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The Spin and Magnetic Moment of Ti^{47} and Ti^{49} and the Magnetic Moment of Ge^{73}

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The spin and magnetic moment of Ti^{47} and Ti^{49} have been measured by nuclear induction. The results are: $I(Ti^{47})=5/2$, $I(Ti^{49})=7/2$, $\mu(Ti^{47})=-(0.78706\pm0.0001)$ nm, $\mu(Ti^{49})=-(1.1022\pm0.0002)$ nm. The magnetic moment of Ge^{73} has been measured by nuclear induction with the result: $\mu(Ge^{73})=-(0.87675\pm0.00012)$ nm. These results are compared to the predictions of the shell model of nuclear structure.

I. TITANIUM 47 AND 49

A NUCLEAR induction signal in $TiCl_4$ which showed a structure has been previously reported;[1] this resonance signal was attributed to either Ti^{47} or Ti^{49}. Using a nuclear induction spectrometer similar to those described by Proctor[2] and by Weaver,[3] recent measurements made with separated Ti isotopes have shown that the structure of the line is not due to chemical effects as was previously thought but is actually the superposition of the close lying resonance lines of Ti^{47} and Ti^{49}. Using two different samples of $TiCl_4$, one containing 63-percent Ti^{47} and only 0.7-percent Ti^{49}, the other containing only 1.2-percent Ti^{47} and 77-percent Ti^{49}, we have observed in the same magnetic field the ratio of the nuclear magnetic resonance frequencies of Ti^{47} and of Ti^{49} to that of D^2 in a sample of D_2O containing 1 molar Mn^{++} ions as a paramagnetic catalyst. Our results are

$$\nu(Ti^{47})/\nu(D^2)=0.36721\pm0.00006, \tag{1}$$

$$\nu(Ti^{49})/\nu(D^2)=0.36731\pm0.00006. \tag{2}$$

The polarity of the Ti^{47} and Ti^{49} signals has been observed to be opposite to that of D^2, indicating that their magnetic moments are negative. Using a sample of $TiCl_4$ containing Ti^{47} and Ti^{49} in their natural abundances, we have furthermore clearly resolved the two Ti resonances under conditions of higher resolution than originally used. The frequency ratios are identical to those of (1) and (2) above. We have also observed in the same magnetic field $\nu(Ti^{49})/\nu(Ti^{47})=1.00026\pm0.00002$. Thus the gyromagnetic ratios of Ti^{47} and Ti^{49} are remarkably close; since the spins are different, as will be shown, this is probably a coincidence.

Ti signals have also been observed in H_2TiF_6 at a frequency approximately 0.1 percent lower than in $TiCl_4$. This "chemical shift"[4] has not yet been measured exactly because of the chemical instability of H_2TiF_6, but its existence indicates a possible uncertainty of this order of magnitude in the magnetic moments of Ti^{47} and Ti^{49} reported below in (6) and (7).

According to Bloch's theory[5] of nuclear induction, the spins $I(a)$ and $I(b)$ of two nuclei a and b may be compared, in principle, by observing the heights $H(a)$, $H(b)$ and the widths $W(a)$, $W(b)$ of the nuclear induction signals for the two nuclei. It can be shown[6] that if slow passage conditions prevail and if the radiofrequency field is small compared to its saturation value, then when the radiofrequency is the same for both nuclei,

$$R\equiv\frac{I(a)[I(a)+1]}{I(b)[I(b)+1]}=\left[\frac{N(b)}{N(a)}\right]\left[\frac{H(a)}{H(b)}\right]\left[\frac{W(a)}{W(b)}\right]^2\left[\frac{\gamma(b)}{\gamma(a)}\right]^3, \tag{3}$$

where $N(a)$, $N(b)$ are the relative number of nuclei and $\gamma(a)$, $\gamma(b)$ are the gyromagnetic ratios. Previous spin determinations[6,7] have compared an unknown spin $I(a)$ to a known spin $I(b)$. However Eq. (3) will also uniquely determine both $I(a)$ and $I(b)$ even if both are unknown [except in the case $I(a)=I(b)$], if the additional assumption is made that the spins have quantized values. In the present case the line shape of the Ti resonances is different from that of Cl^{35} in $TiCl_4$ and a comparison of $I(Ti)$ to $I(Cl^{35})$ is not justified. The line shapes of the Ti^{47} and the Ti^{49} resonances, on the other hand, are identical under widely varying conditions and it is believed that application of Eq. (3) is valid. For a series of 13 measurements of the heights and widths of the Ti^{47} and Ti^{49} resonances in natural abundance $TiCl_4$ we find, using Eq. (3),

$$R\equiv\frac{I(Ti^{47})[I(Ti^{47})+1]}{I(Ti^{49})[I(Ti^{49})+1]}=0.568\pm0.037, \tag{4}$$

where we have used the abundance ratio $N(Ti^{49})/N(Ti^{47})=0.743$, which is the average of the reported values.[8] Both these Ti isotopes are odd nuclei and it may be safely assumed that the spins are half odd integers. The above experimental result then establishes

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that

$$I(\mathrm{Ti}^{47})=5/2, \quad \text{and} \quad I(\mathrm{Ti}^{49})=7/2, \tag{5}$$

for which the ratio $R=0.555$; the nearest other possible R values are excluded: $R=0.636$ for $I(\mathrm{Ti}^{47})=7/2$, $I(\mathrm{Ti}^{49})=9/2$ and $R=0.440$ for $I(\mathrm{Ti}^{47})=7/2$, $I(\mathrm{Ti}^{49})=11/2$.

Using the results (1), (2) and (5) we find for the magnetic moments, without diamagnetic correction,

$$\mu(\mathrm{Ti}^{47})=-(0.78706\pm0.0001)\ \mathrm{nm}, \tag{6}$$

$$\mu(\mathrm{Ti}^{49})=-(1.1022\ \pm0.0002)\ \mathrm{nm}, \tag{7}$$

where we have used in this calculation the ratio $\mu(\mathrm{D}^2)/\mu(\mathrm{H})=0.307015$ as given by Mack[9] and $\mu(\mathrm{H})=2.7925$ as determined by Bloch and Jeffries.[10]

This experiment assigns an $f_{7/2}$ orbit to the odd neutron in Ti^{49}, as anticipated by the nuclear shell model of Mayer[11] and of Jensen, Haxel, and Suess.[12] For Ti^{47}, with $I=5/2$, the situation is more complicated: the single-particle model would predict an $f_{5/2}$ orbit for the odd neutron, whereas this experiment would assign a $d_{5/2}$ orbit. This "discrepancy" is quite analogous to that for the odd-proton nuclei Na^{23} and Mn^{55} as discussed by Mayer,[11] where the empirical ground level can be understood by taking into account all the protons outside the closed shells instead of just the single odd proton. A theoretical explanation has been given by Kurath[13] and by Talmi.[14] It is supposed that Mn^{55} with 25 protons has a $D_{5/2}$ ground state obtained by the jj coupling of the five protons in the incomplete $f_{7/2}$ subshell. This experiment shows that Ti^{47}, with 25 neutrons, behaves similarly, as anticipated by Rosenfeld[15] and others. The five neutrons in the incomplete $f_{7/2}$ subshell can couple to a $D_{5/2}$ state; a simple jj coupling calculation of the resultant magnetic moment yields $\mu=-1.36$ nm, which is nearer to the experimentally observed value than either of the Schmidt limits.

The magnetic moments of Ti^{47} and Ti^{49} as predicted by the scheme of Schawlow and Townes[16] agree well with our measured values (6) and (7).

II. GERMANIUM 73

Using the nuclear induction spectrometer we have observed a nuclear magnetic resonance in pure GeCl_4 at a frequency of 1.48 Mc/sec in a field of 10 000 gauss. We ascribe this resonance to Ge^{73}, the only stable odd isotope of germanium. The observed signal-to-noise ratio agrees approximately with that calculated for Ge^{73} using the spin value of 9/2 as measured by Townes, Mays, and Dailey.[17] We have been unable to observe the Cl^{35} or Cl^{37} resonance signals in GeCl_4, presumably because of excessive electric quadrupolar broadening of the line. However by comparing the Ge^{73} signal to the Cl^{35} signal in TiCl_4 we observe the magnetic moment of Ge^{73} to be negative. This is in agreement with the prediction of the Mayer-Jensen nuclear shell model, which assigns a $g_{9/2}$ orbit to the odd neutron in Ge^{73}. In the same magnetic field the ratio of the nuclear resonance frequency of Ge^{73} in GeCl_4 to that of Cl^{35} in TiCl_4 is observed to be

$$\nu(\mathrm{Ge}^{73})/\nu(\mathrm{Cl}^{35})=0.35572\pm0.00004.$$

We have observed a slight "chemical shift"[4] between the Cl^{35} resonance frequency in TiCl_4 and in an aqueous solution of RbCl. The ratio of the resonance frequencies is found to be 1.00088 ± 0.000025 in these two compounds, respectively. Using this correction and the ratio $\nu(\mathrm{Cl}^{35})/\nu(\mathrm{D}^2)$ in $\mathrm{RbCl}+\mathrm{D}_2\mathrm{O}$ as measured by Walchli, Leyshon, and Scheitlin[18] we find

$$\nu(\mathrm{Ge}^{73})/\nu(\mathrm{D}^2)=0.22725\pm0.00003. \tag{8}$$

From this we find for the nuclear magnetic moment of Ge^{73}, without diamagnetic correction,

$$\mu(\mathrm{Ge}^{73})=-(0.87675\pm0.00012)\ \mathrm{nm}, \tag{9}$$

where we have used in this calculation the ratio $\mu(\mathrm{D}^2)/\mu(\mathrm{H})$ and $\mu(\mathrm{H})$ as given above, and the value 9/2 for the spin of Ge^{73} as measured by Townes *et al.*[17] Our measured value of $\mu(\mathrm{Ge}^{73})$ is considerably less than the predicted values.[19] We have also searched for the Ge^{73} resonance in the powdered element without success. It should be pointed out that possible "chemical shifts"[4] can make the result (9) uncertain, to about 0.1 percent.

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