both at small and at large l_{CR} the enhancement reaches values of the order δ_0/δ_{inh}, whereas in the intermediate region there is a slight decrease, reaching a minimum near $l_{CR} \approx \delta_{inh}\sqrt{1+s}$.

We compare now our results with the data of Refs. 8 and 9. In the absence of spectral diffusion the formulas are almost the same (we note that our Eq. (10), in contrast to Refs. 8 and 9, takes the influence of the nuclei into account). At the same time the estimate proposed in Refs. 8 and 9 for the case $\delta_h \approx l_{CR}$ yields $E_{max} \gg \omega_0/\delta_{inh}$, which deviates greatly with the results of the present article and apparently does not agree with the physical arguments advanced above.

We note finally that Eqs. (10), (12) and (22), (23) are quite similar in structure with the result obtained for the "solid-effect" under conditions of inhomogeneous broadening of EPR.[7,12] In particular, in both case, with increasing $|\Delta|$, the quantity $|E|$ first increases in proportion to $\omega_0 G'(\Delta)/G(\Delta)$, and then decreases in accord with the decrease of the fraction of the active electron spins (the factor α in the notation of Sec. 2). This similarity emphasizes once more the common physical bases of the two dynamic-polarization mechanism, which is connected with thermal mixing in a rotating coordinate system.[7]

The authors thank M. I. Rodak and G. A. Vasnev for interest in the work and for helpful discussions.

1) We use the traditional abbreviation DDR—dipole-dipole reservoir—although it can include also other spin-spin interactions (sey, exchange interactions).

---

[1] B. N. Provotorov, Zh. Eksp. Teor. Fiz. **41**, 1582 (1961) [Sov. Phys. JETP **14**, 1126 (1962)].

[2] L. L. Buishvili, *ibid.* **49**, 1868 (1965) [**22**, 1277 (1966)].

[3] M. A. Kozhushner, *ibid.* **56**, 246 (1969) [**29**, 136 (1969)].

[4] V. A. Atsarkin and M. I. Rodak, Usp. Fiz. Nauk **107**, 3 (1972) [Sov. Phys. Usp. **15**, 251 (1972)].

[5] W. Th. Wenckebach, T. J. B. Swanenburg, and N. J. Poulis, Phys. Rep. C **14**, 183 (1974).

[6] A. Abragam and U. Goldman, Rep. Porgr. Phys. **41**,395 (1978).

[7] V. A. Atsarkin, Usp. Fiz. Nauk **126**, 3 (1978) [Sov. Phys. Usp. **21**, 725 (1978)].

[8] L. L. Buishvili, M. D. Zviadadze, and G. R. Khutsishvili, Zh. Eksp. Teor. Fiz. **56**, 290 (1969) [Sov. Phys. JETP **29**, 159 (1969)].

[9] L. L. Buishvili, M. D. Zviadadze, and N. P. Fokina, Phys. Stat. Sol. (b) 54, 40 (1972).

[10] S. Clough and C. A. Scott, J. Phys., Ser. C **1**, 919 (1968).

[11] L. L. Buishvili, M. D. Zviadadze, and G. R. Khutsishvili, Zh. Eksp. Teor. Fiz. **54**, 876 (1968) [Sov. Phys. JETP **27**, 469 (1968).

[12] D. Wollan, Phys. Rev. B **13**, 3671 (1976).

Translated by J. G. Adashko

Experimental dependence of the volume of solid normal hydrogen on the pressure up to 30 kbar at a temperature 77 K

V. V. Kechin, Yu. M. Pavlyuchenko, A. I. Likhter, and A. N. Utyuzh

Institute of High Pressure Physics, USSR Academy of Sciences

(Submitted 12 January 1979)
Zh. Eksp. Teor. Fiz. 76, 2194–2197 (June 1979)

The piston-displacement method was used to measure the dependence of the molar volume of n-H_2 on the pressure at liquid-nitrogen temperature in the pressure range 4–29 kbar. The results are presented in analytic form that approximates the experimental data with accuracy 0.03 cm^3/mol. The relative jump of the volume at melting amounts to $(4.7 \pm 0.4)\%$.

PACS numbers: 62.50. + p, 65.70. + y

Notwithstanding recent interest in hydrogen, both scientific and applied, the number of experimental investigations of the equation of state of solid hydrogen at high pressures is quite limited. There are particularly few investigations of the $P-V-T$ dependence at high static pressures, i.e., studies that would permit the calculation of the equation of state and of the thermodynamic functions with sufficient accuracy. In fact, at 4.2 K measurement of the $P-V$ dependence were made up to 20 kbar[1] and 25 kbar.[2] On the other hand, at temperatures higher than 4.2 K, the region in which experimental research was performed does not exceed several hundred bars.[3,4]

We present here experimental $P-V$ data for solid normal (75% ortho, 25% para) hydrogen ($n-H_2$) at liquid-nitrogen temperature. The measurements were made with a low-temperature press by the piston-displacement method. The apparatus and the experimental procedure are described in detail in the preceding papers.[5,6] The high-pressure chambers had inside diameters 6–7 mm and were made of steels ÉI958 and ÉP637, of high-strength manganese–nickel steel, and of beryllium bronze. The maximum pressures were 11 kbar in beryllium–bronze chambers and 17–29 kbar in steel chambers. From two to five experiments were performed with each of the four chambers. The volume of the solid-hydrogen sample was 0.5–1 cm^3.

In each experiment we measured the pressure in the cylinder of the press and the displacement of the piston in the high-pressure chamber with increasing (forward travel) and decreasing (backward travel) load. The forward and backward travel did not coincide because of the friction in the piston pairs of the chamber and the press, the value of which in the different experiments was 5–10% of the maximum load. The pressure in the chamber, for each displacement, was assumed to be the average value of the forward and backward travel.[1] The length of the hydrogen sample was determined as the difference between the readings of the displacements of the piston in the experiments with and without the hydrogen sample.[4] The error in the determination of the pressure in the chamber consisted of the error in the measurement of the pressure in the press cylinder by a loaded-piston manometer (0.1%), the error in the measurement of the diameters of the cylinder of the press and of the channel chamber at zero pressure (0.1%), and the uncertainty in the value of the coefficient of the thermal expansion of the steel (0.05%). Neglect of the change in the cross section area of the chamber channel under pressure is the cause of the main error in the determination of the pressure in the chamber, amounting to 0.7% at pressures lower than 15 kbar and to 1.5% at higher pressures. As a result, the total error in the determination of the pressure is 1% for $P < 15$ kbar and ~2% for $P > 15$ kbar. The error in the determination of the hydrogen sample volume is the sum of the error in the measurement in the length of the sample by the cathetometer (0.1%) and the error in the determination of the cross section area of the chamber channel with changing pressure, from an experiment on the compression of indium (0.7%) whose equation of state is known.[1,7] Thus, the error of the V does not exceed 0.8%. Allowance for the pressure error due to the functional connection between the pressure and the volume leads to a final maximum volume error ~1%.

In all, 16 measurements were made of the $P-V$ dependence. In five experiments we measured the volume of not only the solid but also of the fluid phase (starting with 4 kbar), as well as the jump of the volume in the melting–crystalization phase transition. The relative volume jump determined from these experiments is

$$\Delta V/V_{\text{sol}}=(4.7\pm0.4)\,\%, \qquad (1)$$

where $\Delta V = V_{\text{fl}} - V_{\text{sol}}$ is the difference between the volumes of the fluid and solid phases at the melting pressure $P_m = 4.98$ kbar.[8]

To represent the obtained $P-V$ data in analytic form, we tried various equations, including the equations of Birch,[9] Murnaghan,[10] Bohlin,[11] Tait,[12] and others. The calculations have shown that the experimental data are best described by the following empirical equations

$$V=V_0 \exp \{a_1[1-(1+a_2(P-P_0))^{a_3}]\}, \qquad (2)$$

$$V=V_0\{1-a_1 \ln [1+a_2(P-P_0)]\}^{1/a_3}, \qquad (3)$$

$$V=V_0\sum_{k=1}^{3} a_k(P_0/P)^{k/3}, \qquad (4)$$

where V is in cm^3/mol and P is in kbar. The parameters a_1, a_2, and a_3 in these equations were obtained by least squares from a joint reduction of the results of all the experiments. The values of the parameters V_0 were determined in such a way that the molar volume of the solid phase coincided at the melting pressure with the value $V_{\text{sol}} = 14.4$ cm^3/mol obtained by us previously,[5] on the basis of the data of Tsiklis *et al.*,[13] from the pressure dependence of the molar volume of hydrogen gas. Table I lists the values of P_0, V_0, a_1, a_2, and a_3 and of the mean squared error δ for Eqs. (2)–(4). It should be noted that the maximum deviation of the calculated data from the experimental ones in the entire investigated pressure interval does not exceed ±0.06 cm^3/mole (0.5%).

The experimental data for the fluid phase were also reduced by Eqs. (2)–(4). However, since the interval of the experimental data on the pressure was only 1 kbar, we do not present the values of the parameters of the equations for this phase. We note only that our data on the volume of the fluid phase agree within 0.3% with the measurements of Mills *et al.*[14] in the region where the measurements overlap.

TABLE I. Values of the parameters P_0, V_0, a_1, a_2, and a_3 and of the mean squared error δ for Eqs. (2)—(4).

P_0, kbar	V_0, cm^3/mol	a_1	a_2	a_3	δ, cm^3/mol	Level number
10	12.1322	3.49458	0.10753	0.065	0.031	(2)
10	12.1091	0.05675	0.10785	0.25	0.033	(3)
10	12.1230	1.43534	−0.60286	0.16752	0.036	(4)

TABLE II. Smoothed values of molar volume V and of the isothermal modulus of hydrostatic compressure K_T for the fluid and solid phases of n-H$_2$ at $T = 77$ K and different values of P.

P, kbar	V, cm^3/mol	K_T, kbar	P, kbar	V, cm^3/mol	K_T, kbar
Fluid phase			Solid phase		
			11	11.85	45.05
4	15.98	–	12	11.60	49.12
4,5	15.48	–	13	11.37	53.18
5	15.06	–	14	11.17	57.21
			15	10.98	61.22
Solid phase			16	10.81	65.21
			18	10.50	73.15
5	14.38	19.90	20	10.23	81.03
6	13.74	24.20	22	9.99	88.85
7	13.23	28.45	24	9.78	96.63
8	12.80	32.65	26	9.59	104.37
9	12.44	36.81	28	9.41	112.06
10	12.12	40.94	30	9.23	115.90

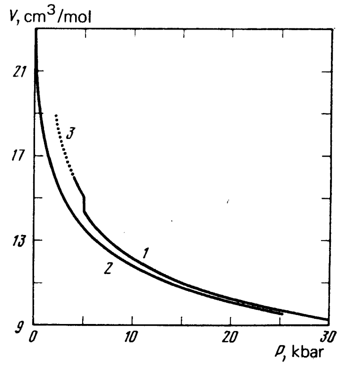

FIG. 1. Molar volume of n-H$_2$ vs. pressure. 1—$T = 77$ K, present data; 2—$T = 4.2$ K (Ref. 2); 3—$T = 77$ K (Ref. 14), fluid phase. The volume jump at $P \approx 5$ kbar on curve 1 corresponds to crystallization.

Kechin *et al.* 1109

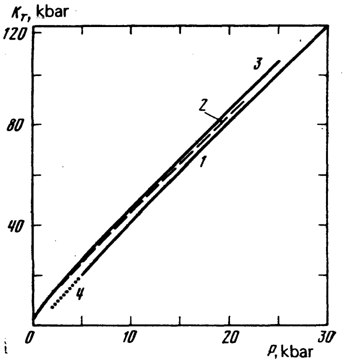

FIG. 2. Dependence of the isothermal modulus of hydrostatic compression of n-H_2 on pressure. 1—77 K, present data; 2—$T=4.2$ K (Ref. 1); 3—$T=4.2$ K (Ref. 2); 4—$T=77$ K (Ref. 14), fluid phase.

Table II gives the values of the molar volume and of the isothermal modulus of hydrostatic compression $K_T = (-V\partial P/\partial V)_T$, calculated from Eq. (2). The same values are shown in Figs. 1 and 2 together with the data obtained by others.

On the basis of the $P-V$ dependence at 77 K and of the data of Anderson and Swenson[2] at 4.2 K we can estimate the average isobaric coefficient of volume expansion $\bar{\alpha}_P = (\Delta V/V\Delta T)_P$. The coefficient $\bar{\alpha}_P$ decreases rapidly ($\bar{\alpha}_P \sim 1/P$) with increasing pressure: $\bar{\alpha}_P \approx 7.5\cdot 10^{-4}$ deg^{-1} at 5 kbar and $\bar{\alpha}_P \approx 1.4 \cdot 10^{-4}$ deg^{-1} at 25 kbar. The contribution made to the pressure by the lattice thermal vibrations (the Mie–Grüneisen thermal pressure), defined as $\Delta P_T(V) = P_T(V) - P_0(V)$, amounts to ~1.1 kbar and is practically independent of volume (it decreases slightly with decreasing volume).

In conclusion, the authors thank L. Z. Ponizovskiĭ for help with the experiment, and O. K. Revyakin and V. M. Blinov for supplying the steels with optimal structure.

[1]J. W. Stewart, J. Phys. Chem. Sol. **1**, 146 (1956).
[2]M. S. Anderson and C. A. Swenson, Phys. Rev. B **10**, 5184 (1974).
[3]R. F. Dwyer, G. A. Cook, O. E. Berwaldt, and H. E. Newis, J. Chem. Phys., **43**, 801, (1965).
[4]G. A. Cook, R. F. Dwyer, O. E. Berwaldt, and H. E. Newis, *ibid.* **43**, 1313 (1965).
[5]V. V. Kechin, A. I. Likhter, Yu. M. Pavlyuchenko, L. Z. Ponizovskiĭ, A. N. Utyuzh, Zh. Eksp. Teor. Fiz. **72**, 345 (1977) [Sov. Phys. JETP **45**, 182 (1977)].
[6]Yu. M. Pavlyuchenko, A. N. Utyuzh, V. V. Kechin, A. I. Likhter, and L. Z. Ponizovskiĭ, and A. P. Novikov, Prib. Tekh. Eksp. No. 2, 204 (1978).
[7]C. A. Swenson, Phys. Rev. **100**, 1607 (1955).
[8]V. V. Kechin, Yu. M. Pavlyuchenko, L. Z. Ponizovskiĭ, A. N. Utyuzh, and A. I. Likhter, Abstracts, 2nd All-Union Conf. on Metal–Dielectric Phase Transitions, L'vov, 1977.
[9]F. Birch, J. Geophys. Res. **57**, 227 (1952).
[10]F. D. Murnaghan, Proc. Nat. Acad. Sci. **30**, 244 (1944).
[11]L. Bohlin, High Temp.-High Pressure **5**, 581 (1973).
[12]P. S. Tait, Reports on Some of the Properties of Water, **47**, 1888.
[13]D. S. Tsiklis, V. Ya. Maslennikova, S. D. Gavrilov, A. N. Egorov, and G. V. Timofeeva, Dokl. Akad. Nauk SSSR **220**, 1384 (1975).
[14]R. L. Mills, D. H. Liebenberg, J. C. Bronson, and L. C. Schmidt, J. Chem. Phys. **66**, 3076 (1977).

Translated by J. G. Adashko

Positive-muon depolarization in weakly doped silicon single crystals

S. G. Barsov, A. L. Getalov, V. A. Gordeev, R. F. Konopleva, S. P. Kruglov,
V. I. Kudinov, L. A. Kuz'min, S. M. Mikirtych'yants, E. V. Minaĭchev,
G. G. Myasishcheva, Yu. V. Obukhov, G. I. Savel'ev, V. G. Firsov, and G. V. Shcherbakov

Institute of Theoretical and Experimental Physics, Leningrad Institute of Nuclear Physics, USSR Academy of Sciences
(Submitted 15 January 1979)
Zh. Eksp. Teor. Fiz. **76**, 2198–2205 (June 1979)

Results are reported of experiments devoted to a study of the depolarization of positive muons in silicon single crystals of both types of conductivity. The existence in silicon of two paramagnetic states and one diamagnetic state that include muons is confirmed. The dependence of the relative fraction of the diamagnetic state on the temperature is investigated. The results are discussed under the assumption that a chemical bond exists between the muon and the crystal lattice of the semiconductor.

PACS numbers: 75.20.Ck

1. INTRODUCTION

The investigation of the interactions of positive muons with the crystal lattice of a semiconductor (the most thoroughly investigated were silicon and germanium) has led to the observation of many phenomeno hitherto not revealed by the method of observing the muon spin precession (rotation) (μSR) for other media. These include the noticeable decrease of the frequency of the hyperfine splitting of muonium atoms imbedded in the crystal lattice of a semiconductor, compared with the vacuum value,[1-3] as well as the presence in silicon, simultaneously