

occurs in the understanding of the low intensity of the ground-state transition in  $\text{P}^{32}$ . Furthermore, the very weak intensities for the ground-state radiations in  $\text{Si}^{29}$  and  $\text{Si}^{30}$  are hard to reconcile with the single unit of angular momentum which must be radiated in these transitions if the spin of  $\frac{1}{2}$  recently suggested for  $\text{Si}^{29}$  is correct.<sup>4</sup>

It is clear that the familiar selection rules concerning differences in parity and spin are not sufficient to account for the relative intensities of ground-state transitions. The experimental data, therefore, indicate the existence of additional parameters which determine the relative intensities of nuclear radiations. We wish to thank Dr. L. G. Elliott for helpful discussions.

<sup>1</sup> Kinsey, Bartholomew, and Walker, *Phys. Rev.* **77**, 723 (1950); **78**, 77 (1950).

<sup>2</sup> E. Feenberg and K. C. Hammack, *Phys. Rev.* **75**, 1877 (1949).

<sup>3</sup> F. B. Shull and E. Feenberg, *Phys. Rev.* **75**, 1768 (1949).

<sup>4</sup> Townes, Mays, and Dailey, *Phys. Rev.* **76**, 700 (1949).

### The Viscosity of Liquid $\text{He}^3$

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March 6, 1950

SOME recently announced results by Weinstock *et al.*<sup>1</sup> show that the viscosity of liquid  $\text{He}^3$  increases smoothly from a value of 22 micropoise at 2.8°K to 30 micropoise at 1.05°K. The curve is everywhere convex to the temperature axis and shows no sign of a discontinuity anywhere in this range. Such a variation of viscosity is similar to that of an ordinary liquid, but it does not seem possible to explain it in the conventional way by assuming that the atoms moving through the liquid have potential barriers to surmount. Liquid  $\text{He}^4$  (above the  $\lambda$ -point) already shows a viscosity increasing with temperature in much the same way as does that of a gas. The density of liquid  $\text{He}^3$  is only just over half that of liquid  $\text{He}^4$ , and the effective height of any potential barrier is therefore correspondingly smaller. The fact that an opposite trend of viscosity is observed in liquid  $\text{He}^3$  therefore points to an increase in mean free path as the temperature falls, which may be explained in one of two ways: (a) by a decrease in the effective cross-section at low velocities of impact of helium atoms (Ramsauer effect); (b) by a decrease in the effective cross section at low temperatures due to the scattered states being already occupied. The existence of such an effect in a Fermi gas was first pointed out by Tomonaga,<sup>2</sup> and a similar point has recently been made by Singwi and Kothari.<sup>3</sup>

We have examined the consequences of effect (a) alone, by extending to  $\text{He}^3$  the calculations of the viscosity of  $\text{He}^4$  gas made by Massey and Mohr,<sup>4</sup> and by Buckingham, Hamilton, and Massey.<sup>5</sup> Two models have been used, the rigid sphere model (with a diameter of 2.1A for a helium atom<sup>4</sup>), and another using an interaction potential formed from repulsive exponential and van der Waals attractive terms. This second potential is one called "potential C" by the second group of authors. Although the

TABLE I. Theoretical values of  $\eta$  (in micropoise) as a function of  $T$ .

$T$ (°K)	Rigid sphere			Potential C			Classical (7)	Complete degeneracy (8)	Observed (9)
	↑↓ (1)	↑↑ (2)	Mixture (3)	↑↓ (4)	↑↑ (5)	Mixture (6)			
0.25				3.6	5.3	4.7	3.6	—	
0.5	1.1	32	3.6	8.0	5.2	5.5	6.3	—	
0.75	1.6	19.5	4.7	6.0	4.8	5.0	8.7	41	
1.0	1.8	14.7	5.3	4.8	6.3	5.8	10.8	23	30.5
1.25	2.3	13.2	5.9	4.4	8.5	6.8	12.3	14.5	
1.5	2.7	12.2	6.4	4.4	11.0	8.0	13.5	10.2	
2.0	3.7	11.1	7.4	4.9	14.8	9.8	15.4	5.8	
2.5	4.7	10.8	8.2	5.7	15.9	11.0	17.0	3.8	22 at
3.0	5.8	11.0	9.0	6.7	15.4	11.6	18.5	2.5	2.80°K

attractive part of potential C is too weak to represent the interaction of He atoms correctly, it happens that the adjustment to the correct magnitude is very nearly compensated by the smaller mass of  $\text{He}^3$ . Consequently the results of previous calculations are readily adapted to give values of viscosity which are probably a good approximation for  $\text{He}^3$ .

In Table I, columns 1 and 2 refer to the rigid sphere model, and assume that the nuclear spins of each colliding pair of atoms are respectively antiparallel and parallel, whereas column 3 represents the consequences of assuming a 3:1 mixture of these two types of collision. Columns 4, 5, and 6 give corresponding results for the interaction potential C. Column 7 gives the viscosity of a classical gas of atoms of diameter 2.1A, while column 8 refers to the formula

$$\eta = (1/15\pi^3) \cdot (2mE_0)^{1/2} / (kT)^2 \cdot (1/Q),$$

obtained by Tomonaga for an almost completely degenerate gas. (His actual expression refers to a mixture of two types of Fermi particle, so we have divided it by 2. The scattering cross section,  $Q$ , has been taken to be  $\pi r^2$ ,  $r$  being taken as 1.05A, the gas-kinetic radius.) Since  $E_0$ , for the observed density ( $\sim 0.07$  g/cm<sup>3</sup>) of liquid  $\text{He}^3$ , corresponds to a Fermi degeneracy temperature of the order of 5°K, the Tomonaga formula is only the limiting form at very low temperatures.

Though it might seem that model 2 (rigid spheres with parallel spins) has at least the correct trend to interpret the observed results, it appears nevertheless that the Ramsauer effect is insufficient by itself to explain them: first, because model 5 shows that alteration of the interaction to a more correct form lowers the predicted viscosity at temperatures below 1.5°K considerably; secondly, because the effect of many-body collisions, neglected in models 1 to 7, can only shorten the mean free path; and thirdly, because models 2 and 5 seem to be practically ruled out by the observation of Sydoriak and Hammel<sup>6</sup> that liquid  $\text{He}^3$  is not ferromagnetic within the range of temperatures considered.

We thus seem forced to conclude that the observed rise in viscosity as the temperature falls is due, at least in part, to the effect of the exclusion principle in reducing the probability of scattering.

<sup>1</sup> Weinstock, Osborne, and Abraham, conference on "Very Low Temperatures," Massachusetts Institute of Technology, 1949.

<sup>2</sup> S. Tomonaga, *Zeits. f. Physik* **110**, 573 (1938).

<sup>3</sup> K. S. Singwi and L. S. Kothari, *Phys. Rev.* **76**, 305 (1949).

<sup>4</sup> H. S. W. Massey and C. B. O. Mohr, *Proc. Roy. Soc. A* **141**, 434 (1934).

<sup>5</sup> Buckingham, Hamilton, and Massey, *Proc. Roy. Soc. A* **179**, 103 (1941).

<sup>6</sup> S. G. Sydoriak and E. F. Hammel, conference on "Very Low Temperatures," Massachusetts Institute of Technology, 1949.

### The Nuclear Magnetic Moment of Praseodymium<sup>141</sup>

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March 13, 1950

BY means of super-regenerative oscillator techniques similar to those previously described,<sup>1,2</sup> a nuclear magnetic resonance absorption peak for  $\text{Pr}^{141}$  has been located. By comparison of the resonance peak with the sodium resonance peak observed simultaneously in the same magnetic field, the following tentative value for the ratio of the resonance frequency of  $\text{Pr}^{141}$  to the resonance frequency of  $\text{Na}^{23}$  in sodium borate in the same applied field was obtained:

$$\nu(\text{Pr}^{141})/\nu(\text{Na}^{23}) = 1.2362 \pm 0.0006.$$

Using Pound's value for the ratio of the resonance frequency of  $\text{Na}^{23}$  to the resonance frequency of the proton in the same field,<sup>3</sup> one obtains the following value for the ratio of the resonance frequency of  $\text{Pr}^{141}$  to that of the proton:

$$\nu(\text{Pr}^{141})/\nu(\text{H}^1) = 0.32698 \pm 0.00016.$$