Nuclear Moments and Isotope Shifts of Tl^{199}, Tl^{200}, Tl^{201}, Tl^{202}, and Tl^{204}—Isotope Shifts in Odd-Odd Nuclei*

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The hyperfine-structure separations and isotope shifts of several radioactive isotopes of thallium have been measured by optical spectroscopic techniques. The results are: $\mu^{199}=1.57$ nm; $\mu^{201}=1.58$ nm; and both $|\mu^{200}|$ and $|\mu^{202}|\leqslant 0.15$ nm. The isotope-shift measurements, which include the first data of this kind obtained for heavy odd-odd nuclei, permitted a comparison of the relative isotope shifts for isotones in mercury and thallium. A marked similarity in the shifts was observed.

THROUGH the use of a large (width, 10 in.) plane, blazed diffraction grating and the development of techniques for the preparation of spectral lamps containing as few as 10^{12} atoms of the desired element, we have succeeded in studying the spectrum of a number of radioactive thallium isotopes having half-lives as short as 7.4 hours. Kuhn and his co-workers[1] have made interesting systematic studies of even-neutron numbered isotopes of medium-A nuclei. For a more general investigation such as the extension of these studies to odd-neutron isotopes of either even or odd Z, the necessity of working with radioactive isotopes is obvious. The fact that quite extensive measurements of the hyperfine-structure separations and isotope shifts in mercury ($Z=80$) were available made it desirable, particularly for the isotope-shift data, for us to study the adjacent element, thallium ($Z=81$).

We have used for our measurements the thallium resonance line 3776 A and the 5350 A line that connect the states shown in Fig. 1. Figure 2 shows the transitions that occur when the nuclear spin $I=\frac{1}{2}$. The Doppler broadening of about 0.030 cm^{-1} in the green line does not permit the resolution of the hfs in the $^2P_{\frac{3}{2}}$ state.[2] The use of a multiple-wavelength mirror monochromator[3] of approximately 40-ft focal length permitted simultaneous photographic recording of these lines.

For the optical spectroscopic work, in contradistinction to atomic-beam magnetic-resonance experiments, we cannot, in usual cases, produce the radioisotopes by neutron-induced reactions. In the present experiments we used α- and d-induced reactions in the M.I.T. cyclotron. With a 30-Mev α-particle beam, having an external beam current of 5–15 μa, we bombarded gold foil in several runs for periods of from 2 to 8 hours. We produced Tl^{200} (27 hr), Tl^{199} (7.4 hr), Tl^{198} (5.3 hr), and Tl^{198*} (1.9 hr). We also made one 300 μa-hr internal beam run. The isotopes Tl^{201} (72 hr), Tl^{202} (12 day), and Tl^{204} (4 yr), as well as the isotopes previously produced, were obtained by deuteron bombardment of natural liquid mercury. For these runs bombardments of 30–35 μa-hr in the external beam at an energy of approximately 15 Mev were used. Gamma-ray spectra and half-life decay curves were used to identify the reaction products.

The results for the magnetic moments of the thallium isotopes are given in Table I. These data were obtained from hfs measurements in the $6p\ ^2P_{\frac{1}{2}}$ and $7s\ ^2S_{\frac{1}{2}}$ states through the use of the Fermi-Segrè formula and the known values of the stable thallium magnetic moments;

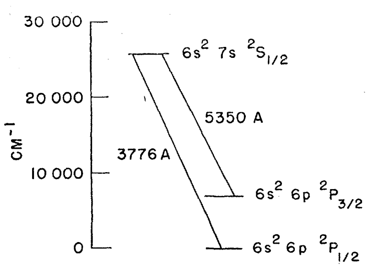

FIG. 1. Electronic energy levels of thallium.

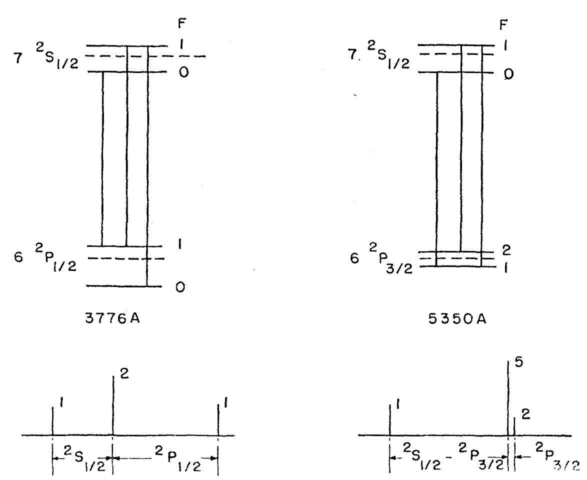

FIG. 2. Hyperfine-structure intervals for a spin $\frac{1}{2}$ thallium isotope. The bottom part of the diagram shows the theoretical structure of the lines with relative intensities indicated.

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[1] H. G. Kuhn and S. A. Ramsden, Proc. Roy. Soc. (London) **A237**, 485 (1956); W. R. Hindmarsh, H. G. Kuhn, and S. A. Ramsden, Proc. Phys. Soc. (London) **A67**, 478 (1954); H. G. Kuhn and A. G. Warner, Proc. Roy. Soc. (London) **A245**, 330 (1958).

[2] G. Gould, Phys. Rev. **101**, 1828 (1956).

[3] H. H. Stroke and K. K. Y. Li, J. Opt. Soc. Am. (to be published).

TABLE I. Magnetic moments of thallium isotopes.

A	I[a]	μ_{exp} (nm)	μ_{th} (nm) I	μ_{th} (nm) II
199	$\frac{1}{2}$	1.57	1.38	1.63
200	2	$\lvert\mu\rvert \leqslant 0.15$		
201	$\frac{1}{2}$	1.58	1.36	1.61
202	2[b]	$\lvert\mu\rvert \leqslant 0.15$		
203	$\frac{1}{2}$	1.60[a]	1.33	1.58
204	2	± 0.089[c]		
205	$\frac{1}{2}$	1.61[a]	1.31	1.56

[a] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[b] L. L. Marino, W. B. Ewbank, H. A. Shugart, and H. B. Silsbee, Bull. Am. Phys. Soc. **3**, 319 (1958).
[c] G. O. Brink, J. C. Hubbs, W. A. Nierenberg, and J. L. Worcester, Phys. Rev. **107**, 189 (1957).

hfs anomalies were neglected. For the odd-A isotopes, we also give the results of configuration-mixing calculations using the theory of Arima and Horie.[4] For the protons the contributions are $(1h_{11/2})^{12}3s_{\frac{1}{2}}$. For the neutrons, choice I in Table I is $(3p_{\frac{3}{2}})^4(1i_{13/2})^{N-110}$, where N is the neutron number of the particular isotope. For choice II in Table I, we take the less likely possibility that the neutron p shells are completely filled before the i shell; that is, the neutron contributions are $(1i_{13/2})^{N-112}$. The single-particle value without configuration mixing is 2.79 nm.

The odd-odd isotopes all have very small moments. Coupling the $s_{\frac{1}{2}}$ proton (with a stable thallium g value) to a $p_{\frac{3}{2}}$ neutron (using the Hg^{201} g value) gives $\mu \approx 1$ nm, a value that is approximately ten times larger than the experimental value. Configuration mixing does not improve the agreement,[5] nor does the coupling of the $s_{\frac{1}{2}}$ proton state to a possible, but unlikely, $2f_{\frac{5}{2}}$ neutron state. If, however, we assume that we couple a $3p_{\frac{1}{2}}$ neutron to the $2+$ core ($g \approx 0.4$) to give a total angular momentum of $\frac{5}{2}$, and then couple this to the $3s_{\frac{1}{2}}$ proton to yield the observed spin of 2, quite good agreement with the value of the moment of Tl^{204} can be obtained, even without admixing other states.[6] Such a coupling scheme might also make a spin of $\frac{5}{2}$ for Hg^{203} plausible; this value would be expected on the basis of its beta decay, in which there is a lack of transitions to the ground state of Tl^{203} which has a spin of $\frac{1}{2}$.

TABLE II. Relative isotope shifts in thallium and mercury.

A	Relative isotope shifts Tl	Relative isotope shifts Hg[a]
198	···	−0.92
199	3.00	−0.80
200	2.86	0
201	2.10	0.30
202	1.76	1.00
203	1.00	···
204	0.61	1.99
205	0	···

[a] H. Kopfermann, *Nuclear Moments*, translated by E. E. Schneider (Academic Press, Inc., New York, 1958), p. 181.

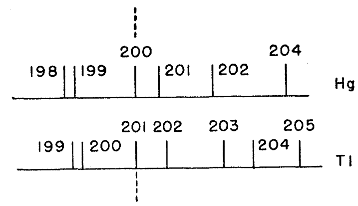

FIG. 3. Relative isotope positions of mercury and thallium.

The results of the isotope-shift measurements are given in Table II. The shifts are measured relative to Tl^{205}, with the Tl^{203}–Tl^{205} shift, which equals 0.059 cm^{-1} in both the green and ultraviolet lines, set equal to 1.00. We also indicate the relative isotope shifts of the adjacent element, mercury. In Fig. 3 we compare these relative isotope shifts as a function of neutron number. This shows a remarkable similarity which indicates that the effect of the addition of neutrons is strongly dependent on the neutron number, but appears to be relatively independent of whether the nucleus has an odd or even number of protons.

A complete report on the experimental techniques used in making these spectroscopic measurements and a detailed discussion of the measurements is being submitted for publication to the *Journal of the Optical Society of America*.

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[4] A. Arima and H. Horie, Progr. Theoret. Phys. (Kyoto) **12**, 623 (1954).

[5] H. Noya, A. Arima, and H. Horie, Progr. Theoret. Phys. (Kyoto) Suppl. **8**, 33 (1958).

[6] The authors are indebted to Professor A. de-Shalit for suggesting this coupling scheme.