Measurements of Bubble Densities in Liquid Hydrogen and Liquid Deuterium

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Abstract

Bubble densities have been measured on tracks of electrons of about 2 GeV/c in a 85 cm bubble chamber at DESY. The chamber was either filled with liquid hydrogen or with liquid deuterium. The measuring procedure including the measurement of all parameters as well as the evaluation of the data is described. Measurements have been made in large temperature and pressure intervals. Points of equal bubble density in a p-T-diagram have been fitted to parabolas through the critical point.

Introduction

The knowledge of bubble density in superheated liquids as used in bubble chambers is important both from practical and theoretical points of view.

For the use of bubble chambers in high energy physics bubble density gives additional information about the velocity of particles. The bubble density b may be described as $b = C \frac{1}{\beta^2}$. β is the ratio of the velocity of the particle and the velocity of light. C is a function of the thermodynamical properties of the liquid and could be calculated with a detailed knowledge of the process of bubble creation [1, 2, 3]. Measurements of the bubble density may give additional information about this process.

Bubble densities have been measured in several liquids [3, 4, 5]. Up to now there exist only few results for hydrogen and no information about deuterium.

Previously published measurements in hydrogen [6] have been repeated with higher accuracy due to an improved calibration of the pressure measuring device.

Experimental Arrangement

The bubble chamber was filled with hydrogen and deuterium respectively. The chamber itself was operated in the usual way. Only modifications of the optical system were made for the special purpose of measuring bubble densities.

The static pressure p_s inside the liquid of the chamber was held more than 0.3 kp/cm^2 above the equilibrium vapour pressure in order to reach and maintain stable chamber conditions between the expansions. It was measured by a precision manometer with an error of less than $\pm$ 0.03 kp/cm^2.

The chamber was expanded by a piston with an expansion rate of 1 sec^{-1}.

Pressure variations Δp were measured with a piezo quartz gauge, which was calibrated dynamically under operation conditions [7]. The error for the dynamic pressure $p = p_s - \Delta p$ is less than $\pm$ 0.1 kp/cm^2.

The static temperature T_s was measured by vapour pressure thermometers with an accuracy of ± 0.03 °K. The expansion of the chamber leads to a quasi adiabatic reduction in temperature ΔT. The rate of temperature change with pressure can be calculated from one of the following equivalent formulas in the case of an adiabatic process.

(1)
$$\left(\frac{d\,T}{d\,p}\right)_{ad} = \frac{\beta}{\alpha}\left(1 - \frac{1}{\gamma}\right)$$

(2)
$$\left(\frac{d\,T}{d\,p}\right)_{ad} = \frac{1}{\alpha}\left(\beta - \beta'\right)$$

(3)
$$\left(\frac{d\,T}{d\,p}\right)_{ad} = \alpha \cdot \frac{T}{c_p\,\varrho_l}$$

with $\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$ = factor of thermal expansion

$\beta = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T$ = isothermal compressibility

$\beta' = -\frac{1}{V}\left(\frac{d\,V}{d\,p}\right)_{ad}$ = adiabatic compressibility

$\gamma = \frac{c_p}{c_v}$ = ratio of specific heats

c_p = specific heat at constant pressure

c_v = specific heat at constant volume

ϱ_l = density of liquid

In the case of deuterium some of the thermodynamic properties are not available, as, for instance, α or β, so that $\left(\frac{d\,T}{d\,p}\right)_{ad}$ cannot be calculated from formulas (1), (2), or (3).

An approximation for the temperature drop is given by [8]

(4)
$$\frac{\Delta T}{\Delta p} = \frac{\gamma - 1}{1 + \frac{1}{\beta'}\,\frac{d\,\varepsilon}{d\,p_v}} \cdot \frac{d\,T}{d\,p_v}$$

p_v is the vapour pressure

β' can be estimated from p v diagrams

ε is the expansion ratio $\frac{\Delta v}{V}$

$\frac{d\varepsilon}{dp_v}$ is the slope of the curve $p_v(\varepsilon)$ which seperates the phase regions of pure liquid and liquid/vapour in equilibrium.

The main uncertainty in formula (4) arises from $\gamma = \frac{c_p}{c_v}$, which is not available for deuterium in the region of interest. As we had some starting points at lower temperature, we extrapolated them to higher temperatures in relation to the hydrogen data, using a plot in reduced temperature units. The rate of temperature reduction is of the order of 0.1 $^{o}K/kp/cm^2$. With the knowledge of the temperature drop due to the expansion we estimated the total error of temperature measurements to be about ± 0.05 ^{o}K.

The bubbles inside the liquid were produced by a beam of about 2 GeV/c electrons from the DESY synchrotron. As these electrons are extremely relativistic, small deviations in energy should not affect the ionisation power along the tracks.

The expansion system was operated with the maximum possible amplitude at given static temperature T_s and static pressure p_s. The time of beam injection was shifted between the moment when the pressure curve passed the vapour pressure and the moment when the minimum of the expansion was reached. Varying the time of injection in this way we could choose the dynamic pressure at the time of creation of bubbles without disturbing the thermal equilibrium in the chamber. This method requires a very short beam pulse. In our case with a pulse length of about 10 μs the error in pressure introduced by the fastest pressure variation rate of 1 kp/cm^2msec was of the order of 0.01 kp/cm^2. This is small compared with the measuring error of the dynamic pressure. In order to be sure that the bubble density measured in this way does not depend on the pressure variation at beam injection, the measurements had to be extended to the time region after the minimum of the pressure curve. This has been done in the case of deuterium. Within the errors of our measurement we did not find any differences in bubble densities between corresponding pressures before and after the minimum (see Fig. 2).

Bubbles can be photographed only after a certain time of growth, when they have reached a size sufficient for optical resolution. Due to the statistical distribution of bubbles along the track, some of them may have grown together to form a single bubble within this time, so that one has to correct the density on the photograph for this effect. In order to get an idea of the magnitude of this correction, we photographed the bubbles at three different times, 0.5 msec, 1.0 msec, 1.5 msec after beam injection. A linear extrapolation of these three densities to the time of injection should give a good approximation to the real bubble density. Measurements in propane [4, 5] indicate that at very high bubble densities the time dependence of bubble density is no longer linear. This effect can be neglected at the bubble densities discussed in this paper.

Track photographs have been taken with two different optical systems. A magnification of 1:1 in bright field illumination was used for high and mean bubble densities. For low densities a demagnfication of 1:8 and a dark field illumination were used. The optical resolution was 10^{-3} cm in the case of scale 1:1 and about 10^{-2} cm for the 1:8 scale.

More than 200 bubbles were counted for each measured point. The bubble density which we got by this method should have a mainly statistical error of less than 10 %. The method of direct bubble counting was chosen because on all our photographs the bubble density was small enough, so that each bubble of a track could be recognized in the 1:1 scale. The possibility of recognizing all bubbles depends strongly on the size of the bubbles. In the case of hydrogen the diameters of the measured bubbles were smaller than 0.15 mm. Thus we should be able to count some 60 b/cm without any loss.

Experimental Results

Bubble densities have been measured at static temperatures T_s: 25°, 26°, 27°, 28°K in liquid hydrogen and at 30°, 31°, 32°K in liquid deuterium. The temperature at the moment of injection was calculated from formulas (1)-(4). Different pressure drops at constant static temperature T_s and constant static pressure p_s result in different dynamic temperatures T. As there are only small differences between the dynamic temperatures in the sensitive region, results are shown in Fig. 1 for hydrogen and Fig. 2 for deuterium at mean temperatures $\bar{T}$.

Measurements at each mean temperature $\bar{T}$ have been fitted to a straight line. The intersecting point of this line with the pressure axis at zero density gives a limit of sensitivity for this temperature. Several published measurements in hydrogen and propane seem to indicate a deviation from linearity at low bubble densities [4, 5]. Therefore the limit of sensitivity should lie above the extrapolated limit.

A visual method using a television camera [7] gives a limit of sensitivity which coincides practically within the errors with the extrapolated value from bubble counting in the case of hydrogen. In deuterium the two limits differ by about 0.3 kp/cm^2.

The slope of the straight lines in Figs. 1 and 2 is not identical for all temperatures. In the case of hydrogen it varies from - 29.4 b/cm kp/cm^2 at 24.79 °K to - 76.9 b/cm kp/cm^2 at 27.73 °K. In deuterium the slope changes from - 11.4 b/cm kp/cm^2 at 29.69 °K to - 30.8 b/cm kp/cm^2 at 31.69 °K.

If we compare our measurements in hydrogen with those of Biswas et al., [9] we find a rough agreement within the errors of measurement. As other authors [10] have done we represent our results by the p-T diagrams Fig. 3 for hydrogen and Fig. 4 for deuterium. Lines of constant bubble densities as well as the limits of sensitivity have been extracted from Figs. 1 and 2. Points of equal density have been fitted to a parabola through the critical point.

$$p = p_c + a(T-T_c) + b(T-T_c)^2 \tag{5}$$

p_c and T_c are the critical pressure and the critical temperature, respectively.

The dotted lines indicate a limit of sensitivity which was independently measured by the method mentioned above. The parameters a and b for this limit as well as the critical data p_c and T_c are given in Table I.

Summary

Bubble densities for liquid hydrogen and liquid deuterium have been measured between 24.77 and 27.78 °K, 29.70 and 31.75 °K respectively.

Bubble densities as a function of pressure for constant temperatures have been fitted by straight lines, which have been extrapolated to find a lowest value for the limit of sensitivity. The slope of these lines in the b,p-diagram is not constant for all temperatures, but increases for higher temperatures.

At a total view of the measured regions the slope in deuterium is lower than in hydrogen by an average factor of 2.5, i.e. a bubble chamber filled with deuterium is less sensitive to pressure variations.

For deuterium the visually measured limit of sensitivity differs from the extrapolated zero density by about 0.3 kp/cm^2.

In the case of hydrogen a difference could not be found within our measuring accuracy.

Generally higher pressure drops are needed in deuterium to achieve the same bubble density as in hydrogen. As is usual in bubble chambers, the maximum pressure drop is limited; difficulties may arise if higher bubble densities are desired.

Acknowledgements

We are greatly indebted to Professor M.W. Teucher and Dr. E. Lohrmann for their continued interest and encouragement in the course of these investigation. We also thank our bubble chamber team, especially W. Eschricht, H. J. Fiebig, U. Knopf, K. D. Nowakowski, O. Peters, and W. Stahlschmidt. For the measuring of the films we thank Miss I. Kurth, R. Lange and Miss S. Nolte.

Furthermore we have to thank the DESY machine group as well as the beam operating crew for the excellent performance of the synchrotron and the beam.

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Table 1

Parameters of parabolas giving the limits of sensitivity in liquid hydrogen and liquid deuterium

	T_c °K	p_c kp/cm^2	a kp/cm^2 °K	b kp/cm^2 °K^2
Hydrogen	32.976	13.180	2.039±0.006	0.0768±0.0008
Deuterium	38.35	16.45	2.374±0.012	0.0853±0.0016

Figure Captions

Fig. 1 Bubble density as a function of pressure in liquid hydrogen

Fig. 2 Bubble density as a function of pressure in liquid deuterium.
Dots indicate bubble densities obtained by injecting the electron beam before the minimum pressure was reached.
Circles indicate bubble densities for beam injection after the minimum pressure.

Fig. 3 Bubble density in a p-T diagram for liquid hydrogen. The limit of sensitivity has been measured by a visual method [7].

Fig. 4 Bubble density in a p-T diagram for liquid deuterium. The limit of sensitivity has been measured by a visual method [7].

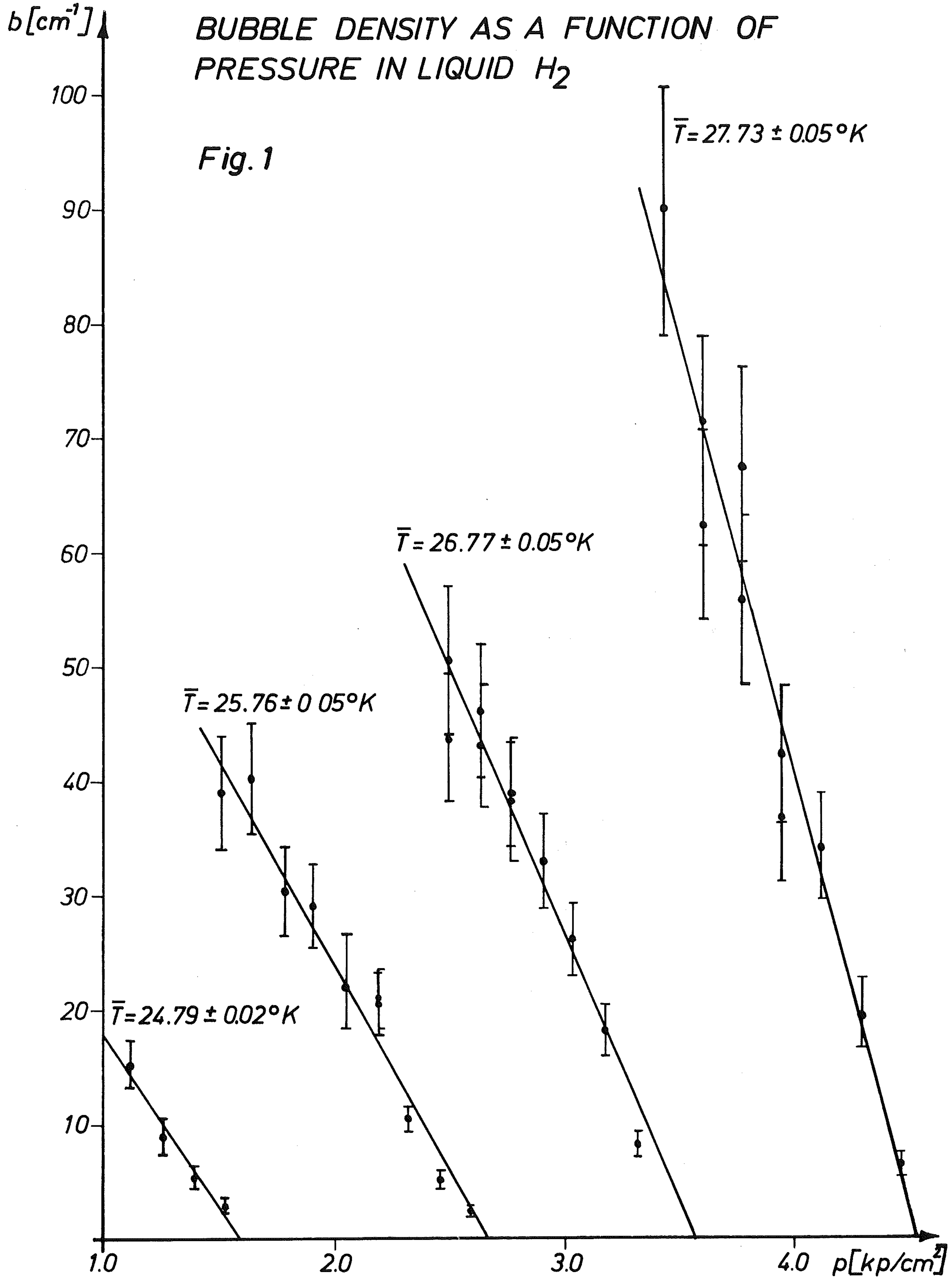
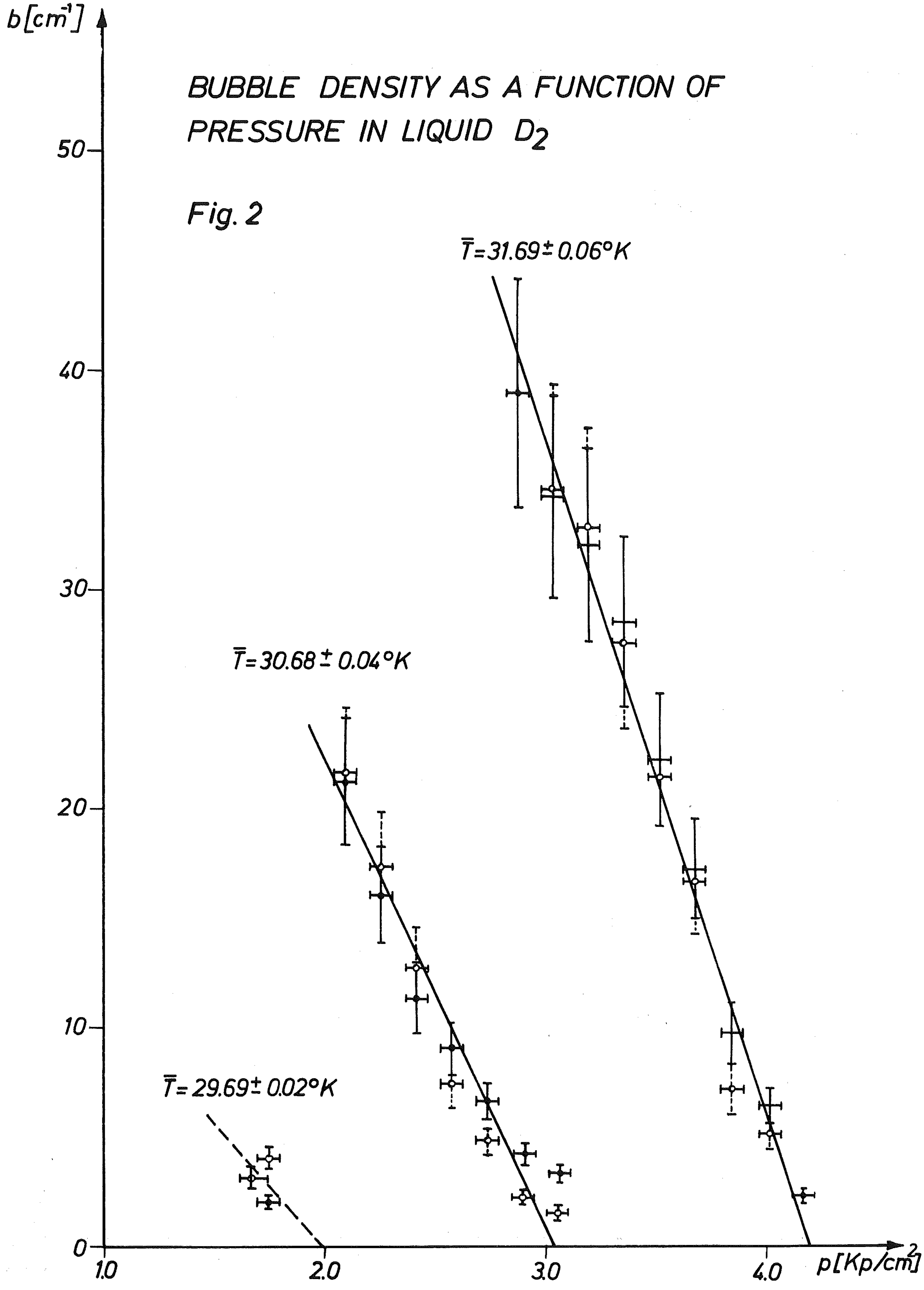


Fig. 1

BUBBLE DENSITY AS A FUNCTION OF PRESSURE IN LIQUID H_2



BUBBLE DENSITY AS A FUNCTION OF PRESSURE IN LIQUID D_2

Fig. 2

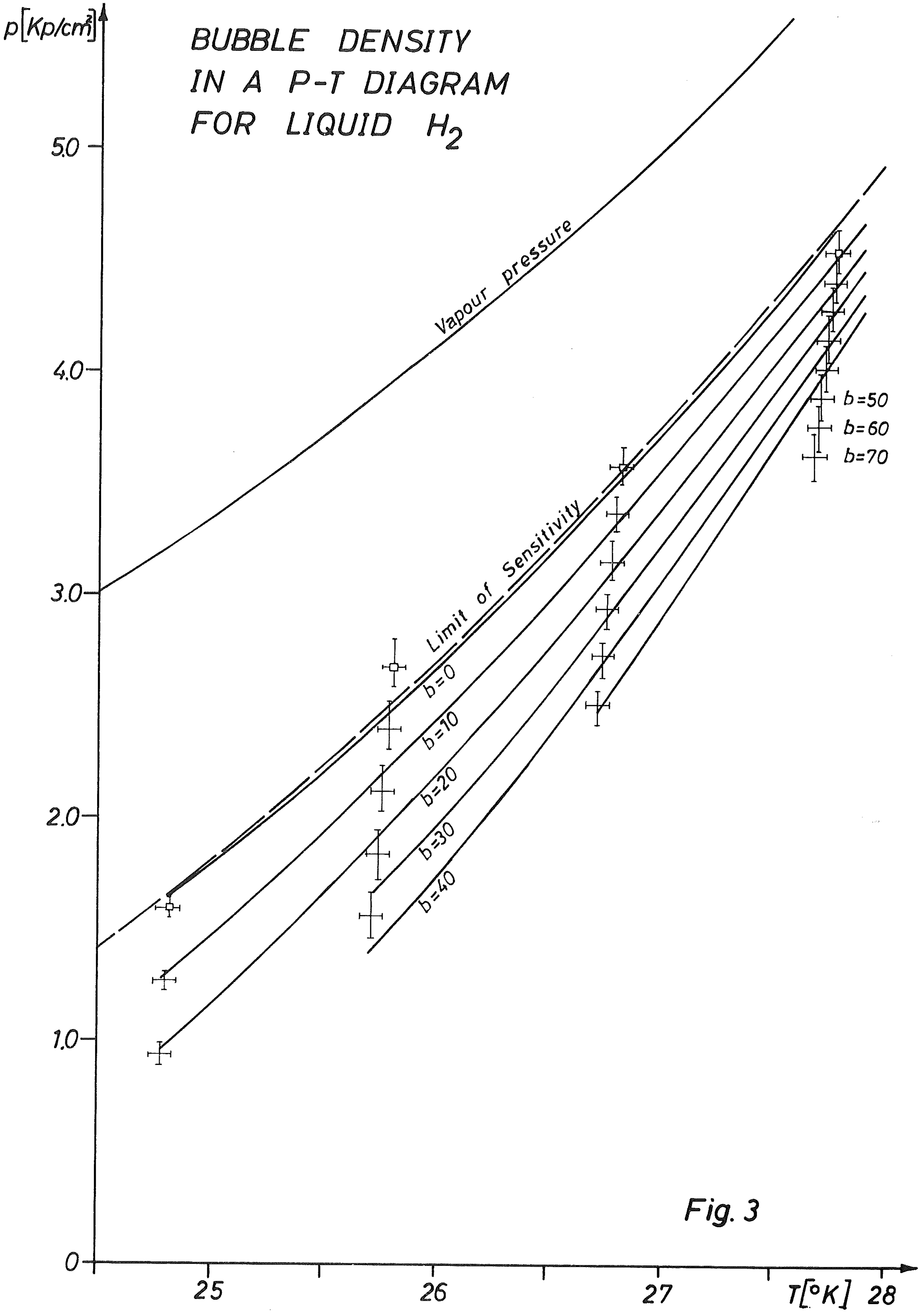
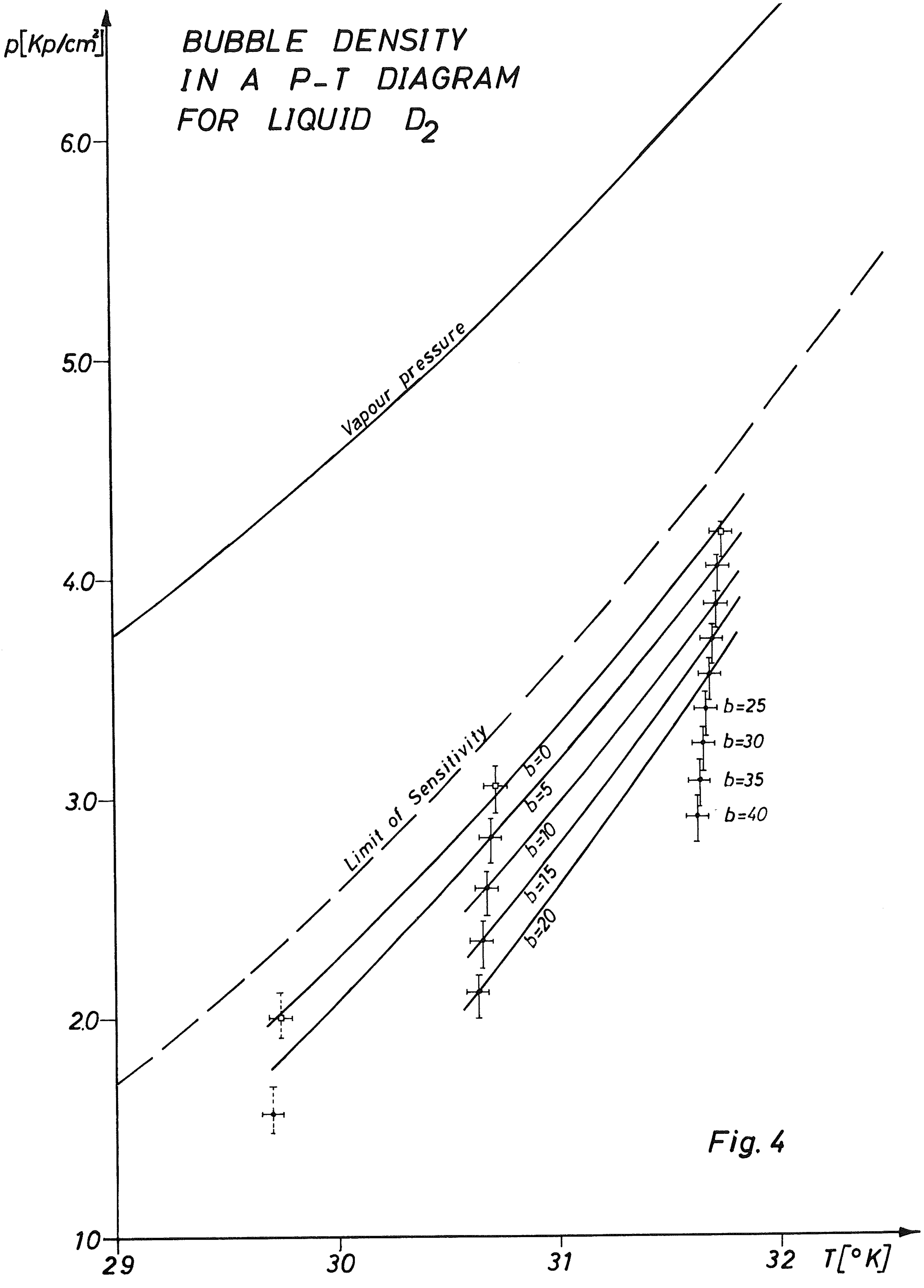

BUBBLE DENSITY
IN A P-T DIAGRAM
FOR LIQUID H_2
p [Kp/cm²]
5.0
4.0
3.0
2.0
1.0
0
25
26
27
28
T [°K]
Vapour pressure
Limit of Sensitivity
b=0
b=10
b=20
b=30
b=40
b=50
b=60
b=70

Fig. 3



BUBBLE DENSITY IN A P-T DIAGRAM FOR LIQUID D_2

Fig. 4