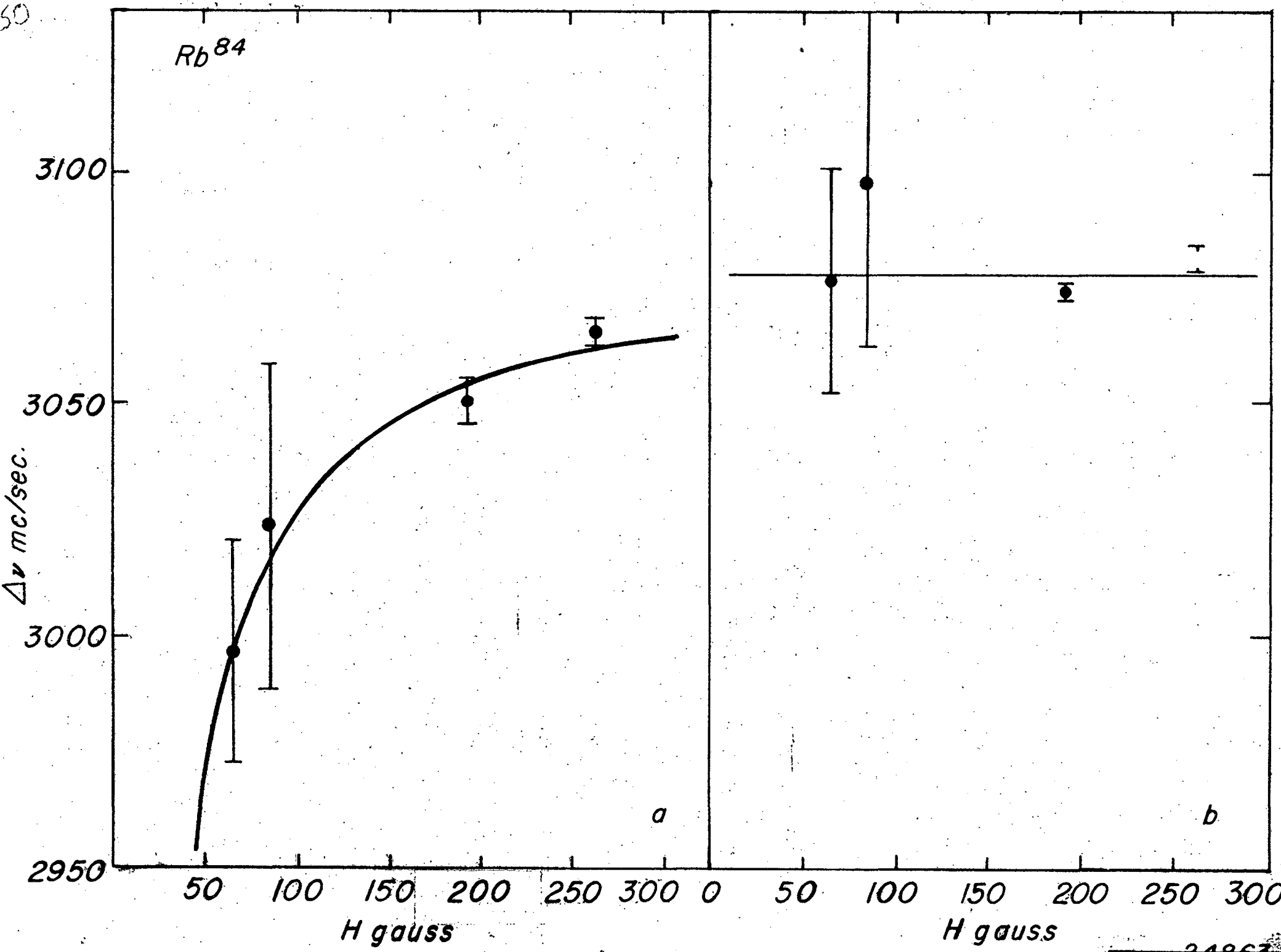

Rb 84
3100
3050
3000
2950
Δν mc/sec.
50
100
150
200
250
300
H gauss
a
0
50
100
150
200
250
300
H gauss
b

FIG-5

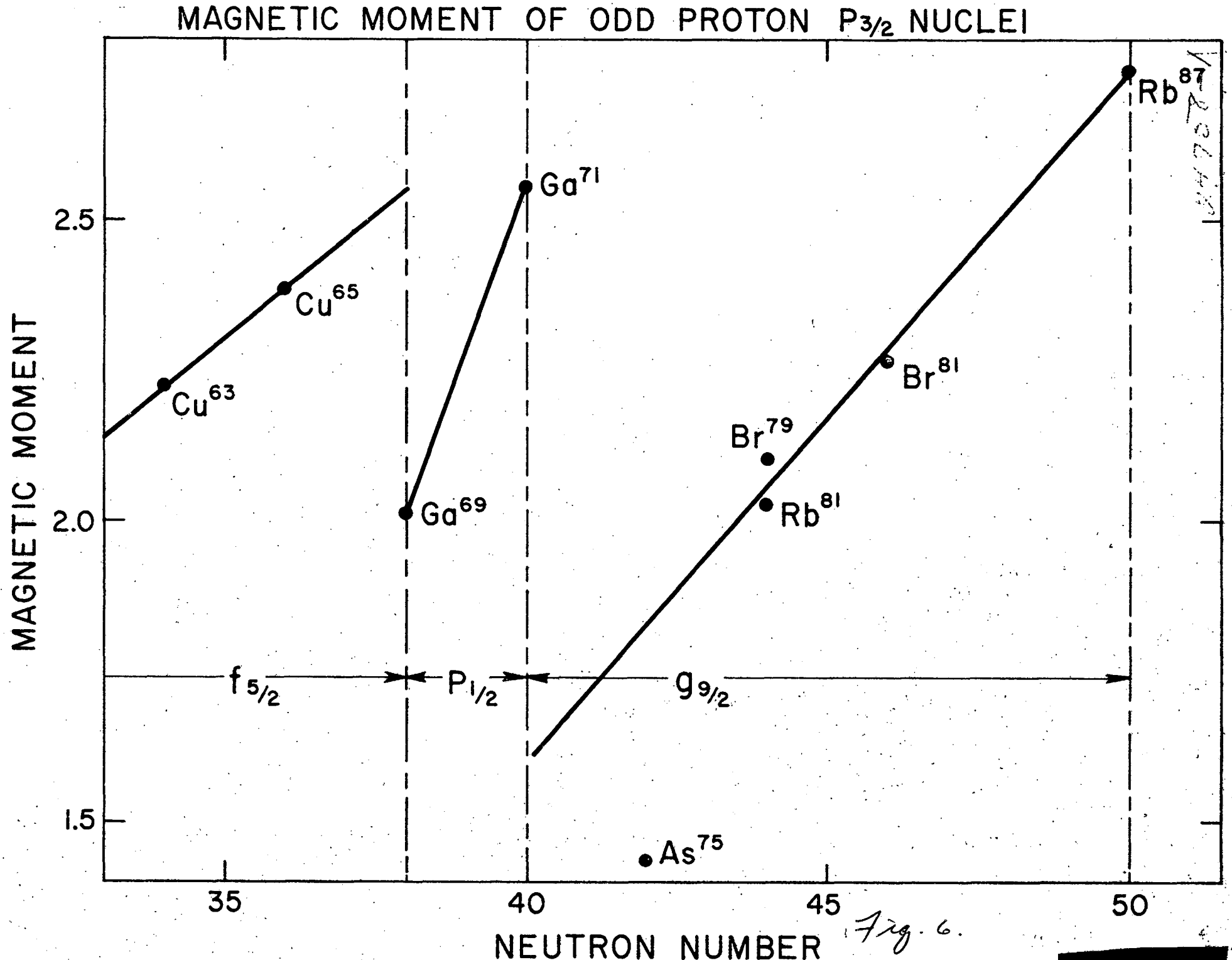


Fig. 6.

[redacted]