Adiabatic equation of state for hydrogen up to 150 kbar

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A method for measuring the pressure and the results of the determination of the adiabatic equation for solid hydrogen up to 150 kbar are presented. The compression was performed by the method of the metallic Z-pinch, the density was measured by x-ray analysis, and the pressure was measured using the equation of state for a reference material.

It is apparently possible to create a pressure of several megabars in molecular hydrogen at relatively low temperatures and to obtain metallic hydrogen only with adiabatic compression. The results of adiabatic compression of hydrogen are presented in Refs. 1 and 2, but the pressure in these studies was measured by the method of

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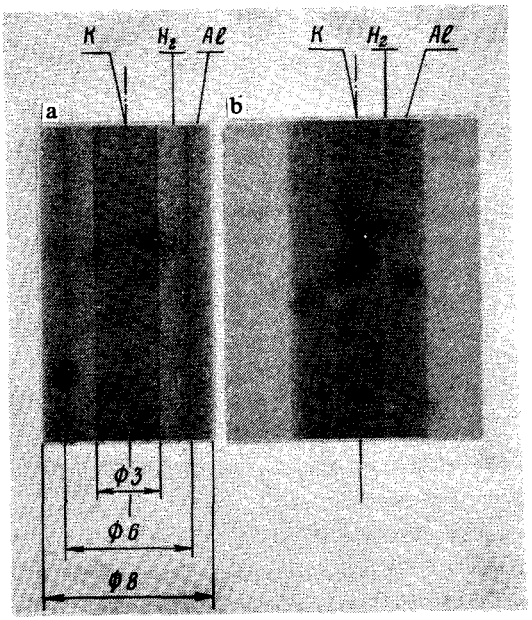

FIG. 1. X-ray photograph. a) Starting time; b) moment of compression.

numerical modelling, which involves an uncontrollable error due to the uncertain accuracy of the approximations used.[3,4] In this paper, we use a more accurate, direct method for measuring pressure and we present an adiabatic equation of state for hydrogen up to 150 kbar obtained with the help of this method.

The compression was performed by the method of the metallic Z-pinch.[6] The method for determining the equation of state is illustrated in Fig. 1, which shows an x-ray picture of a cylindrical "sandwich" consisting of three substances: the outer material is aluminum, along which pressure-forming current flows; the material in the center consists of hydrogen; and the interior material is the reference material whose equation of state is known with high accuracy. Here we use potassium as the reference material.[6] To increase the contrast, all materials were separated by 10-μm nickel tubes. The relative compression of the hydrogen and of the reference material was determined from the x-ray photographs made initially and during compression, and the pressure was determined from the equation of state of the reference material. The hydrogen pressure was determined under the assumption that the hydrogen pressure was equal to the pressure of the reference material.

The initial parameters of the normal hydrogen were: $T = 4.2$ K and $P = 1$ bar. The working part of the tube was 30 mm long; the radii are shown in Fig. 1. A current with amplitude 0.5–1.5 MA and quarter-period 3.5 μs was generated by a storage battery. The maximum magnetic pressure was $H_0/8\pi = 22.5$ kbar, but with the dynamic compression the hydrogen pressure greatly exceeded the magnetic field pressure.[5]

The x-ray photographs were made using an apparatus with the following characteristics: the visible focus was 0.3 mm, the pulse duration was 15 ns, and the effective rigidity ~ 100 keV. The radiation was recorded with x-ray film without amplifying screens. The distance between the focus and the tube was 1 mm, and the distance from the axis of the tube to the film was 15 mm.

The accuracy of this method is determined by the following factors: the error in the measurement of the hydrogen density and the density of the reference material, the error in the equation of state of the reference material, and the degree of radial homogeneity of the material, in particular, the assumption of equal pressures in hydrogen and in the reference material. The accuracy of the density measurements is determined by the error in the measurements of the radii, the error in the measurements of initial parameters and the mass loss due to outflow of material along the axis. An analysis of the x-ray photographs showed the possibility of measuring the radius with an error less than 10 μm. The motion of the tube does not "smear" the x-ray photograph, because the exposure time is quite short.

The absence of outflow of hydrogen was proved experimentally as follows. The hydrogen region at the center (along the tube) was separated by two ring-shaped barriers consisting of copper foil 20 μm thick and with a diameter of 4 mm, positioned at a distance of 6 mm. A comparison of x-ray photographs made initially and at the time of maximum compression showed the absence of outflow with an error of less than 0.1%. The absence of outflow could also be confirmed by the uniform (along the tube, with the exception of 2–3 mm from the ends) compression of the tube.

The degree of radial homogeneity was established by numerical calculations, performed in the one-dimensional MHD approximation.[5] The calculations showed that the degree of inhomogeneity at the times recorded was less than 5%. An experiment in which hydrogen was frozen instead of potassium was performed to confirm the radial homogeneity. The measured degree of inhomogeneity $\Delta P/P < 1\%$.

The relative error in determining the pressure is $\Delta P/P = B/P \cdot \Delta V/V$, where $B = -\partial P/\partial V$ is the volume modulus of compression. To obtain the highest accuracy a material must therefore be chosen with the highest compressibility (small B) and one for which the equation of state is known with highest possible accuracy in the measured pressure range. For this reason, it is best to use cesium as a standard for $P \leqslant 22$ kbar, potassium for $P \leqslant 300$, and sodium for $P \leqslant 1$ mbar. The equations of state of these substances were calculated in Ref. 6 with an error apparently to within 3%. At high pressures the accuracy of the equations of state is not known and materials whose equations of state were measured in shock-wave experiments must be used.

The assumption that the process is quasi-isentropic , as already noted in Ref. 5, was confirmed by numerical calculations; the difference between the average computed temperature and the adiabatic temperature, assuming that the viscosity of hydrogen in low, lies within the range of computational errors. The computed temperature is $T < 100$ K; for this reason, first of all, hydrogen remains solid; secondly, the thermal pressure $P_T \ll P_x$, so that the zero isotherm within the limits of the measurement error coincides with the adiabatic isotherm. The calculations also show that the inner surface of the aluminum tube is not heated by the current that flows along it.

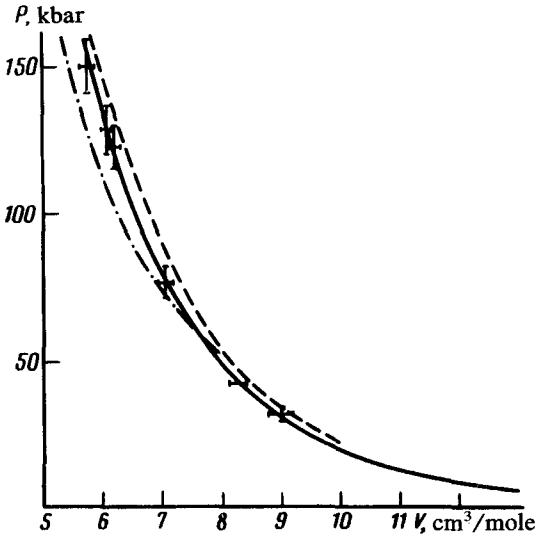

FIG. 2. Experimental points obtained by us (it is assumed that $V_0 = 22.65$ cm^3/mole). Zero isotherms: solid curve,[8] dashed curve,[10] dot-dashed curve.[11]

The experimental results are shown in Fig. 2. The experimental points were obtained at pressures of 150, 129, 123, 77, and 32 kbar with a maximum computational error $\Delta P/P = 6\%$ and $\Delta V/V = 2\%$, ignoring the error in the equation of state of potassium. One point was obtained using cesium as the reference material. Cesium has phase transitions Cs II–III at $P = 42.2$ kbar and Cs III–IV at $P = 42.7$ kbar,[7] which occur with a large total change of volume $\Delta V/V = 12\%$. By selecting the current and the recording time, it was possible to measure the pressure at which these transitions occur. It is then evident that the error in the measurement of the pressure $\Delta P = 0.5$ kbar (ignoring the temperature dependence of the transition pressure).

The experimental points which we obtained "lie" within $\sim 1\%$ on the equation of state for hydrogen. This equation was obtained in Ref. 8 by interpolation of the results in Ref. 9, taking into account the asymptotic behavior for small values of V. Figure 2 also shows the experimental dependences of $P(V)$, obtained in Refs. 10 and 11. The rather large disagreement between the results in Refs. 10 and 11 and our results lies beyond the limits of the cited accuracy.

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