

We know that³

$$|\Gamma(\alpha + i\beta)| = \frac{\Gamma(1 + \alpha)}{\alpha} \prod_{n=0}^{\infty} \left[1 + \frac{\beta^2}{(\alpha + n)^2} \right]^{-1}, \quad (3)$$

where α and β are real. Making use of relation (3) we have

$$F(z, W) = f p^{2s-2} e^{\pi\delta} \prod_{n=0}^{\infty} \left[1 + \frac{\delta^2}{(s+n)^2} \right]^{-1}, \quad (4)$$

where f is a factor independent of W . If we set $s=1$, we have the nonrelativistic Kurie approximation

$$F_k = f e^{\pi\delta} \prod_{n=0}^{\infty} \left[1 + \frac{\delta^2}{(n+1)^2} \right]^{-1} \\ = f 2\pi\delta / (1 - e^{-2\pi\delta}). \quad (5)$$

Therefore

$$F = F_k p^{2s-2} \prod_{n=0}^{\infty} \left\{ \left[1 + \frac{\delta^2}{(n+1)^2} \right] / \left[1 + \frac{\delta^2}{(n+s)^2} \right] \right\}. \quad (6)$$

The infinite product in (6) converges at a reasonable rate. Table I gives the accuracy of the different prevailing approximations for the three typical cases of the light nucleus S^{36} , the medium nucleus Cu^{64} (negatron emission), and the heavy nucleus RaE , and the comparison with the exact calculations. In this table F is an abbreviation for $F(z, W)$ as given in Eq. (6), F_B denotes Bethe's approximation

$$F_B = F_k p^{2s-2} (\delta^2 + \frac{1}{4})^{s-1}, \quad (7)$$

F_F denotes Fermi's approximation for heavy nuclei

$$F_F = 1/p - 0.355 \quad (8)$$

where p is the momentum in units of mc.

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¹ C. Longmire and H. Brown, *Phys. Rev.* **75**, 264 (1949); I. Feister, *Phys. Rev.* **78**, 375 (1950); H. Hall, *Phys. Rev.* **79**, 745 (1950).

² E. J. Konopinski, *Revs. Modern Phys.* **15**, 209 (1943).

³ Godefroy, *La Fonction Gamma* (1901), p. 14.

Internal Motion of Hydrogen Absorbed in Tantalum

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THE metals which absorb hydrogen are usually divided into two groups, the so-called good absorbers (Ti, Zr, Th, V, Ta, Pd), which have decreasing solubility of hydrogen with temperature, and the poor absorbers (Ni, Fe, Co, Cu), which have increasing solubility of hydrogen with temperature. The poor absorbers are thought to allow the protons to move freely through the lattice without any effect on the lattice structure whereas the good absorbers are believed to form definite metal hydrides having a different lattice structure from the pure metal. The latter are supposed to have the hydrogen atoms tightly bound to the metal atoms.¹

Previous observations of nuclear magnetic resonance² absorption lines indicated, however, that in tantalum the protons have strong internal motion at room temperature. To verify this result further an experiment was performed to freeze in the proton motion by lowering the temperatures of the tantalum lattice. This was done successfully at a temperature of about 215°K. Beginning with a line width of less than one gauss at room temperature the line remains narrow down to 215°K. Over a range of 20° about this point it undergoes a pronounced widening, indicating that the protons are being frozen in position.

Thus in the range of temperature where solubility measurements of hydrogen in metals have been made in the past³ (i.e., from room temperature up) our experiment indicates that the hydrogen atoms are not tightly bound to the metal atoms. In this respect tantalum resembles the poor absorbers.

The tantalum sample was in powdered form and had a hydrogen concentration of 53.5 atomic percent. Previous observation showed that the line width, at least at room temperature, was not affected appreciably by the degree of concentration of hydrogen. However, at this temperature the tantalum line is so narrow as to be determined by the magnetic field inhomogeneity so that small differences in line width due to differences in concentration may be masked.

Specific heat anomalies have been observed in the tantalum-hydrogen system, within the temperature range where our line width changes have been detected.⁴ The specific heat curves have maxima in the region 220° to 265°K, the height of the maxima and the temperatures at which they occur being proportional to the amount of dissolved hydrogen. However, only small concentrations of hydrogen have been used in these experiments (i.e., 0 to 12 atomic percent). According to Hagg⁵ the structure of the tantalum lattice changes from a body centered cubic lattice to hexagonal close packing at about 12 atomic percent hydrogen. The sample used in our experiment would then have a lattice which is hexagonal close packed. This may account for the fact that the specific heat anomalies occur at slightly higher temperatures than the resonance line width discontinuity.

Kelley⁴ suggests that the specific heat anomaly is due "to the differences in the number of possible ways of arranging the hydrogen particles among the positions in the tantalum lattice available at the higher and lower temperatures." This, of course, conforms to the idea that the protons are frozen in at the lower temperatures.

¹ R. H. Fowler and C. J. Smithells, *Proc. Roy. Soc. (London)* **A160**, 37 (1937).

² M. A. Garstens, *Phys. Rev.* **79**, 397 (1950).

³ C. J. Smithells, *Gases and Metals* (1937).

⁴ K. K. Kelley, *J. Chem. Phys.* **8**, 316 (1940).

⁵ Hagg, *Z. physik. Chem.* **B11**, 433 (1931).

Erratum: Acceleration of Stripped C¹² and C¹³ Nuclei in the Cyclotron

[*Phys. Rev.* **80**, 486 (1950)]

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THE Editors regret a typographical error in the list of authors of this letter as originally printed. "Putnam" should be replaced by "Putnam" as above.

Ratio of the Quadrupole Moments of Cl³⁵ and Cl³⁷

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RECENT measurements of the ratio of the quadrupole moments of Cl³⁵ and Cl³⁷ by several observers using different methods are in disagreement by amounts which are considerably

TABLE I. Data on the quadrupole coupling constants of Cl³⁵ and Cl³⁷.

Method	$eqQ(Cl^{35})/eqQ(Cl^{37})$
Direct quadrupole transitions in solid <i>trans</i> -dichloroethylene $CHCl = CHCl$	1.2661 ± 0.0002 ^a
Atomic beam magnetic resonance method. Cl	1.2795 ± 0.0008 ^b
Microwave spectra of CH ₃ Cl	1.273 ± 0.004 ^c
Microwave spectra of FCl	1.2704 ± 0.004 ^d
Microwave spectra of BrCl	1.2768 ± 0.004 ^e

^a H. G. Dehmelt and H. Krüger, *Naturwiss.* **37**, 111 (1950).

^b Davis, Feld, Zabel, and Zacharias, *Phys. Rev.* **76**, 1076 (1949).

^c Gordy, Simmons, and Smith, *Phys. Rev.* **74**, 243 (1948).

^d Gilbert, Roberts, and Griswold, *Phys. Rev.* **76**, 1723 (1948).

^e Smith, Tidwell, and Williams, *Phys. Rev.* **79**, 1007 (1950).

TABLE II. New measurements of the coupling constants.

Substance	Interval	Cl ³⁵ (Mc)	$eqQ(\text{Cl}^{35})$ (Mc)	Cl ³⁷ (Mc)	$\frac{eqQ(\text{Cl}^{35})}{eqQ(\text{Cl}^{37})}$
CH ₃ Cl	($F=3/2 \rightarrow 3/2$) - ($F=3/2 \rightarrow 5/2$)	18.695	74.77 ± 0.015	14.731	1.2691 ± 0.0003
$J=0 \rightarrow 1$ $K=0$	($F=3/2 \rightarrow 5/2$) - ($F=3/2 \rightarrow 1/2$)	14.952		11.780	
CiCN	($F_1=1/2 \rightarrow 3/2$) - ($F_1=1/2 \rightarrow 1/2$)	20.843	83.33 ± 0.02	16.436	1.2682 ± 0.0006
$J=1 \rightarrow 2$	($F_1=1/2 \rightarrow 1/2$) - ($F_1=3/2 \rightarrow 3/2$)	16.849		13.333	
GeH ₃ Cl	($F=5/2 \rightarrow 3/2, 5/2, 7/2$) - ($F=7/2 \rightarrow 5/2, 7/2, 9/2$)	11.734	46.95 ± 0.015	9.262	1.2670 ± 0.0005
$J=2 \rightarrow 3$	($F=5/2 \rightarrow 5/2, 7/2, 9/2$) - ($F=1/2 \rightarrow 3/2$)	8.418			

outside the limits of the quoted experimental errors. Table I lists the various results obtained hitherto for the ratios of the quadrupole coupling constants, the quoted errors, and the method of measurement.

Probably at least some of the ratios given in Table I are in error. Although the very nice experiment of Dehmelt and Krüger should yield the most accurate ratio, their value is made somewhat doubtful by preliminary results obtained by Wang using the same technique.¹ For the same molecule he obtained 1.2682 ± 0.004 . The atomic beam measurement should be rather accurate, but may be questioned because the ratio of magnetic moments of the two Cl isotopes from the same measurement is also distinctly different from the ratio obtained by nuclear induction methods, and this difference is so far unexplained. A recalculation of the theoretical BrCl spectrum and comparison with experimental measurements indicates that perhaps the accuracy of the Cl³⁵/Cl³⁷ ratio obtained therefrom has been overestimated.

Because of these uncertainties we have redetermined the ratio $eqQ(\text{Cl}^{35})/eqQ(\text{Cl}^{37})$ from the microwave spectrum of CH₃Cl, CiCN, and GeH₃Cl. With the very high resolution afforded by a balanced microwave bridge spectrometer,² the intervals from which the quadrupole couplings were determined were measured to 8 kc or better, and hence rather accurate values of quadrupole couplings were obtained. The results of these measurements are given in Table II along with the computed quadrupole coupling ratios. These results are averages of as many as five different sets of determinations for a given molecule on as many different days. For no set were values found which would make the quadrupole coupling ratios in GeH₃Cl and CH₃Cl overlap. Although some of the discrepancies shown in Table I are probably due to errors or to the differing types of experiments used, it seems clear from repeated measurements with the same technique on CH₃Cl and GeH₃Cl that the apparent ratio of quadrupole coupling constants of the two Cl isotopes depends slightly on the molecular environment.

The CiCN spectrum is somewhat complex because of the occurrence of two quadrupolar nuclei in the same molecule. The experimental results were fitted to a theoretical calculation which included all known effects of important size except for a possible magnetic coupling between the nitrogen nucleus and the molecular rotation.

The two measured intervals in GeH₃Cl³⁵ did not agree exactly with the spacings expected for pure quadrupole coupling. This deviation was attributed to a magnetic coupling of the type $c(\mathbf{I} \cdot \mathbf{J})$ with $c = -4 \pm 3$ kc. Inserting this very small correction, one obtains for this molecule $\frac{eqQ(\text{Cl}^{35})}{eqQ(\text{Cl}^{37})} = 1.2670 \pm 0.0005$. Similarly, if a magnetic coupling of the form $c(\mathbf{I} \cdot \mathbf{J})$ is assumed for Cl in CH₃Cl, the constant c would have the very small value, 0.4 ± 0.8 kc.

The only other pair of isotopes for which the quadrupole moment ratios have been measured with some accuracy is Br⁷⁹ and Br⁸¹, which in BrCN and CH₃Br seem to agree within experimental accuracy of one part in 2500.

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¹ T. C. Wang, Columbia University, private communication.

² Columbia Radiation Laboratory Report, June 30, 1949, unpublished.

Polarization of the Nucleus by Electric Fields*

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THE preceding letter¹ shows that the ratio of quadrupole moments of Cl³⁵ and Cl³⁷ in CH₃Cl appears to be slightly different from that found in GeH₃Cl. It will be shown below that the most reasonable explanation of this difference is a fictitious quadrupole moment due to anisotropic polarization of the Cl nuclei by molecular electric fields.

Two molecular effects which might change the apparent ratio of the quadrupole moments from one molecule to another are the pseudoquadrupole effect discussed by Foley² and the variation in zero-point vibration with isotopic mass.

A reasonable estimate of the pseudoquadrupole effect makes it too small to account for the observed change by a factor of 10⁴. In order to obtain an effect of the correct magnitude, electronic levels within 1 cm⁻¹ of the molecular ground state would need to be assumed.

From measured changes of quadrupole coupling with vibration in several molecules, an upper limit for the expected change in quadrupole coupling due to isotopic mass variation is one part in 2500. If the observed effect were due to zero-point vibrations in GeH₃Cl the change in Cl quadrupole coupling per quantum of vibration energy would need to be -10 percent. Actual rough measurement shows this change to be +3 percent ± 3 percent. Although the effect of vibration in CH₃Cl has not been measured specifically, the quadrupole coupling change per vibrational excitation would have the ridiculously large value of 20 percent if it is to explain the variation in apparent quadrupole moment ratios, and hence this explanation is ruled out.

Two other effects which can produce a variation in the apparent quadrupole moment ratio are a second-order perturbation of the electronic levels by the nuclear quadrupole coupling and a penetration of the nuclear volume by electronic charge. The variation due to either one of these effects, however, would be much too small to account for the observed discrepancy.

A reasonable explanation of the discrepancy is that a polarization of the Cl nuclei occurs in the molecular electric fields. If the nuclear polarizability depends on the direction of polarization with respect to the spin axis of the nucleus, then the classical