quenching cross section of such gases as CO, NO, H_2, or O_2. With these gases, the pressure broadening correction would be negligible since a measurable quenching effect is produced at much lower gas pressures. Moreover, for the gases H_2 and O_2 the difficulty arising from the presence of the band fluorescence would be very much reduced. In these cases the quenching processes do not produce metastable mercury atoms, which are the source of the band fluorescence.

The author wishes to express his thanks to M. A. Biondi, T. Holstein, and A. V. Phelps for many helpful discussions; to A. O. McCoubrey for his aid during the course of the experiment, and to D. Alpert for his active interest and advice.

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

Hyperfine Structures of Silver and Gold by the Atomic Beam Magnetic Resonance Method*

GÜNTER WESSEL† AND HIN LEW
Division of Physics, National Research Council, Ottawa, Canada

(Received July 24, 1953)

An ionizer of the electron bombardment type has been applied to a beam of atoms in a magnetic resonance apparatus. The ionization efficiency for potassium atoms has been found to be 1 part in 3000. The new ionizer has made it possible to study the hyperfine structures and the g factors of the ground states of silver and gold, two elements which cannot be detected by the surface ionization method commonly used heretofore. The measurements yield the following results:

$$\begin{aligned}
|\Delta\nu(\mathrm{Ag}^{107})| &= 1712.56\pm0.04\ \mathrm{Mc/sec},\\
|\Delta\nu(\mathrm{Ag}^{109})| &= 1976.94\pm0.04\ \mathrm{Mc/sec},\\
g_J(\mathrm{Ag})/g_J(\mathrm{Cs}) &= 0.99987\pm0.00010,\\
|\Delta\nu(\mathrm{Au}^{197})| &= 6107.1\pm1.0\ \mathrm{Mc/sec},\\
g_J(\mathrm{Au})/g_J(\mathrm{Cs}) &= 1.00081\pm0.00005.
\end{aligned}$$

I. INTRODUCTION

A SERIOUS limitation to the scope of the molecular or atomic beam method of radio-frequency spectroscopy has been the difficulty of detecting the neutral atoms or molecules after they have passed through the various deflecting fields of the apparatus. Hitherto there have been two main types of detectors in use. They are the Pirani gauge, which can be used for gases only, and the surface ionization detector. The latter consists of a heated filament on which the atoms to be detected impinge. If the ionization potential of the atom is lower than the work function of the filament, or at most slightly higher, the atom has a high probability of being re-emitted as a positive ion. Thus far, aside from the halogens, only atoms with ionization potentials of 6 volts or less have been detected by this technique. In the case of the halogens,[1] negative ions are formed by electron attachment. Other detectors, as for example one which makes use of the radioactivity[2] of radioactive isotopes, are limited in their applicability to special groups of elements. In an attempt to make a detector that would be applicable to all atoms, we have constructed an ionizer which depends on electron bombardment. The design is based on an ion source developed by Heil[3] and applied to mass spectrometry by Paul.[4] Estimates from Paul's work indicated that the efficiency of such an ionizer should be sufficient even for the low intensities usually encountered in atomic beam work where the density of atoms in the beam may be less than that in the vacuum of the apparatus. Our experiments have confirmed these estimates. However, although the ionizer is probably capable of ionizing any atom or molecule, it cannot be claimed that all detection problems in the field of molecular beams have been overcome. Because of the relatively low efficiency (about 1 part in 3000) and because of the inevitable background resulting from the ionization of the residual gases in the vacuum, a strong source of atoms is required at the source end of the resonance apparatus. The source strength needed is such that the ionizer will probably be restricted to atoms which can be obtained in quantities of appreciable fractions of a gram. The exact amount, of course, will depend on the geometry of the apparatus and the complexity of the spectrum.

Tests of the electron bombardment ionizer have been made with the stable isotopes of silver and gold. These elements are particularly suited for the tests because they cannot be detected by the surface ionization

---

* First reported as an abstract in Bull. Am. Phys. Soc. 28, No. 3, 52 (1953).

† National Research Laboratories Postdoctorate Fellow.

[1] Davis, Feld, Zabel, and Zacharias, Phys. Rev. 76, 1076 (1949).

[2] E. H. Bellamy and K. F. Smith, Phil. Mag. 44, 33 (1953).

[3] H. Heil, Z. Physik 120, 212 (1943).

[4] W. Paul, Z. Physik 124, 244 (1948).

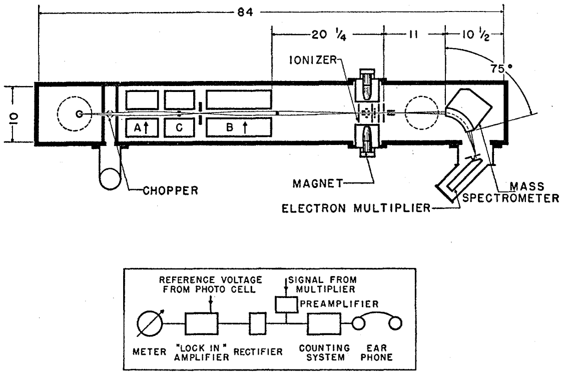

FIG. 1. The atomic beam apparatus (all dimensions in inches) and the amplification system for the electron multiplier signal.

method (ionization potentials 7.57 and 9.22 electron volts, respectively), they are readily available in sufficiently large quantities, and they are relatively easy to vaporize. Furthermore, their ground-state hyperfine structures are simple, consisting of only one interval ($\Delta\nu$) arising from the interaction of a nuclear moment with a $^2S_{\frac{1}{2}}$ electronic state. The $\Delta\nu$'s have, in fact, been determined optically to precisions of a few percent. Brix, Kopfermann, Martin, and Walcher[5] found for the silver isotopes,

$$\Delta\nu(\mathrm{Ag}^{107}) = -(57\pm2)10^{-3}\ \mathrm{cm}^{-1} = -(1710\pm60)\ \mathrm{Mc/sec},$$
$$\Delta\nu(\mathrm{Ag}^{109}) = -(66\pm2)10^{-3}\ \mathrm{cm}^{-1} = -(1980\pm60)\ \mathrm{Mc/sec}.$$

Kelly[6] found for gold

$$\Delta\nu(\mathrm{Au}^{197}) = 0.210\ \mathrm{cm}^{-1} = 6300\ \mathrm{Mc/sec},$$

with an estimated error of 6 percent. Using the Goudsmit-Fermi-Segrè relation, these authors calculated the magnetic dipole moments of the respective nuclei and found

$$\mu(\mathrm{Ag}^{107}) = -0.111\ \mathrm{n.m.},$$
$$\mu(\mathrm{Ag}^{109}) = -0.129\ \mathrm{n.m.},$$
$$\mu(\mathrm{Au}^{197}) = +0.136\ \mathrm{n.m.}$$

In addition to being suitable for tests of the ionizer, the silver isotopes are of interest from the point of view of the hyperfine structure anomaly.[7,8] For this relatively heavy pair of isotopes, it has been estimated that the anomaly may be of the order of 0.5 percent. A precise measurement of the $\Delta\nu$'s will permit a check of the theory when the nuclear g values are precisely known at some future time.[‡]

II. THE EXPERIMENTAL ARRANGEMENT

(a) The Atomic Beam Apparatus

The atomic beam apparatus in which the present experiments were carried out is shown diagrammatically in Fig. 1. Except for the ionizer and its associated components, this apparatus is identical with that used by Lew[9] in the study of praseodymium and already described in conjunction with that work. Associated with the electron bombardment ionizer are a rotating chopper, for interrupting the beam at 10 cycles per second (for reasons given below), and a mass spectrometer system that is behind the ionizer instead of being in front of it. The magnet for the mass spectrometer is a 75° sector with a 1.27-cm gap and a radius of curvature of 12.4 cm. The exciting winding consists of 40 turns of $\frac{3}{16}$-inch outside diameter copper tubing insulated with Teflon tape. The beam chopper consists of a vertical tube with four vertical slots cut in it equally spaced around the circumference. It is driven by an external motor through a shaft which enters the vacuum chamber through a Garlock "Klozure" seal.

The oven for the generation of beams of silver and gold differs from that used for praseodymium only in that graphite is substituted for molybdenum as the material for the heating jacket. A thoria crucible is used to contain the metal as before but is kept from

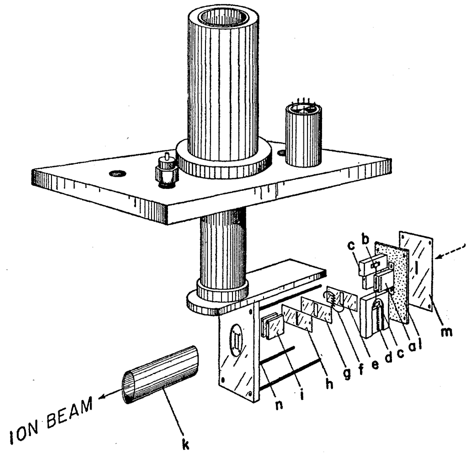

FIG. 2. The electron bombardment ionizer.

---

[5] Brix, Kopfermann, Martin, and Walcher, Z. Physik **130**, 88 (1951). The same lines had been measured previously in absorption by D. A. Jackson and H. Kuhn [Proc. Roy. Soc. (London) **A158**, 372 (1937)] and in emission by Crawford, Schawlow, Gray, and Kelly [Can. J. Research **A28**, 558 (1950)], but the assignment of the hfs components to the isotopes had been either uncertain or in error. It should be pointed out, however, that in the evaluation of the $\Delta\nu$'s, Brix, Kopfermann, Martin, and Walcher used the more precise measurements of Crawford, Schawlow, Gray, and Kelly with the proper assignment.

[6] F. M. Kelley, Proc. Phys. Soc. (London) **A65**, 250 (1952). See also earlier work by R. Ritschl [Naturwiss. **19**, 690 (1931)]; R. M. Elliot and J. Wulff [Phys. Rev. **55**, 170 (1939)]; and L. Sibaiya [Proc. Indian Acad. Sci. **2**, 313 (1935)].

[7] A. Bohr and V. F. Weisskopf, Phys. Rev. **77**, 94 (1950).

[8] A. Bohr, Phys. Rev. **81**, 331 (1951).

[‡] *Note added in proof.*—Recent measurements by C. D. Jeffries and P. B. Sogo using the method of nuclear induction yielded the following results for the nuclear moments of silver: $\mu(\mathrm{Ag}^{107}) = -0.113024\pm0.000013$ n.m., $\mu(\mathrm{Ag}^{109}) = -0.129936\pm0.000013$ n.m. Combining these measurements with the present measurements of $\Delta\nu$ the hfs anomaly turns out to be $\Delta = -(0.416\pm0.008)$ percent. We are indebted to Dr. Jeffries and Dr. Sogo for informing us of their results prior to publication.

[9] H. Lew, Phys. Rev. **91**, 619 (1953).

direct contact with the graphite jacket by means of some tantalum foil.

(b) The Ionizer

Ionization of the atoms in the beam is accomplished by means of electrons oscillating back and forth transversely across the beam. The electrons are guided in their oscillations by a magnetic field of a few hundred gauss directed parallel to the oscillations. An exploded view of the device is shown in Fig. 2. The permanent magnet which supplies the guide field is not shown. The ionizer assembly is mounted on the end of a tubular liquid air trap which extends into the vacuum envelope of the apparatus and the seal is made vacuum tight by means of Apiezon "*Q*" wax. All electrical leads go through the plate.

Ionization of the atoms takes place in the chamber *a* through which the atomic beam passes. This chamber is a rectangular box which is open at both ends and which has a vertical slit in each of the broad faces. Tungsten filaments, measuring 0.005 cm×0.038 cm in cross section, are mounted opposite these slits. One of these filaments *b* is shown stretched between two stainless steel clamps *c*. The lower of these two clamps can slide up and down in a groove. A coil spring *d* attached to the lower clamp keeps the tungsten filament taut. All these parts are mounted on a fired lava piece *l*.

Electrons emitted by the heated tungsten filaments are accelerated into the chamber *a* to an energy of from 30 to 100 electron volts. The total current is usually between 3 and 15 milliamperes. The ions that are formed are pulled out of the ionization region by an electrode *e* and further accelerated by electrodes *g* and *h*. The potential of *e* relative to the chamber *a* is from 0 to 20 volts. The potential of the chamber *a* relative to *h*, which is necessarily at ground potential, depends on the mass of the ion and the strength of the magnetic field in the mass spectrometer magnet. For the silver isotopes it is usually around +1300 volts. The electrode *g* is at some intermediate potential adjusted experimentally for maximum ion intensity. The exit slit in *h* as well as the entrance slit in *m* measures 0.038 cm×1.27 cm. The electrostatic deflecting plates *i* permit the ion beam to be directed more accurately at the mass spectrometer magnet. The copper tube *k* is merely a shield between the ions and the stray fields of lead-in wires.

Located between the electrodes *e* and *g* and at the same potential as *e* is a tungsten grid *f* which can be heated electrically. Its purpose is to serve as a surface ionization detector for the alkalis. Although it intercepts only about 8 percent of the incident beam, its efficiency of ionization for alkali atoms which do strike it is so high (substantially 100 percent) that the net efficiency for alkalis is much higher than that of the electron bombardment ionizer. In fact, on ionizing a beam of potassium atoms first with the tungsten grid and then with electron bombardment ionizer and assuming that the tungsten grid is 100 percent efficient, we have estimated that the electron bombardment ionizer ionizes 1 out of every 3000 K^{39} atoms. In the present experiment, the tungsten grid is used mainly for the detection of the Cs atoms used in the calibration of the *C* field.

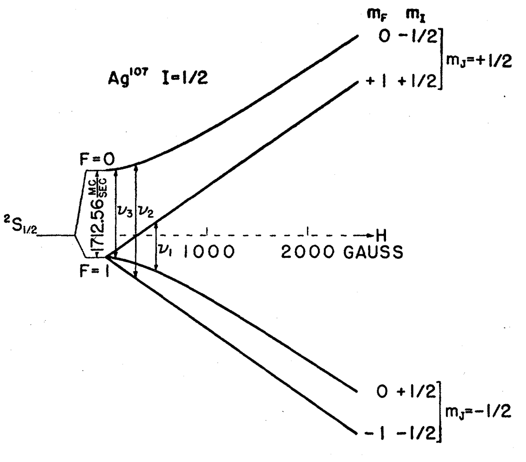

FIG. 3. Energy levels of Ag^{107} in the $5s\,^2S_{\frac{1}{2}}$ state in an external magnetic field.

The entire ionizer assembly is easily demountable for such repairs as the replacement of the filaments. In operation the pole pieces of the external magnet supplying the guide field are adjusted for the best signal-to-noise ratio.

(c) The Electrical System

As shown in the lower part of Fig. 1 the signal from the electron multiplier may be fed either into a conventional counting system with aural monitoring or into a rectifier and a narrow-band 10 cycle/sec amplifier with the final indication given on a meter. The pulse counting system may be used when the background from the ionizer at the mass number under study is small compared with the desired signal. In this case it is not necessary to modulate the atomic beam. In most cases, however, despite the selectivity of the mass spectrometer, the background is so large that the 10-cps system is necessary to improve the signal-to-noise ratio. The background, being unmodulated, does not get through the amplification system. The improvement in signal-to-noise ratio may be as high as a hundred-fold. The narrow-band amplifier employed is of the "lock-in" type[10] which requires a reference signal of the same frequency as the signal under measurement and of constant phase relative to the latter. This reference signal is generated by a photoelectric cell actuated by a modulated light beam. The modulation is accomplished by a rotating disk with sectors cut out and driven by the same motor as that which drives the atomic beam chopper.

---

[10] Amplifier for Golay infrared detector, the Eppley Laboratory, Inc., Newport, Rhode Island.

TABLE I. Observed $\Delta F=\pm 1$ transitions in $\mathrm{Ag}^{107,109}$.

(a) Field-dependent transition ν_1 and ν_2 in Ag (in Mc/sec).

Ag^{107}			Ag^{109}		
ν_1	ν_2	$\nu_2-\nu_1=-\Delta\nu$	ν_1	ν_2	$\nu_2-\nu_1=-\Delta\nu$
4.52	1717.06	1712.54	17.68	1995.01	1977.33
6.84	1719.41	1712.57	21.06	1998.00	1976.94
25.28	1738.05	1712.77	21.31	1998.31	1977.00
			22.83	1999.67	1976.84
			25.58	2002.38	1976.80
			46.38	2023.20	1976.82
			71.40	2048.44	1977.04
Average: 1712.6±0.1			Average: 1976.97±0.10		

(b) Field-independent transition ν_3 in Ag (in Mc/sec).

Ag^{107}			Ag^{109}		
ν_3	ν_1	$-\Delta\nu$	ν_3	ν_1	$-\Delta\nu$
1712.55	4.52	1712.53	1976.92	3.15	1976.91
1712.61	6.84	1712.56	1976.99	4.39	1976.97
1712.75	12.27	1712.57	1976.98	5.98	1976.95
1713.32	25.28	1712.57	1976.99	9.01	1976.91
			1977.03	9.30	1976.95
Average: 1712.56±0.04			Average: 1976.94±0.04		

The electronic instruments of the pulse counting system are of standard commercial manufacture. The frequency generating and measuring instruments are the same as those used by Lew.[9]

III. THE HYPERFINE STRUCTURE OF THE GROUND STATE OF SILVER

The two silver isotopes 107 and 109 both have nuclear spins of $\frac{1}{2}$ and negative magnetic dipole moments.[5] Their ground-state hyperfine structures consist of two levels $F=0$ and $F=1$ with the former lying higher. In the presence of a magnetic field, these levels split up in the manner shown in Fig. 3. Although the figure is drawn to scale for Ag^{107}, it holds very closely for Ag^{109} whose $\Delta\nu$ differs from that of Ag^{107} by only about 15 percent. In each of these isotopes, three transitions,

$$\nu_1(F=1,\ m_F=1\rightarrow F=1,\ m_F=0),$$

$$\nu_2(F=0,\ m_F=0\rightarrow F=1,\ m_F=-1),$$

and

$$\nu_3(F=0,\ m_F=0\rightarrow F=1,\ m_F=0),$$

are observable in the present atomic beam apparatus. The Breit-Rabi formula yields for these transitions the following expressions:

$$\begin{aligned} \nu_1&=g_I\mu_0H-\tfrac{1}{2}\Delta\nu\{(1+x^2)^{\frac{1}{2}}-1-x\},\\ \nu_2&=g_I\mu_0H-\tfrac{1}{2}\Delta\nu\{(1+x^2)^{\frac{1}{2}}+1-x\},\qquad (1)\\ \nu_3&=-\Delta\nu(1+x^2)^{\frac{1}{2}}, \end{aligned}$$

where

$$x=(g_J-g_I)\mu_0H/\Delta\nu. \qquad (2)$$

It is to be noted that in these expressions, because of the inverted order of the hyperfine structure levels, $\Delta\nu$ is a negative quantity. At any given field strength H, a very simple relation exists between ν_1, ν_2, and $\Delta\nu$, namely,

$$\nu_2-\nu_1=-\Delta\nu. \qquad (3)$$

Hence by measuring the frequencies ν_1 and ν_2 at the same field H, the hyperfine structure interval may be obtained by simple subtraction. In Table I(a) are shown some measurements of these two transitions together with their differences. The differences agree to within 1 part in 10 000. The precision of this method of measurement is limited by the width of the lines due to the inhomogeneity of the C field and by the drift of the C field. The transition ν_3, however, is less subject to these limitations because at low fields it is, in first-order approximation, independent of field. Its narrower line and the small correction owing to a finite field permits a more accurate value of $\Delta\nu$ to be found. The small field correction is accomplished by measuring ν_1 at the same time as ν_3.

Measurements of ν_3[11] are shown in Table I(b). The $\Delta\nu$ obtained by means of ν_3 is seen to be more accurate than that obtained by means of ν_1 and ν_2. As final values for the hyperfine structure separations of the ground states of the silver isotopes, we find

$$\Delta\nu(\mathrm{Ag}^{107})=-(1712.56\pm 0.04)\ \mathrm{Mc/sec},$$

$$\Delta\nu(\mathrm{Ag}^{109})=-(1976.94\pm 0.04)\ \mathrm{Mc/sec},$$

where the sign, as previously mentioned, is taken from optical spectroscopy.

A comparison of ν_1 with the low-frequency line ($F=4$, $m_F=-3\rightarrow F=4$, $m_F=-4$) of Cs^{133} at the same field H yields the ratio $g_J(\mathrm{Ag})/g_J(\mathrm{Cs}^{133})$ of the g factors of the ground states of these elements. The low-frequency line of Cs is given by

$$\nu(\mathrm{Cs})=g_I(\mathrm{Cs})\mu_0H+\tfrac{1}{2}\Delta\nu(\mathrm{Cs})\{(1-\tfrac{3}{2}x+x^2)^{\frac{1}{2}}-1+x\}, \qquad (4)$$

where x is defined by Eq. (2) with constants appropriate to Cs^{133}. In this expression and in that for ν_1 given in

TABLE II. $\Delta F=0$ transition in $\mathrm{Ag}^{107,109}$, with "C" field calibration by Cs frequency.

Isotope	ν_1(Mc/sec)	ν(Cs) (Mc/sec)	$g_J(\mathrm{Ag})/g_J(\mathrm{Cs})$
Ag^{107}	575.470	125.685	0.99982
	575.575	125.658	1.00018
	575.800	125.708	1.00017
	848.822	180.761	0.99972
	848.939	180.761	0.99984
	849.066	180.800	0.99974
Ag^{109}	827.309	181.141	0.99989
	827.433	181.187	0.99980
	827.510	181.207	0.99977
	827.609	181.230	0.99978
	827.860	181.270	0.99982
			Average: 0.99987±0.00010

---

[11] The transition ν_3 requires an rf field which is parallel to the steady C field. In the present experiments, the rf loop is so oriented that the resulting rf magnetic field is mainly perpendicular to the C field with only a weak component parallel to the field. The observed ν_3 transitions are therefore much weaker than ν_1 or ν_2 but adequate for accurate measurements.

Eq. (1), the g_J's appear, of course, through the x's. Since the ratio of the g_J's cannot be obtained in explicit form from Eqs. (1) and (4), it is arrived at by successive approximations. Of the various terms appearing in these expressions, those involving the nuclear g factors g_I, of the respective atoms are of the order of a thousandth of the other terms. Hence, although the g_I of the silver isotopes are known only to 3 percent from optical spectroscopy,[12] the resulting uncertainty in the calculated g_J is less than the uncertainties in the measurements. The constants used in the calculation of g_J are, then, for Ag

$$g_I(\text{Ag}^{107}) = +0.000121, \quad g_I(\text{Ag}^{109}) = +0.000141;$$

and, for Cs (Lyons,[13] Kusch and Taub[14]),

$$\Delta\nu(\text{Cs}^{133}) = 9192.632 \pm 0.002 \text{ Mc/sec},$$
$$g_I(\text{Cs}^{133}) = -0.0003991.$$

In Table II are shown the silver transitions ν_1 with the corresponding cesium transitions at the same field. The calculated ratio of the g_J's is shown in the last column. Within the accuracy of the measurements, this ratio is the same for the two isotopes. This is also to be expected on theoretical grounds. The average of all the measurements is

$$g_J(\text{Ag})/g_J(\text{Cs}^{133}) = 0.99987 \pm 0.00010.$$

From the work of various authors,[15] it has been found that the g_J of Cs is

$$g_J(\text{Cs}) = 2(1.00125 \pm 0.00003).$$

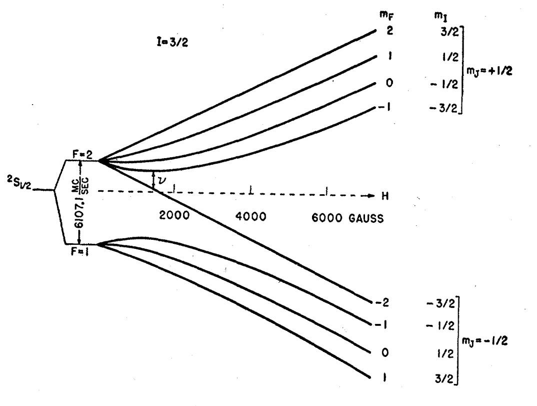

FIG. 4. Energy levels of Au^{197} in the $6s\,{}^2S_{\frac{1}{2}}$ state in an external magnetic field.

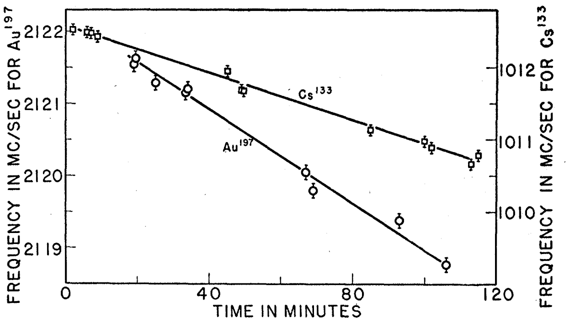

FIG. 5. Observed "low frequency" transitions in Au^{197} and Cs^{133} as function of time, "C" field drifting.

Hence,

$$g_J(\text{Ag}) = 2(1.00112 \pm 0.00010).$$

To within the stated precision, this agrees with the anomalous gyromagnetic ratio of the free electron [2(1.001146±0.000012)]. The low precision of the measurements arises mainly from the width of the lines and the drift of the C field.

IV. THE HYPERFINE STRUCTURE OF THE GROUND STATE OF Au^{197}

With a nuclear spin $I=\frac{3}{2}$ and a ${}^2S_{\frac{1}{2}}$ electronic ground state, the hyperfine structure of Au^{197} in a magnetic field is as shown in Fig. 4. Only the low-frequency line ($F=2$, $m_F=-1 \rightarrow F=2$, $m_F=-2$) has been measured in the present experiments and the zero-field separation $\Delta\nu$ calculated by means of the Breit-Rabi formula. A direct measurement of a transition between $F=2$ and $F=1$ was not done because oscillators in the region of 6000 Mc/sec were not on hand. The low-frequency line is given by the expression

$$\nu = g_I \mu_0 H + \tfrac{1}{2}\Delta\nu\{(1-x+x^2)^{\frac{1}{2}} - 1 + x\}, \tag{5}$$

where x is defined by Eq. (2) with constants appropriate to Au. As in the case of silver, the optical value of g_I of gold may be used here. According to Kelly's[6] value of the nuclear magnetic dipole moment of gold, we have

$$g_I(\text{Au}) = -0.0000494.$$

Using the low-frequency transition of Cs^{133} [Eq. (4)] to eliminate H for any given value of H there remain two unknowns in Eq. (5), namely $\Delta\nu$ and $g_J(\text{Au})/g_J(\text{Cs})$. For any given measurement of ν, an arbitrary value may be assigned to either of these two unknowns and the other one calculated. However, since the relation between $\Delta\nu$ and the ratio of the g_J's varies with H, only for one pair of values, the correct pair, will the equation be satisfied for different magnetic fields.

When a series of measurements is taken over a period of several hours in the present experiments, no attempt is made to keep the C field constant, but it is allowed to drift. The time of making each observation is noted and the results plotted against a time scale. A typical run taken at a field of about 1705 gauss is shown in Fig. 5

---

[12] The uncertainty of 6 percent in the magnetic moments of silver stated by Brix, Kopfermann, Martin, and Walcher (reference 5) includes a 3 percent uncertainty in their $\Delta\nu$'s. The present work has shown, however, that the latter are accurate to better than 0.2 percent, and hence the only uncertainty in the magnetic moments arises from the application of the Goudsmit-Fermi-Segrè formula. This uncertainty has been estimated by the aforementioned authors to be at most 3 percent.

[13] H. Lyons, Ann. N. Y. Acad. Sci. **55**, 831 (1952).

[14] P. Kusch and H. Taub, Phys. Rev. **75**, 1477 (1949).

[15] The exact manner in which $g_J(\text{Cs})$ has been deduced is given in Brix, Eisinger, Lew, and Wessel (following paper), Phys. Rev. **92**, 647 (1953).

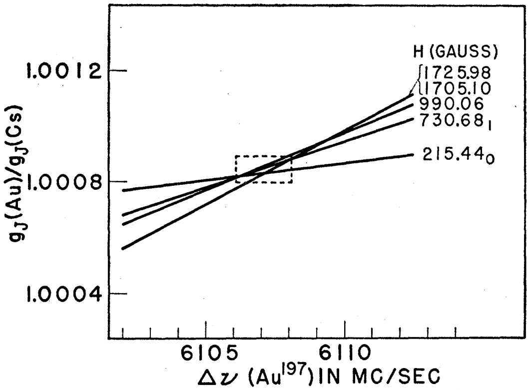

FIG. 6. g_J(Au)/g_J(Cs) as function of $\Delta\nu$(Au^{197}), evaluated from the Breit-Rabi formula using sets of observed values ν(Au) and ν(Cs) at various field strengths H.

where the gold transition frequencies are shown on the left and those of Cs on the right. Any pair of values corresponding to the same time may be used in Eq. (5) for the calculation of $\Delta\nu$ and g_J(Au)/g_J(Cs). Since one of these may be chosen of arbitrary value, and the other calculated, a range of reasonable values has been chosen for g_J(Au)/g_J(Cs) and the $\Delta\nu$ calculated. The pairs of values so obtained are plotted against each other in the manner shown in Fig. 6. The different straight lines correspond to measurements at different field settings. These should all intersect at one point. The dotted rectangle gives the estimated point of intersection and probable error. The values of $\Delta\nu$ and g_J(Au)/g_J(Cs) found are

$$\Delta\nu(\mathrm{Au}) = 6107.1 \pm 1.0 \text{ Mc/sec},$$

$$g_J(\mathrm{Au})/g_J(\mathrm{Cs}) = 1.00081 \pm 0.00005.$$

If again we take $g_J(\mathrm{Cs}) = 2(1.00125)$, we get

$$g_J(\mathrm{Au}) = 2(1.00206 \pm 0.00006).$$

This is larger than the gyromagnetic ratio of the free electron by 1 part in 10^3. It is of interest to note that a similar, though smaller, excess has been observed in the case of the $^2S_{\frac{1}{2}}$ ground states of Rb and Cs by Kusch and Taub.[14]

V. THE NUCLEAR MAGNETIC DIPOLE MOMENTS

The present measurements are not sufficiently accurate to permit the extraction of an accurate value of g_I directly from the Breit-Rabi formula and the observations. It is possible, however, to obtain approximate values of g_I from the observed hfs separation by means of the Goudsmit-Fermi-Segrè formula. This has been done for silver by Brix, Kopfermann, Martin, and Walcher[5] and for gold by Kelly,[6] with spectroscopic values of the hfs separations being used in both cases. In the case of silver, the present work has shown that the errors in the spectroscopic values of the hfs separations are less than 0.2 percent. Since this is much less than the uncertainties in the application of the Goudsmit-Fermi-Segrè formula, no change in the values of the nuclear moments of silver from the spectroscopic values is warranted. They remain as previously quoted

$$\mu(\mathrm{Ag}^{107}) = -0.111 \text{ nm}, \quad \mu(\mathrm{Ag}^{109}) = -0.129 \text{ nm}.$$

In the case of gold, however, the value of the hfs separation used by Kelly is 3.2 percent higher than our more accurate value. Adjusting his value of $\mu = 0.136$ n.m. to take this error into account, we find $\mu = 0.132$ n.m.

A large source of uncertainty in the application of the Goudsmit-Fermi-Segrè formula lies in the evaluation of the Fermi-Segrè factor $1 - d\sigma/dn$, where σ is the quantum defect and n the principal quantum number. It has been pointed out by von Siemens[16] that, for the $6s\ ^2S_{\frac{1}{2}}$ ground state of Au, the value of $1 - d\sigma/dn$ is sensitive to the assumed functional relationship between σ and the term value T. The relationship assumed by Kelly, following Crawford and Schawlow,[17] is $\sigma = \alpha + \beta T$, and the value found for the Fermi-Segrè factor is 1.424. Von Siemens, assuming $\sigma = \alpha_0 + \alpha_1 T + \alpha_2 T^2$, finds for this factor the value 1.481. With the present value of $\Delta\nu$, the calculated magnetic moment then becomes 0.127 n.m. Spectroscopic work[6,16] on the $5d^{10}7s\ ^2S_{\frac{1}{2}}$ and the $5d^9 6s^2\ ^2D_{\frac{5}{2}}$ states of Au yields values of 0.135 ± 0.003 and 0.14 ± 0.02 n.m., respectively, for the magnetic moment. For the $^2S_{\frac{1}{2}}$ terms, in addition to the uncertainty in $d\sigma/dn$, there exists an uncertainty in the Bohr-Weisskopf correction[7] which is much larger in the case of Au (about 10 percent) than in the case of Ag (about 1 percent). In view of these considerations, it is felt that the best value of the magnetic moment of Au that can be given at present is

$$\mu = 0.13 \pm 0.01 \text{ n.m.}$$

The authors wish to thank Dr. P. Brix and Dr. J. T. Eisinger for helpful discussions.

---

[16] W. von Siemens, dissertation, Göttingen, 1952 (unpublished).

[17] M. F. Crawford and A. L. Schawlow, Phys. Rev. 76, 1310 (1949).