IV. NUCLEAR MAGNETIC RESONANCE AND HYPERFINE STRUCTURE

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A. LEVEL CROSSINGS IN MERCURY 195* (40 hour) AND MERCURY 193* (11 hour)

New precision measurements of the hyperfine-structure interaction constants in radioactive mercury isotopes by optical detection of Zeeman level crossings[1] have been made. The magnetic fields at which the various crossings were observed are shown in Table IV-1, in terms of measured proton resonance frequencies. These values are still preliminary, since the analysis of systematic errors has not been completed. From the data in Table IV-1, the best values of the magnetic dipole interaction constants (A) and the electric quadrupole interaction constants (B) in the $6s6p\,^3P_1$ state are obtained (Table IV-2). The calculations were carried out on the IBM 7090 computer at the Computation Center, M.I.T., by using the program HYPERFINE 3-9.[2]

The ratio of the previously measured[1] interaction constants for Hg^{195} (9.5 hour) and Hg^{199} (both nuclear spin 1/2) has been calculated to be

$$\frac{A_{195}\left(^3P_1\right)}{A_{199}\left(^3P_1\right)} = \frac{f_p(195)}{f_p(199)} = 1.071925(63).$$

Combining this ratio with the recent direct measurement of the magnetic-moment ratio for these isotopes by Walter and Stavn,[3] we obtain a preliminary value for the Bohr-Weisskopf hyperfine-structure anomaly:

$$\Delta = 0.1466(85) \text{ per cent.}$$

This value for the anomaly will be refined by introducing single-electron interaction constants and second-order corrections to the energy levels, before comparing it with the value obtained from nuclear theory.[4]

The apparatus used in these experiments is shown schematically in Fig. IV-1, and the system assembly is shown in the photograph of Fig. IV-2. It is similar to that used by Hirsch.[5] Light from an electrodeless air-cooled Hg^{198} lamp (inside the scanning magnet) passes through a collimating lens and a quarter-wave plate-polarizer combination (which passes only one component of the Zeeman triplet when the light emerges parallel to the scanning field[6]) to a cell containing the vapor of the radioactive isotope

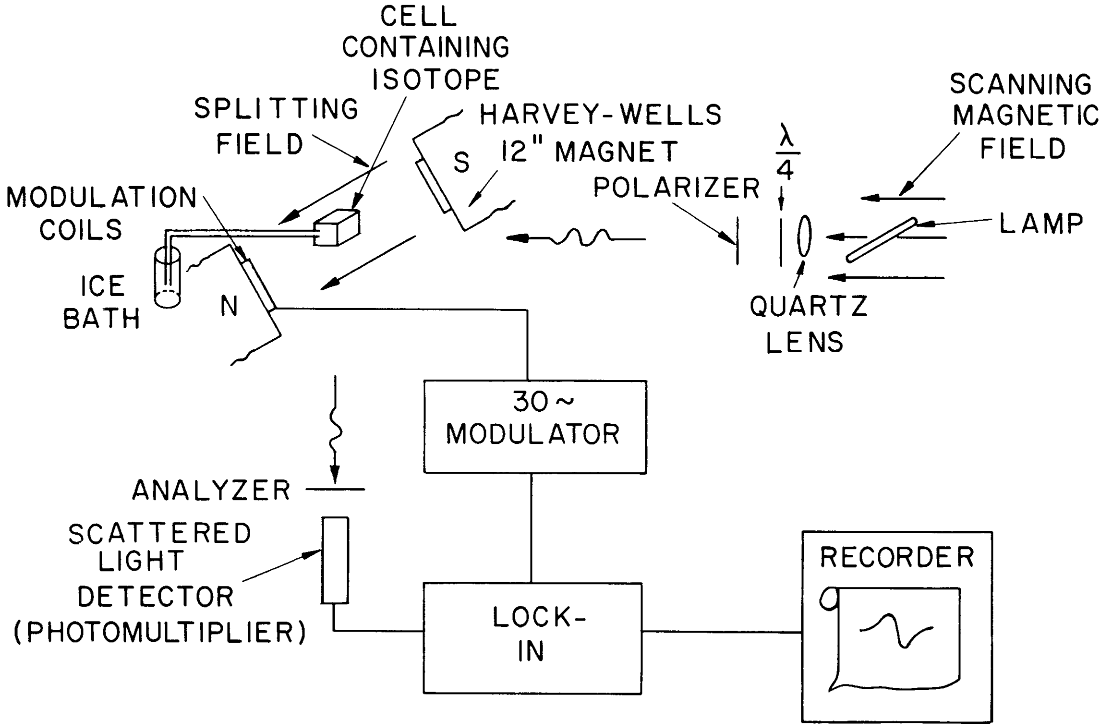

Fig. IV-1. Experimental arrangement for level-crossing work.

that is to be studied. The cell is in the gap of a Harvey-Wells 12-inch magnet of high homogeneity. The 2537 Å resonance radiation scattered from the vapor in the cell is monitored by a 1P28 photomultiplier and recorded as the "splitting field" of the Harvey-Wells magnet is slowly varied. There is a coherent contribution to the scattering from two Zeeman sublevels when they cross (become degenerate), at a particular value of the applied magnetic field, which changes the angular distribution of the scattered light. The resulting intensity resonance in the light scattered at 90° (a Lorentzian line of 1-10 gauss width) permits measurement of the crossing field to high accuracy (Table IV-1). Field modulation and phase-sensitive detection are used to increase sensitivity.

Field modulation was necessary in order to observe the second and third crossings in Hg^{195*}, since the intensity change at the crossings was less than 0.1 per cent. Although three attempts have been made, the corresponding crossings in Hg^{193*} have not been observed thus far, probably because of the presence of noise from other mercury isotopes in the cell.

In preparing for the Hg^{193*} experiment and in order to track down systematic errors in the Hg^{195} and Hg^{195*} measurements, a better way of measuring the magnetic field at a level crossing was worked out. At Professor Bitter's suggestion, the radioactive

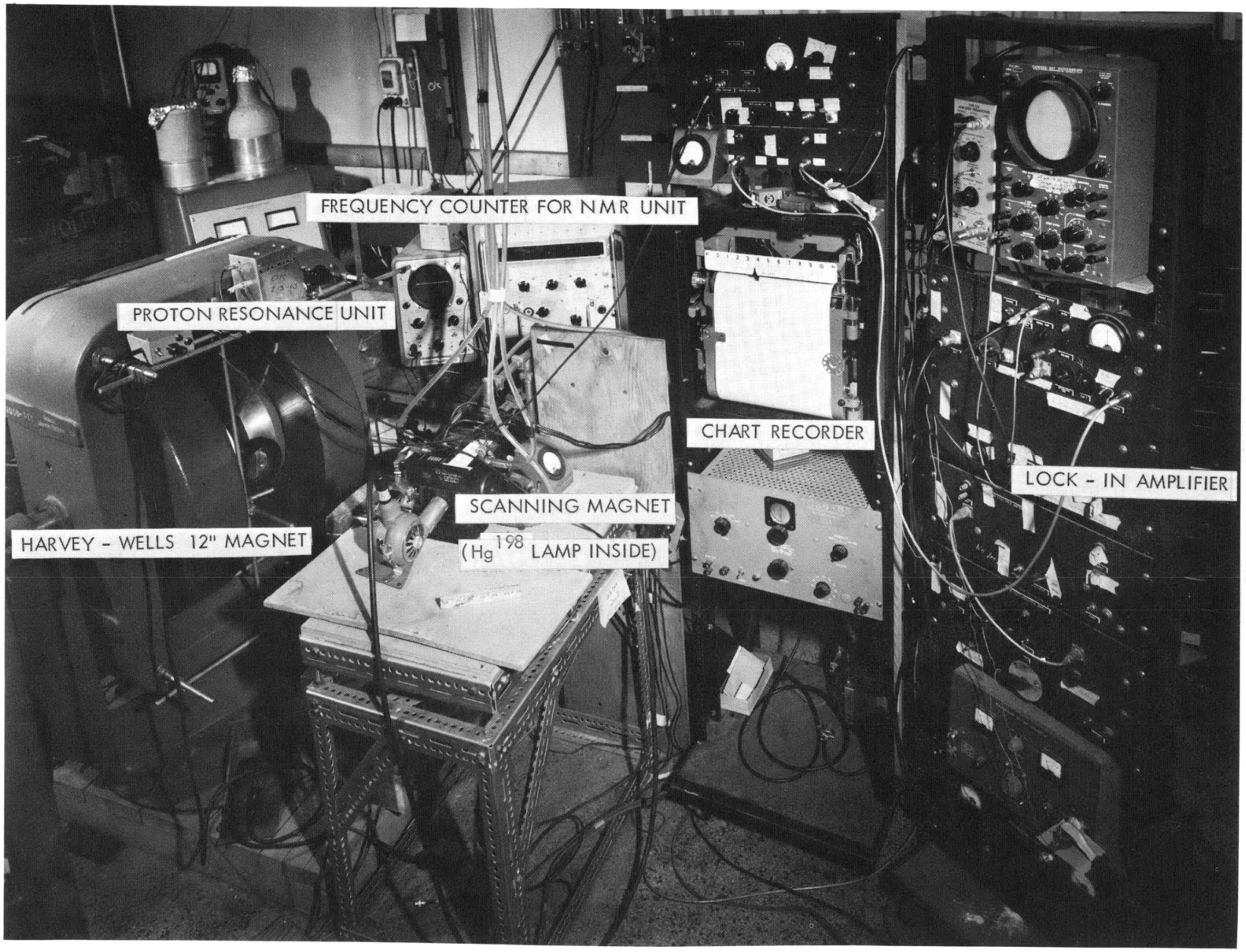

Fig. IV-2. The level-crossing apparatus.

Table IV-1. Proton resonance frequencies for level crossings. (Cell-to-probe correction, +1:25400, included in Hg^{195} and Hg^{195*} data.)

Isotope	Crossing	Frequency
Hg^{195}	$F = \frac{3}{2}, m = -\frac{3}{2}$ $F = \frac{1}{2}, m = +\frac{1}{2}$	32371.3 ± 1.2 kc
Hg^{195*}	$F = \frac{15}{2}, m = \frac{15}{2}$ $F = \frac{13}{2}, m = \frac{11}{2}$	33928.1 ± 1.9
	$F = \frac{13}{2}, m = \frac{11}{2}$ $F = \frac{13}{2}, m = \frac{7}{2}$	32684.1 ± 2.7
	$F = \frac{13}{2}, m = \frac{9}{2}$ $F = \frac{13}{2}, m = \frac{5}{2}$	31580.7 ± 21.0
(Hg^{199}	$F = \frac{3}{2}, m = -\frac{3}{2}$ $F = \frac{1}{2}, m = +\frac{1}{2}$	30199.2 ± .8)
Hg^{193*}	$F = \frac{15}{2}, m = \frac{15}{2}$ $F = \frac{13}{2}, m = \frac{11}{2}$	34380.5 ± 2.0

Errors are 3σ

Table IV-2. Values of the hyperfine interaction constants.

Quantity	Spectroscopic Results[a]	Present Work
$A_{195}(^3P_1)$	15838 ± 130 mc	15813.4 ± .4 mc
$A_{195*}(^3P_1)$	-2367 ± 7	-2368.3 ± .1
$B_{195*}(^3P_1)$	-794 ± 90	-788.0 ± 2.7
$\dfrac{A_{195}(^3P_1)}{A_{199}(^3P_1)} \approx \dfrac{f_p(195)}{f_p(199)}$		1.071925 ± .000063
A_{193*}	-2398 ± 18	-2400.1 ± 1.0[b]

[a] W. J. Tomlinson III and H. H. Stroke, see Section IV-B and Quarterly Progress Report No. 66, Research Laboratory of Electronics, M.I.T., July 15, 1962, p. 18.

[b] Preliminary value: it is assumed that B is nearly the same as for Hg^{195*}.

cell was positioned slightly away from the center of the magnet gap, in the median plane between the cylindrical pole pieces. The proton resonance probe that measures the field was then placed in a symmetrical position on the opposite side of the gap center from the cell (see Fig. IV-3). The magnet homogeneity was sufficient so that this had little effect on linewidths, but the field difference between the cell and probe was considerably reduced. The residual correction (approximately 0.075 gauss) was less than the linewidth of the proton resonance signal. We found that it is possible to estimate this residual correction by observation of a beat pattern in the envelope of the magnetic-resonance side-wiggles; this pattern appeared when two proton resonance probes were connected in parallel and placed in the cell and in the probe positions. The probe at the cell position sees a slightly different field from the second probe. The beat pattern arises from the difference between the Larmor precession frequencies for the two samples. It is rendered visible on an oscilloscope with a calibrated time base. This beat effect, which I discovered independently, was, to my knowledge, first observed by R. Gabillard.[7]

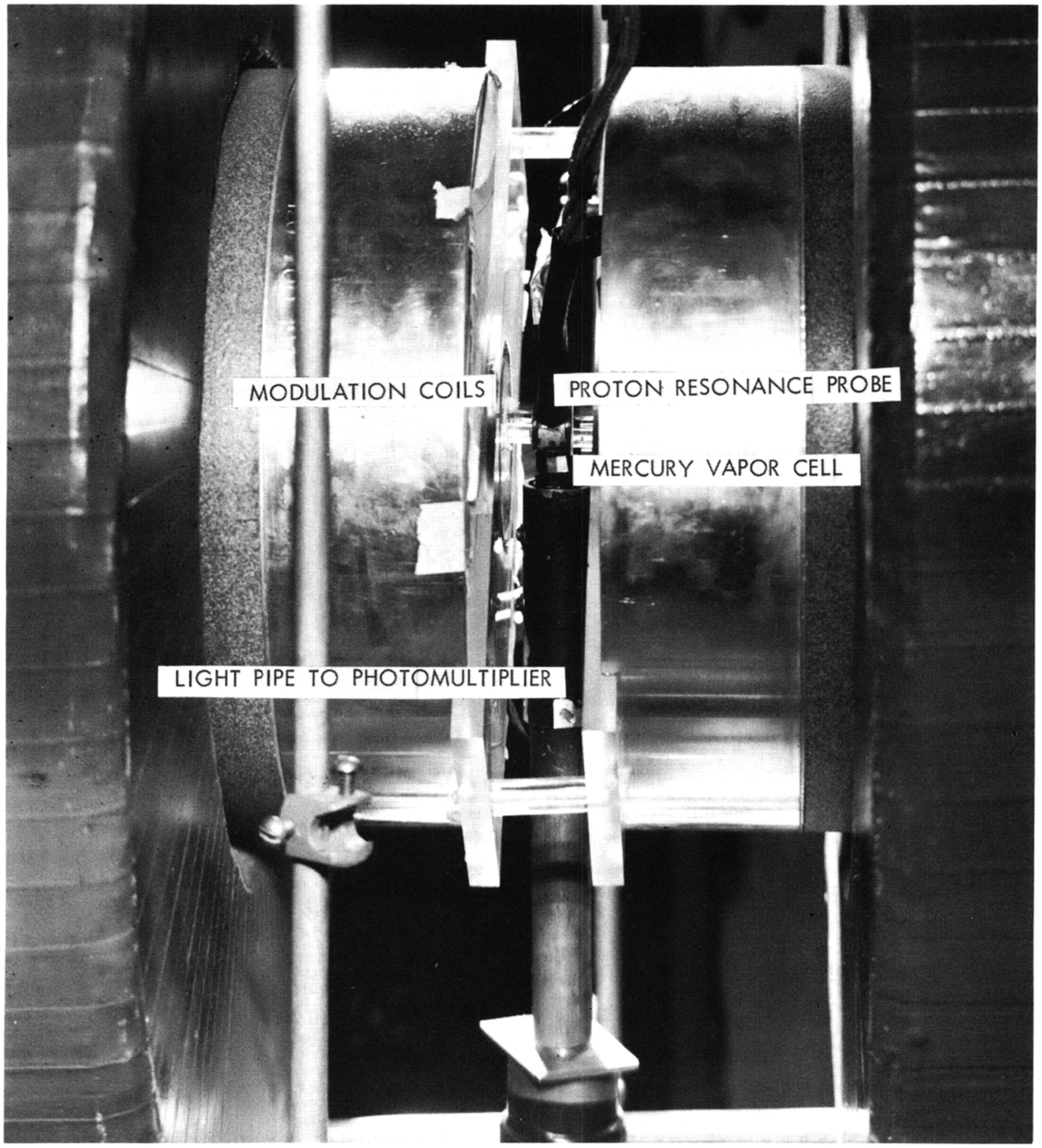

Fig. IV-3. Close-up of magnet gap showing modulation coils, cell, and probe in position.

The position of the level crossing in Hg^{199} was remeasured with the cell and probe in symmetrical positions as a calibration. The results agree quite well with the very precise measurements of Kaul.[8]

A preliminary report of this work was presented at the American Physical Society 1963 Annual Meeting, in New York.[9] A final report will be submitted as a thesis to the Department of Physics, M. I. T., in partial fulfillment of the requirements for the degree of Doctor of Philosophy. We are grateful to A. Koehler and the Cyclotron Group, Harvard University, for the bombardments.

W. W. Smith

References

1. W. W. Smith, Level crossings in mercury 195 and mercury 195^*, Quarterly Progress Report No. 67, Research Laboratory of Electronics, M. I. T., October 15, 1962, pp. 28-29.
2. Obtained from Professor H. Shugart, Lawrence Radiation Laboratory, University of California, Berkeley, 1962.
3. M. J. Stavn, S. B. Thesis, Department of Physics, M. I. T., June 1963.
4. H. H. Stroke, R. J. Blin-Stoyle, and V. Jaccarino, Phys. Rev. 123, 1326-1348 (1961).
5. H. R. Hirsch, Ph.D. Thesis, Department of Physics, M. I. T., September 1960.
6. W. W. Smith, A compact magneto-optic scanning apparatus, Quarterly Progress Report No. 63, Research Laboratory of Electronics, M. I. T., October 15, 1961, pp. 83-85.
7. P. Girivet, La Résonance Paramagnétique Nucléaire (Centre National de la Recherche Scientifique, Paris, 1955), pp. 145-146.
8. R. D. Kaul, Ph.D. Thesis, Department of Physics, Case Institute of Technology, Cleveland, Ohio, 1963.
9. W. W. Smith, Bull. Am. Phys. Soc. 8, 9 (1963).

B. HYPERFINE STRUCTURE AND ISOTOPE SHIFT IN Hg^{193}, Hg^{193m}, AND Hg^{192}

The experimental work in our investigation of the hyperfine structure and isotope shift of the neutron-deficient mercury isotopes has been completed. Analysis of the results of the last few runs is still in progress, but we have obtained the following preliminary results:

Hg^{193} $I = \frac{1}{2}$

$$A\left({}^3S_1\right) \approx (800\pm30)\ \text{mK}$$

Hg^{193m} $I = \frac{13}{2}$

Hg^{193m} $A\left({}^3P_1\right) = (-80.0 \pm .6)$ mK

$B\left({}^3P_1\right) = (-23 \pm 15)$ mK

$A\left({}^3S_1\right) = (-116.5 \pm 1.0)$ mK

Isotope shifts relative to Hg^{196} (2537 Å line)

$Hg^{193} = (180 \pm 30)$ mK

$Hg^{193m} = (240 \pm 15)$ mK

$Hg^{192} = (315 \pm 30)$ mK

For Hg^{193m}, the A value for the ${}^3P_1$ state is in fairly good agreement with the results of Davis, Kleiman, and Aung,[1] and with those of W. W. Smith (see Section IV-A), but the B value is considerably different from that of Davis and his co-workers. The Hg^{193m} isotope shift is also in fairly good agreement with their values.[1] The data for Hg^{193} and Hg^{192} are not as accurate as those for Hg^{193m}, but the results tend to support our hypothesis concerning the causes of odd-even staggering in isotope shift.[2]

W. J. Tomlinson III, H. H. Stroke

References

1. S. P. Davis, H. Kleiman, and T. Aung, J. Opt. Soc. Am. 53, 506A (1963).
2. W. J. Tomlinson and H. H. Stroke, Phys. Rev. Letters 8, 436 (1962).

C. ERRATUM

In Quarterly Progress Report No. 68 (page 21), in the report entitled "Hyperfine Structure and Isotope Shifts in Neutron-Deficient Mercury Isotopes," the first sentence of the last paragraph should read:

"We have also obtained a corrected value for the Hg^{194}-Hg^{198} isotope shift in the 2537 Å line (0.280 ± .015) cm^{-1}."

W. J. Tomlinson III, H. H. Stroke

D. THE MAGNETIC MOMENT OF MERCURY 195 BY MEANS OF OPTICAL PUMPING

Optical pumping enables the techniques of nuclear magnetic resonance to be applied to dilute gases and vapors. The possibility of applying this technique to the measurement of magnetic moments of radioactive nuclei was first demonstrated with Hg^{197} (65 hours) in our laboratory.[1] Orientation of a second radioactive mercury isotope, Hg^{195} (9.5 hours), by optical pumping has now been achieved.

A single quartz cell was filled with the stable isotope Hg^{199} ($I = 1/2$) and the 9.5 h radio isotope Hg^{195}. Nuclear magnetic resonance in the oriented vapor of each isotope was optically detected in the light scattered from the cell.

Resonances, 30-50 cps wide, were observed at 726 kc and 678 kc. The measured ratio $\mu_{195}/\mu_{199} = 1.070356(66)$. Using Cagnac's Hg^{199} result,[2] we obtain $\mu_{195} = 0.190813(12)\ \mu_H$, and $\mu_{195} = 0.532892(33)$ nuclear magnetons without diamagnetic correction. The errors quoted are three times the standard deviations. Complete details of this experiment are reported in a Bachelor's thesis submitted by Melvin J. Stavn to the Department of Physics, M.I.T., May 17, 1963.

W. T. Walter, M. J. Stavn

References

1. W. T. Walter, Ph.D. Thesis, Department of Physics, M.I.T., 1962; Quarterly Progress Report No. 65, Research Laboratory of Electronics, M.I.T., April 15, 1962, p. 39.

2. B. Cagnac, Ann. phys. 6, 467 (1961).