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G. Horlitz and S. Wolff
Deutsches Elektronen-Synchrotron DESY Hamburg

and

G. Harigel
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Abstract

The formation of single bubbles by β-electrons from the decay of tritium has been investigated in the DESY 85 cm hydrogen bubble chamber. The probability of bubble formation was measured at 24.8 K and 25.7 K and for different dynamic pressures. The atomic tritium concentration (c = number of tritium atoms / number of hydrogen atoms) varied between 10^{-15} and 10^{-11}. A method for extrapolating the results to deuterium is described.

I. Introduction

Surface waters in the northern hemisphere are the main source for hydrogen and deuterium production. They are increasingly contaminated by radioactive tritium, which has a half-life of 12.46 y and emits β^--particles with a maximum energy of 18.6 keV.

Tritium is produced to some extend in the upper atmosphere by interaction of cosmis radiation with nitrogen and to a much higher rate in the stratosphere by thermonuclear testing; furthermore it is released by nuclear power stations and uranium processing plants. Today the total accumulative input has resulted in several hundreds of T.U. in precipitation, 100 - 200 T.U. for rivers and lakes, 20 T.U. in surface sea water and 1 - 5 T.U. for ocean waters (T.U. = tritium unit = ^3H / 10^{18} H) [1), 2)]. If no precautions are taken during the isotope separation, these contaminations may result in a tritium-to-deuterium ratio of up to 10^{-12}. For big bubble chambers large quantities of deuterium will be needed; its price and availability vary considerably with the tritium content.

One aim of the present experiment was to get an overall impression of the influence of tritium-decay on bubble chamber operation and subsequent track evaluation, both for dark and bright field pictures. The decay electrons can produce bubbles, which are able to disturb the analysis of bubble chamber pictures (cf. fig. 1). This effect depends on the number of decays between the beginning of the sensitive time and the photography of tracks, on dark or bright field illumination, on the optical demagnification, and on the volume of the chamber. For test purposes and comparison a beam of ionizing particles from the DESY machine was used.

The main purpose of the present study was, however, to derive quantitative relations between the bubble production probability from tritium decay (number of bubbles per unit volume of the liquid) and the liquid temperature and dynamic pressure in the chamber.

Although our experiment has been performed in liquid hydrogen for financial reasons, the results can be applied to the operation of tritium contaminated deuterium in bubble chambers without any difficulties by using former experimental results for bubble growth and density of minimum ionizing particles in hydrogen and deuterium [3),4)]. Present results, obtained in a medium sized bubble chamber, can be extrapolated to any chamber and its particular operating conditions, thus allowing the determination of the tolerable tritium contamination of deuterium for any specific experiment.

II. Measuring Procedure

The measurements have been performed on the 85 cm cryogenic bubble chamber at DESY. The chamber was filled with liquid hydrogen and expanded at a rate of 1 expansion per second to a pressure region where liquid hydrogen is sensitive to bubble nucleation for ionizing particles. The static temperature T_s of the chamber was measured by vapour pressure thermometers and stabilized within $\pm$ 0.03 K. The static pressure p_s (between the expansions) was stabilized within $\pm$ 0.03 bar. The dynamic pressure p(t) was measured with piezoelectric pressure transducers. The expansion system was running very stable so that over the whole time of our measurements no significant deviation of pressure curves from each other could be detected. Due to errors coming from the calibration [5)] of these transducers the accuracy of the pressure measurement was $\pm$ 0.1 bar.

The pressure vs time curve for T_s = 25.0 K is shown in fig.2. The mean half width of this curve is 14 ms. The pressure limit of sensitivity was detected by the aid of a beam of charged particles from the synchrotron. The occurrence of bubbles and tracks could be seen on a television screen. The time t_o at which the pressure dropped below the limit of sensitivity was defined as the time zero for each measurement. The pressure minimum was reached about 3 ms

after t_o. At about 8 ms after t_o the pressure crossed the limit of sensitivity again, this time with a positive time gradient.

The fast pressure drop in the chamber gives an adiabatic temperature reduction [5] of the order of $\leq$ 0.1 K/bar. In the tables and the drawings of our results this temperature reduction is included in the given temperature values T_{min}. The total error in temperature measurements is about $\pm$ 0.05 K.

Starting with pure liquid hydrogen in the chamber the tritium concentration was increased by filling rarefied gaseous tritium into the lower part of the chamber liquid in several steps and in well defined quantities. The condensation of tritium and its dilution in the liquid was supported by keeping the expansion system running during this process while all valves to the chamber were closed. Before and after the measurements at each tritium concentration a sample of evapourated liquid was extracted from the chamber which was analyzed later in order to confirm the calculated values.

Measurements have been made at the concentrations, temperatures and pressures shown in table 1.

At each concentration a part of the chamber (the depth of the chamber is 40 cm) was photographed with dark field illumination and a demagnification of 1 : 15. For some concentrations we photographed simultaneously another part of the chamber in bright field illumination and a 1 : 15 or a 1 : 65 demagnification in order to get information about the resolution limit for the photography of isolated bubbles and to simulate conditions of large bubble chambers. The set-up of the bright field measurements and the results will be described elsewhere [6].

Two sets of experiments were done: First, for all tritium concentrations the flash delay with respect to the time t_o at which the pressure dropped below the limit of sensitivity, was kept constant.

A relatively large delay time of 6 ms was chosen. For comparison the chamber was also photographed with a charged particle beam. This beam was injected at the pressure minimum which was at 3 ms, so that bubbles along the beam tracks had a growth time of 3 ms before being photographed. The above flash delay was chosen in order to establish experimental conditions similar to the conditions in big bubble chambers. In these large chambers flash delays of the order of 4 - 8 ms will probably be required because of the necessity of bubble sizes superior to the bubble diameters in small chambers. Furthermore, these measurements at a fixed flash delay give an independent check of the tritium concentration.

Second, at all tritium concentrations $\geq 5 \times 10^{-13}$ the bubbles in the chamber (without beam) have been photographed at various delay times after t_o in steps of $\Delta t = 1$ ms in order to measure the dependence of bubble density B (bubbles/cm^3) upon time for the total expansion cycle and to derive its dependence upon pressure.

For each measuring point - i.e. for a combination of one tritium concentration, one temperature of the liquid, one static and one minimum pressure, one flash delay - 20 photographs have been taken. For each frame between 50 and 100 bubbles have been counted in the central region of the picture where illumination was homogeneous. The calculated errors are the standard deviations for the mean values of the different counts.

III. Results of Measurements

The results for a constant flash delay of 6 ms are given in fig.3. The straight line (I) indicates the bubble density B if the probability for a tritium decay to give a bubble were exactly one. The measured bubble density should in general be smaller and on a straight line parallel to this line. There is a slight deviation

from parallelity. This can be explained by the loss of bubble counts at high bubble densities (overlapping bubble images due to the depth of the chamber) or by small changes of the expansion curve during the experiment. Below a tritium contamination of 10^{-15} the bubble density is about 10^{-3} bubbles per cm^3 and is independent of the number of tritium decays (II). This is the background of spurious bubbles in the chamber.

From the measurements of the bubble density B for various flash delays the dependence of B upon the dynamic pressure p(t) can be derived. As an example the measured bubble density as a function of time at a liquid temperature T_{min} = 24.8 K and a minimum pressure p_{min} = 1.26 bar is given in fig. 4, curve A. After the passage of the limit of sensitivity, which is at t = 0 ms, the bubble density is zero and increases with time. The rate of increase has its maximum between 2 and 3 ms which corresponds to the minimum of the pressure. Then the time gradient of the bubble density decreases and becomes zero again when the pressure has passed the limit of sensitivity at about 8 ms. Afterwards the bubble density remains almost constant at its maximum for some time before bubbles will be compressed by the increasing pressure.

Within the accuracy of our experiment the rate $\frac{dB}{dt}$ of bubble production per cm^3 as a function of pressure (fig. 5) indicates a linear dependence. This corresponds to the linearity of bubble density b as a function of pressure at bubble formation along tracks of charged particles [3), 4)].

The rate of bubble production $\frac{dB}{dt}$ is proportional to the rate of tritium decays $\frac{dn}{dt}$ in a cm^3 of liquid. We define the probability for bubble creation at tritium decay by

$$(1) \qquad \frac{dB}{dt} = w \cdot \frac{dn}{dt} \quad ,$$

w depends on the thermodynamic properties of the liquid. For a

constant tritium concentration c, $\frac{dn}{dt}$ is constant and (according to fig. 5) we can put

$$(2) \qquad w = a_o + a_1 \cdot p$$

The parameters a_o and a_1 have to be determined.

At the end of the sensitive time of the chamber (t_e) the bubble density is

$$(3) \qquad B_e = \int_{t_o=0}^{t_e} \frac{dB}{dt}\, dt = a_o \cdot \frac{dn}{dt}\, t_e + a_1 \cdot \frac{dn}{dt} \int_{t_o=0}^{t_e} p(t)\, dt$$

As the pressure p can be expressed as

$$(4) \qquad p(t) = p_{sens} - \Delta p(t)$$

where p_{sens} is the limit of sensitivity, we have

$$(5) \qquad B_e = a_o \cdot \frac{dn}{dt}\, t_e + a_1 \cdot \frac{dn}{dt}\, p_{sens}\, t_e - a_1 \cdot \frac{dn}{dt} \int_{t_o=0}^{t_e} \Delta p(t)\, dt$$

The integral in the last term is the area between the pressure-time curve and a straight line at $p = p_{sens}$ (compare fig. 2).

With the condition $B_e = 0$ for $t_e = t_o$ follows

$$(6) \qquad a_1 = - \frac{a_o}{p_{sens}}$$

and

$$(7) \qquad B_e = a_o \cdot \frac{dn}{dt}\, \frac{1}{p_{sens}} \int_{t_o=0}^{t_e} \Delta p(t)\, dt$$

a_o can now be calculated by measuring B_e for a known pressure curve. With a_o known, the function B(t) can be calculated for the entire expansion cycle. This calculated curve (fig. 4, curve B) is compared with the measured one (curve A). Up to about 5 ms the

measured curve coincides with the calculated one within the limits of our accuracy. At the end of the sensitive period bubbles are growing slower because of the rising pressure. Therefore, bubbles which are created late become also visible very late. Consequently the saturation value of the measured bubble density occurs later than calculated.

The parameters a_1 and a_o have been determined from several measurements at $T_{min} = 24.8$ K and $T_{min} = 25.7$ K. A mean value for a_1 is calculated for each temperature. The corresponding functions for w(p) are indicated in fig. 6.

The dashed lines give the limits of accuracy due to the errors in the determination of the absolute values of pressure. The maximum value for the probability is w = 1. Due to the low energy of the decay electrons ($\leq$ 18.6 keV) and their short range in liquid hydrogen (< 120 µm) it is impossible for one electron to create more than one visible bubble.

IV. Extrapolation of the Results to Deuterium

In the present experiment in liquid hydrogen a linear dependence of bubble density B in tritium decay upon pressure was found for two liquid temperatures. A similar linear dependence exists between bubble densities b along tracks of ionizing particles. This analogy indicates, that there is no basic difference in the production mechanism for bubble nuclei: in both instances, bubbles are created by δ-electrons and there exists a proportionality between track bubble density b and bubble creation probability at tritium decay w. A reasonable assumption is that the same proportionality between b and w remains valid for deuterium. Especially zero probability is identical with zero bubble density in both liquids. Therefore extrapolations of the probability w of bubble formation at tritium

decay from hydrogen to deuterium are justified and have been done by using earlier measurements on track bubble densities b [3), 4)] and growth factors A [3)]. (A is defined by $r = A\sqrt{t}$, r = bubble radius in cm, t = growth time in s).

The bubble density b as well as the growth factor A are reversible functions of the pressure p and the temperature T in the liquid.

$$(8) \qquad \begin{aligned} b &= f\,(p, T) & p &= f^{*}\,(b, T) \\ A &= g\,(p, T) & p &= g^{*}\,(A, T) \end{aligned}$$

The functions f^{*} and g^{*} with b and A as parameters are given in fig. 7 for hydrogen and in fig. 8 for deuterium. Using the above assumptions, instead of curves of constant bubble density b, curves of constant w could be drawn into figs. 7 and 8 which are parallel to the density curves.

From fig. 6 we take the pressure for both temperatures at which we have measured the probability w = 0.5:

$$(9) \qquad \begin{aligned} p(T = 24.76\ \text{K},\ w = 0.5) &= 1.29\ \text{bar} \\ p(T = 25.78\ \text{K},\ w = 0.5) &= 2.20\ \text{bar} \end{aligned}$$

The temperatures given here have been corrected for the isenthalpic temperature change for the above dynamic pressures.

With these pressure and temperature values we step into fig. 7. The two points which are indicated with their measuring errors define the w = 0.5 curve which coincides with the b = 11 cm^{-1} curve. This relation is assumed to be valid in deuterium as well and is shown in fig. 8, giving points of w = 0.5.

With the aid of the b = 0 cm^{-1} curve (identical with the w = 0 line) it is possible to derive figures showing w as a function of pressure p for all interesting temperatures. As an example fig. 9 gives w (p) for the two temperatures 30.0 K and 31.0 K. However it should be mentioned that there is a difference between the two lines

"b = 0 cm^{-1}" and "limit of sensitivity" shown in figs. 7 and 8 (see figure captions). This difference which is due to deviations from linearity of the relation between bubble density and pressure is more pronounced in deuterium. Consequently for small probabilities ($w < 0.15$) a deviation from linearity of the curves of fig. 9 has to be expected (dotted lines).

V. Conclusions

The probability w of bubble nucleation in tritium decay in liquid hydrogen is a linear function of the dynamic pressure p(t) at constant temperature T. This behaviour is similar to that of the bubble density b measured in tracks of ionizing particles. The probability w increases with decreasing pressure at constant temperature and with increasing temperature at constant pressure. In the region where the linear dependence of bubble density b on pressure is also valid in deuterium the probability w can be calculated for this liquid also. The results can be used for the determination of bubble densities B in any chamber.

Acknowledgement

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References

1) International Atomic Energy Agency, Vienna, Technical Reports Series No. 96 (1969), No. 117 (1970), No. 129 (1971)

2) R.M.Brown, International Atomic Energy Agency, Vienna, in "Isotope Hydrology, 1970", and private communication

3) S.Wolff, "Blasenbildung und Blasenwachstum in einer mit Wasserstoff und Deuterium gefüllten Blasenkammer", Thesis, Hamburg (1969)

4) G.Horlitz, S.Wolff, and G.Harigel, DESY 68/45, (1968)

5) G.Horlitz, S.Wolff and G.Harigel, Nucl. Instr.Meth. 65, 353, (1968)

6) G.Harigel, G.Horlitz and S.Wolff, to be published

Table 1 Chamber Conditions and Tritium Concentrations

chamber conditions	tritium concentrations c = number of tritium atoms/number of hydrogen atoms												
T_s=25.0 K T_{min}=24.8 K p_s=3.93 bar p_{min}=1.26bar	$<1\cdot10^{-15}$	$1\cdot10^{-15}$	$3\cdot10^{-15}$	$1\cdot10^{-14}$	$3\cdot10^{-14}$	$5\cdot10^{-14}$	$1\cdot10^{-13}$	$2\cdot10^{-13}$	$5\cdot10^{-13}$	$1\cdot10^{-12}$	$2\cdot10^{-12}$	$5\cdot10^{-12}$	$1\cdot10^{-11}$
T_s=26.0 K T_{min}=25.7 K p_s= 4.55 bar p_{min}=1.76bar									$5\cdot10^{-13}$	$1\cdot10^{-12}$	$2\cdot10^{-12}$	$5\cdot10^{-12}$	$1\cdot10^{-11}$
T_s=26.0 K T_{min}=25.7 K p_s=5.10 bar p_{min}=2.05bar									$5\cdot10^{-13}$	$1\cdot10^{-12}$			

Figure Captions

Fig. 1 Bubble Chamber Photograph at a Tritium Contamination of 5×10^{-12}.
Chamber conditions: T_{min} = 24.8 K (temperature of the liquid at the minimum of the expansion curve), P_{min} = 1.26 bar (pressure at the minimum of the expansion curve), t_f = 6 ms (time of flash firing, i.e. the photograph has been taken 6 ms after the pressure in the chamber has dropped below the limit of sensitivity), beam injection 3 ms before firing the flashs.

Fig. 2 Dynamic Pressure p as a Function of Time t.
T_s = static temperature = 25.o K, P_s = static pressure before the expansion, p_{sens} = pressure below which the liquid is sensitive against bubble nucleation by ionizing particles (limit of sensitivity), p_{min} = minimum of the dynamic pressure, t_o = first time when $p = p_{sens}$, t_e = time when the sensitive period of the chamber is finished.

Fig. 3 Measured Bubble Density B as a Function of Tritium Contamination c at a Flash Delay of 6 ms.
The line denoted by I gives the case when each tritium decay results in the creation of a bubble. Line II gives the background of spurious bubbles in our chamber.

Fig. 4 Bubble Density B as a Function of Time t.
The solid line A connects the measured points. The dashed line B gives a calculated B(t) curve assuming a linear dependence of pressure p for the probability w of bubble formation. T_{min} = 24.8 K, p_{min} = 1.26 bar, $c = 5 \times 10^{-13}$

Fig. 5 Rate of Change of Bubble Density $\frac{dB}{dt}$ as a Function of Pressure p.
Same conditions as for fig. 4.

Fig. 6 Probability w of Bubble Creation at Tritium Decay in Liquid Hydrogen as a Function of Pressure p.
The temperatures indicated are the liquid temperatures T_{min} at the minimum of the dynamic pressure. The dashed lines give the limits of accuracy due to the errors in the determination of the absolute values of pressures.

Fig. 7 Bubble Density b and Growth Factor A for Minimum Ionising Particles in a p - T Diagram for Liquid Hydrogen.
Curves of equal bubble density or equal growth factor are indicated. The curve b = 0 has been achieved by linear extrapolation to zero of the bubble densities as a function of pressure. In addition there is the limit of sensitivity measured by looking at the whole chamber and measuring the pressure when the first bubbles start to appear. The measurements of bubble densities B for tritium contamination have been performed at the two points indicated in the diagram.

Fig. 8 Bubble Density b and Growth Factor A for Minimum Ionising Particles in a p - T Diagram for Liquid Deuterium.
For explanations look at figure captions of fig. 7. The dashed lines denoted by u and v indicate points of bubble chamber expansions at dynamic temperatures of 30 K and 31 K at zero bubble density. Here the isenthalpic temperature drop during the expansion is taken into account.

Fig. 9 Probability w of Bubble Creation at Tritium Decay in Liquid Deuterium as a Function of Pressure p.
The solid lines are extracted from lines u and v of fig. 8. The dashed lines are giving the maximum error. The dotted lines indicate the expected deviations from linearity.

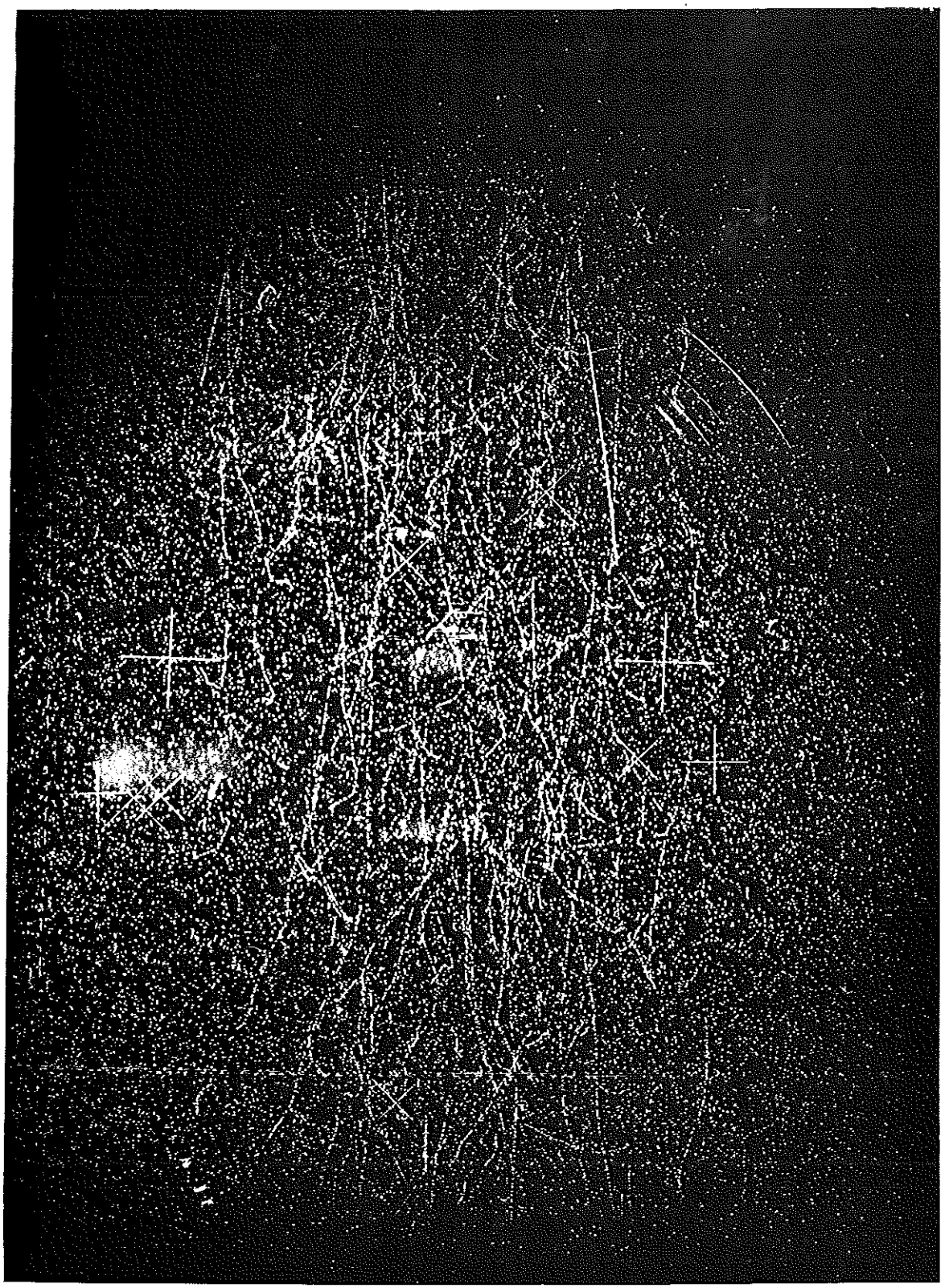

Fig. 1 Bubble Chamber Photograph at a Tritium Contamination of 5×10^{-12}

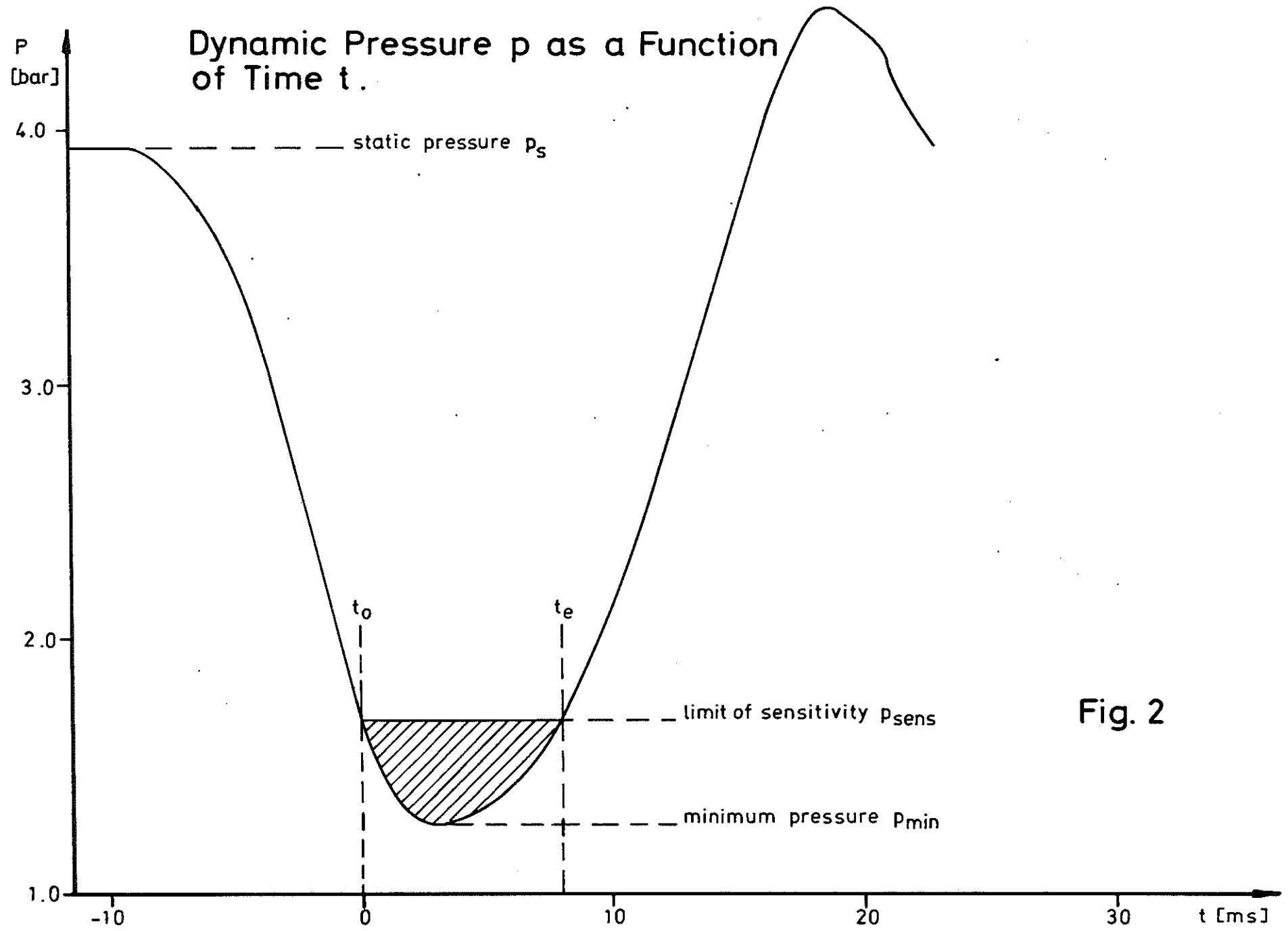
Dynamic Pressure p as a Function of Time t.
P [bar]
4.0
3.0
2.0
1.0
static pressure p_s
t_o
t_e
limit of sensitivity p_{sens}
minimum pressure p_{min}
-10
0
10
20
30
t [ms]

Fig. 2

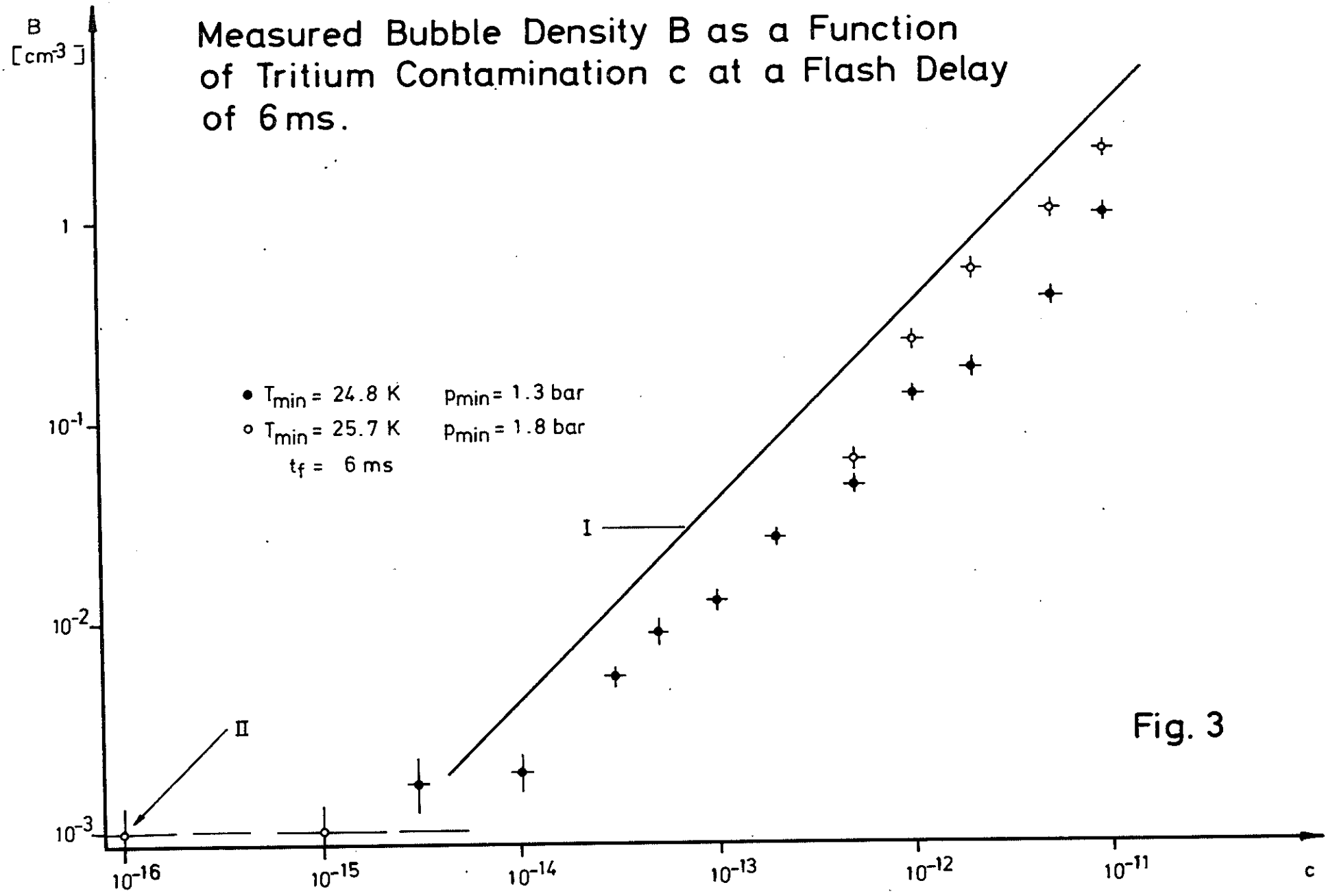
Measured Bubble Density B as a Function of Tritium Contamination c at a Flash Delay of 6 ms.
B [cm-3]
1
10-1
10-2
10-3
• Tmin = 24.8 K
pmin = 1.3 bar
○ Tmin = 25.7 K
pmin = 1.8 bar
tf = 6 ms
I
II
10-16
10-15
10-14
10-13
10-12
10-11
c

Fig. 3

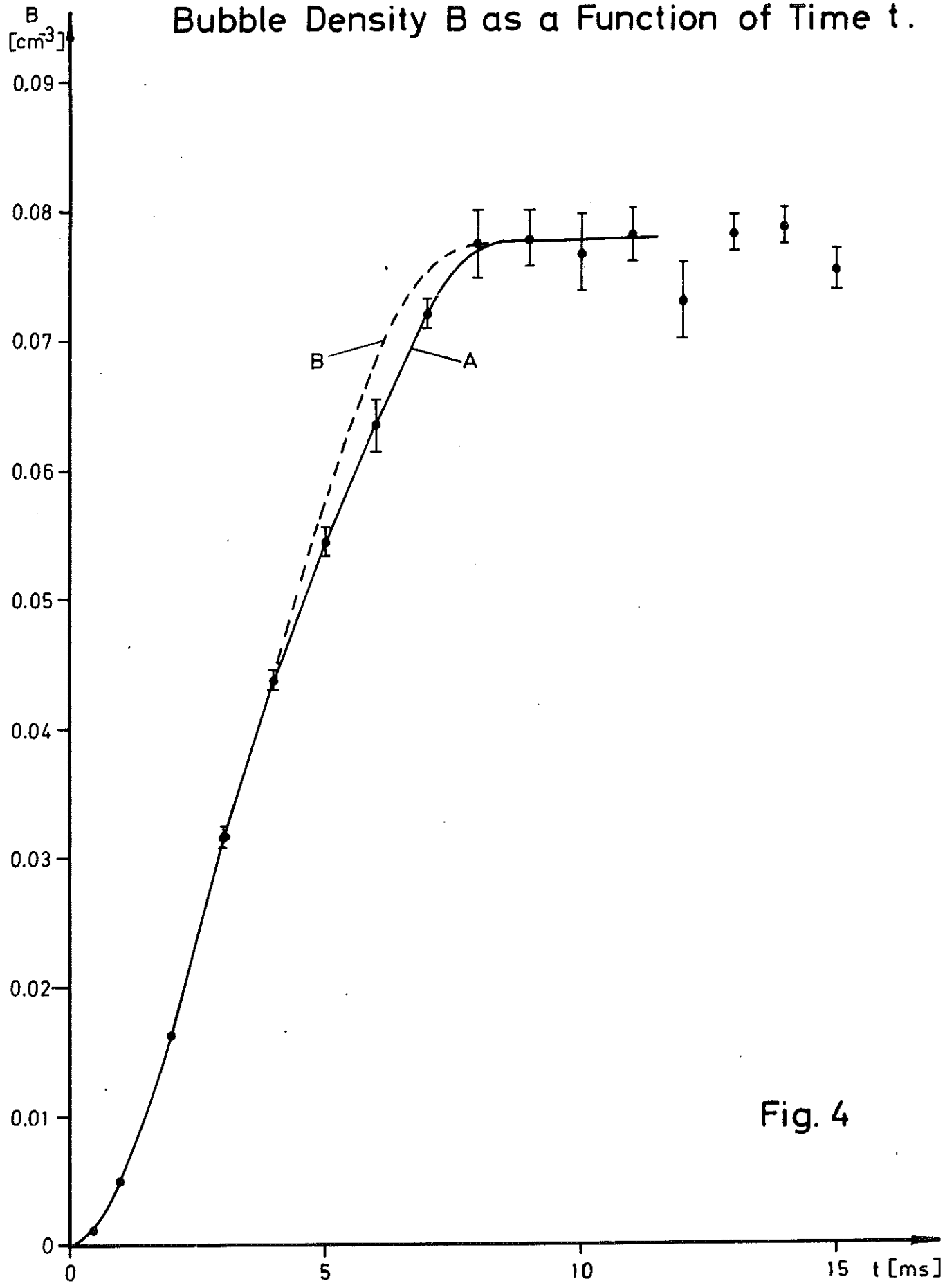
Bubble Density B as a Function of Time t.
B [cm^3]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
B
A
0
5
10
15
t [ms]

Fig. 4

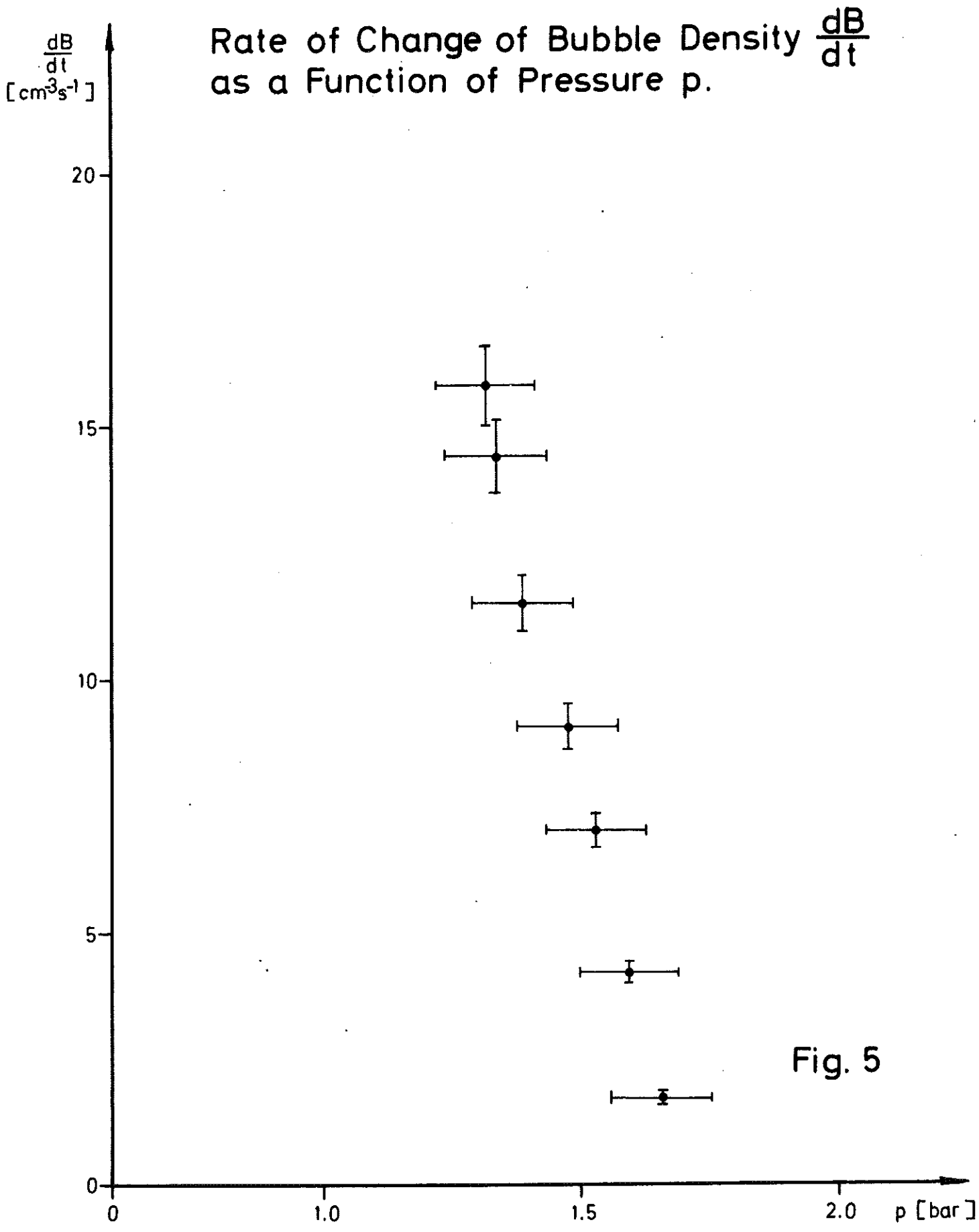
Rate of Change of Bubble Density dB/dt as a Function of Pressure p.
dB/dt [cm⁻³s⁻¹]
20
15
10
5
0
0
1.0
1.5
2.0
p [bar]

Fig. 5

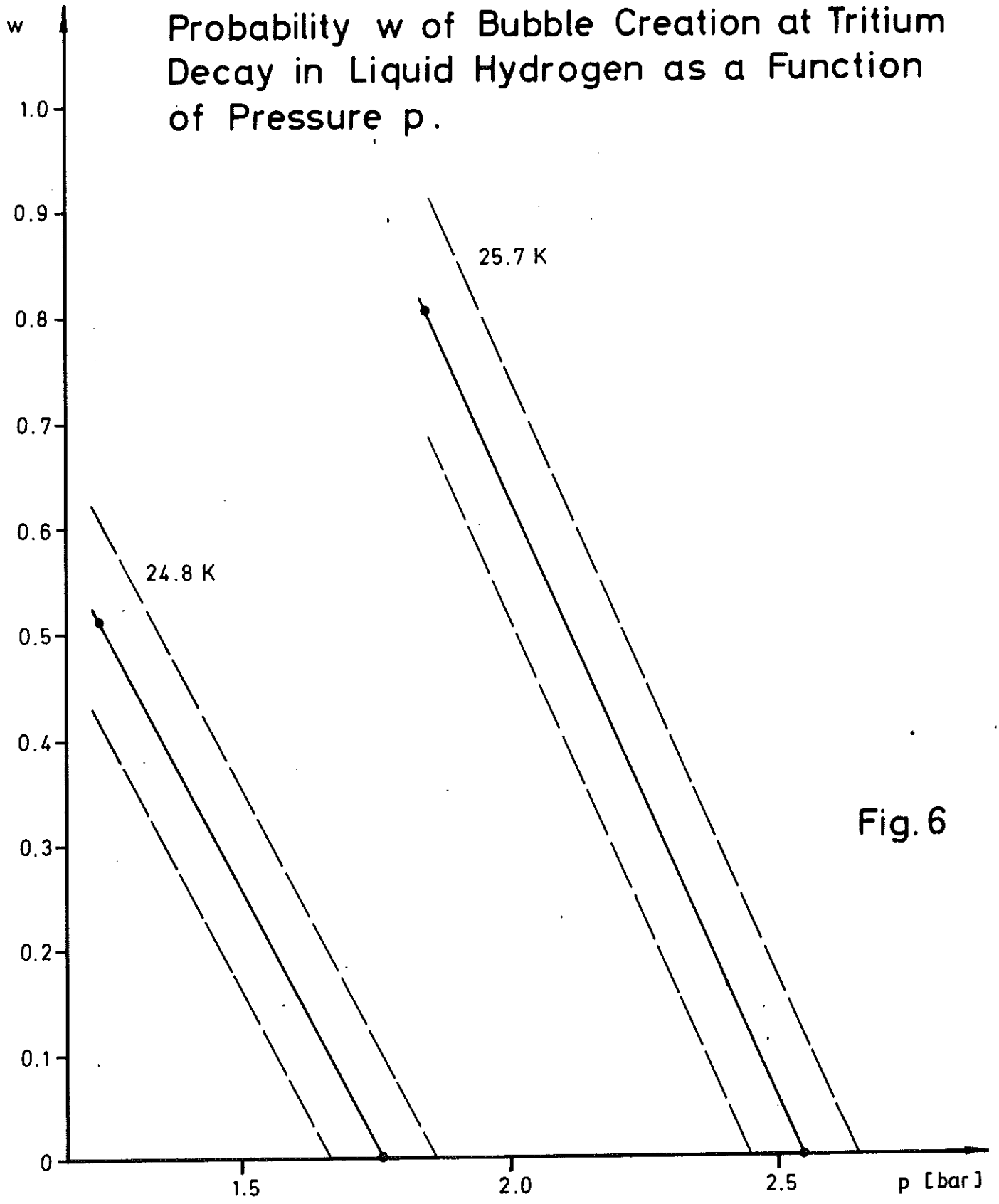
Probability w of Bubble Creation at Tritium Decay in Liquid Hydrogen as a Function of Pressure p.
w
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
25.7 K
24.8 K
1.5
2.0
2.5
p [bar]

Fig. 6

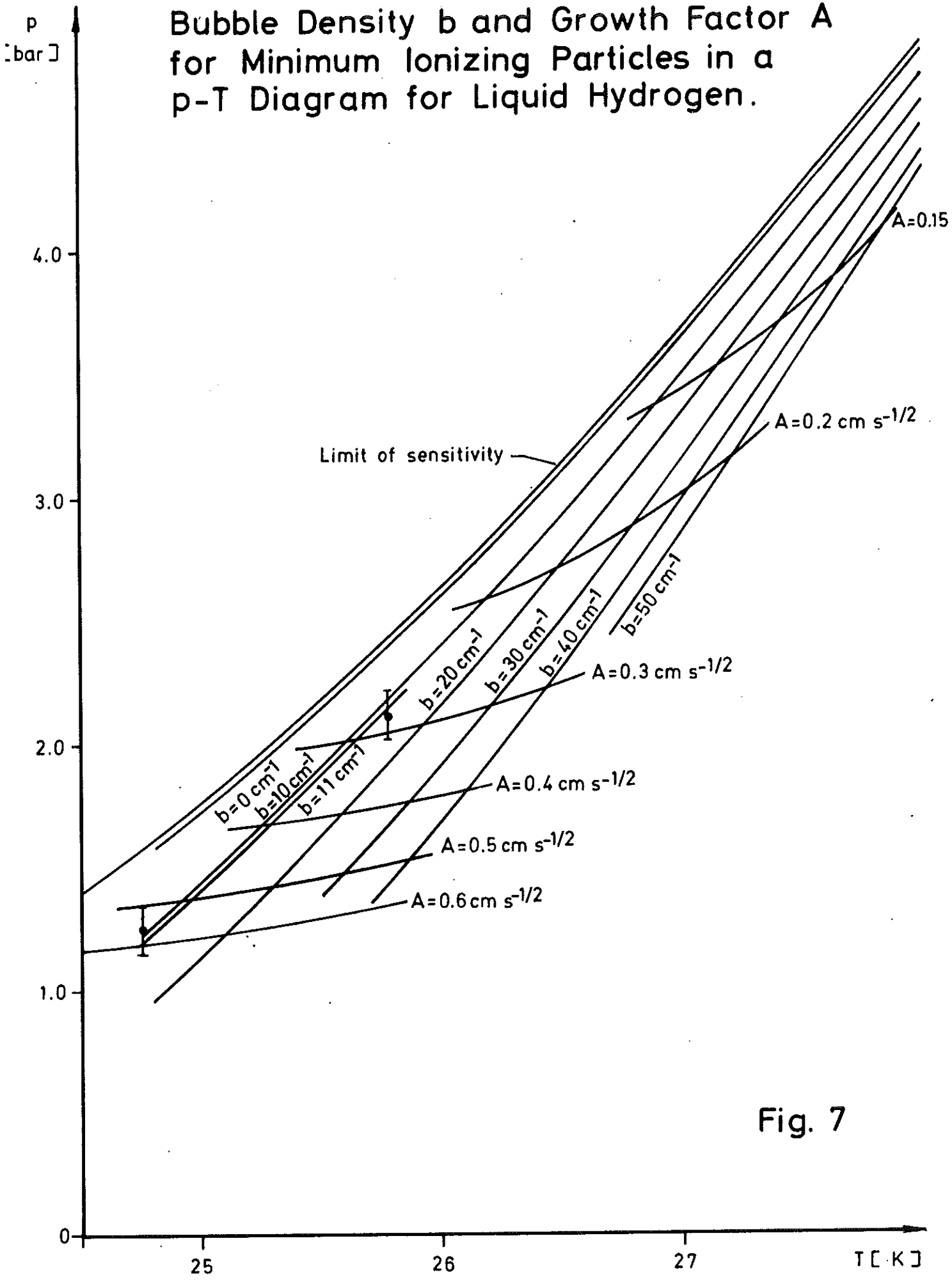
Bubble Density b and Growth Factor A for Minimum Ionizing Particles in a p-T Diagram for Liquid Hydrogen.
p [bar]
4.0
3.0
2.0
1.0
0
25
26
27
T [K]
Limit of sensitivity
A=0.15
A=0.2 cm s-1/2
A=0.3 cm s-1/2
A=0.4 cm s-1/2
A=0.5 cm s-1/2
A=0.6 cm s-1/2
b=0 cm-1
b=10 cm-1
b=11 cm-1
b=20 cm-1
b=30 cm-1
b=40 cm-1
b=50 cm-1

Fig. 7

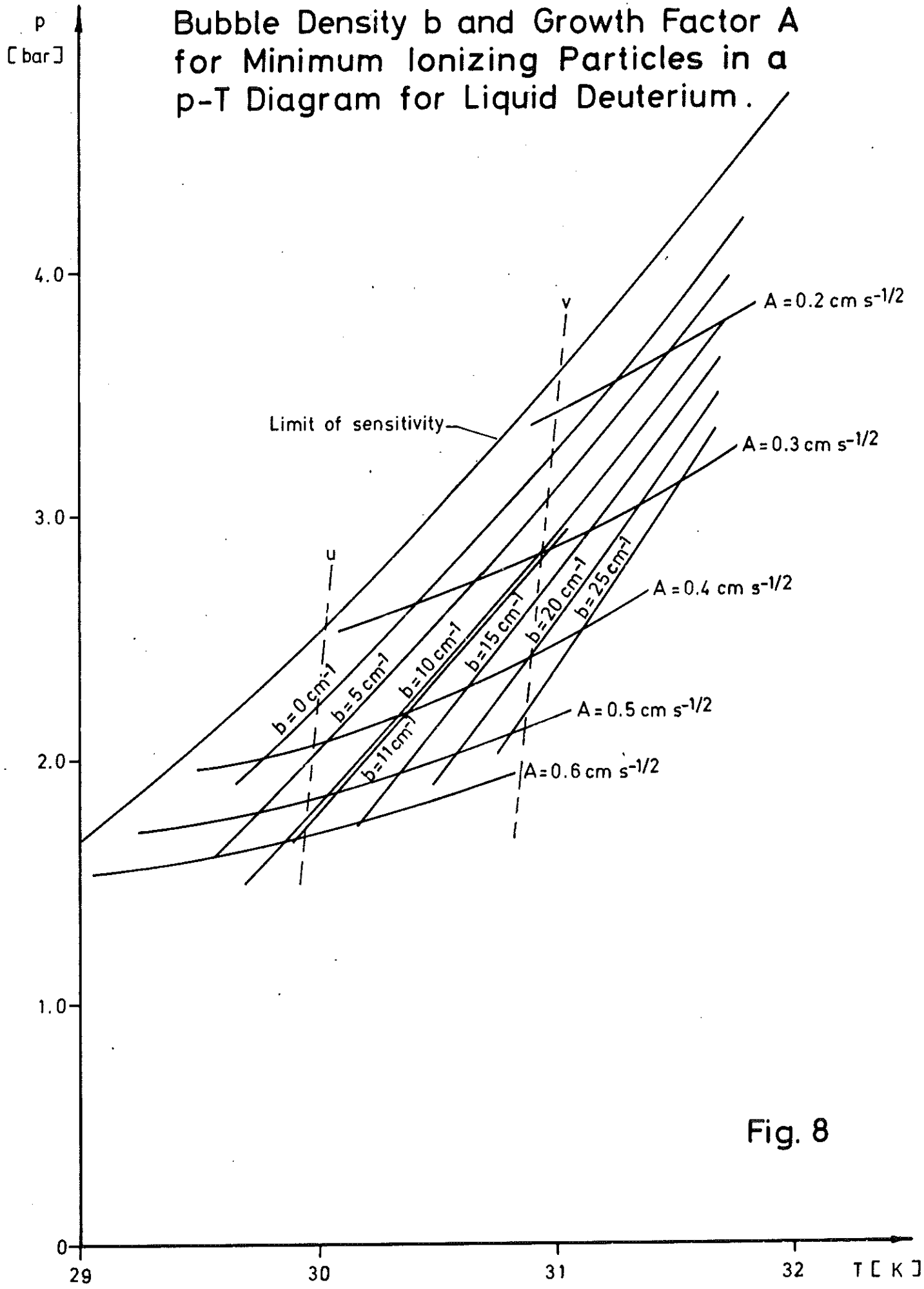
Bubble Density b and Growth Factor A for Minimum Ionizing Particles in a p-T Diagram for Liquid Deuterium.
p [bar]
4.0
3.0
2.0
1.0
0
29
30
31
32
T [K]
Limit of sensitivity
u
v
b=0 cm⁻¹
b=5 cm⁻¹
b=10 cm⁻¹
b=11 cm⁻¹
b=15 cm⁻¹
b=20 cm⁻¹
b=25 cm⁻¹
A = 0.2 cm s^-1/2
A = 0.3 cm s^-1/2
A = 0.4 cm s^-1/2
A = 0.5 cm s^-1/2
A = 0.6 cm s^-1/2

Fig. 8

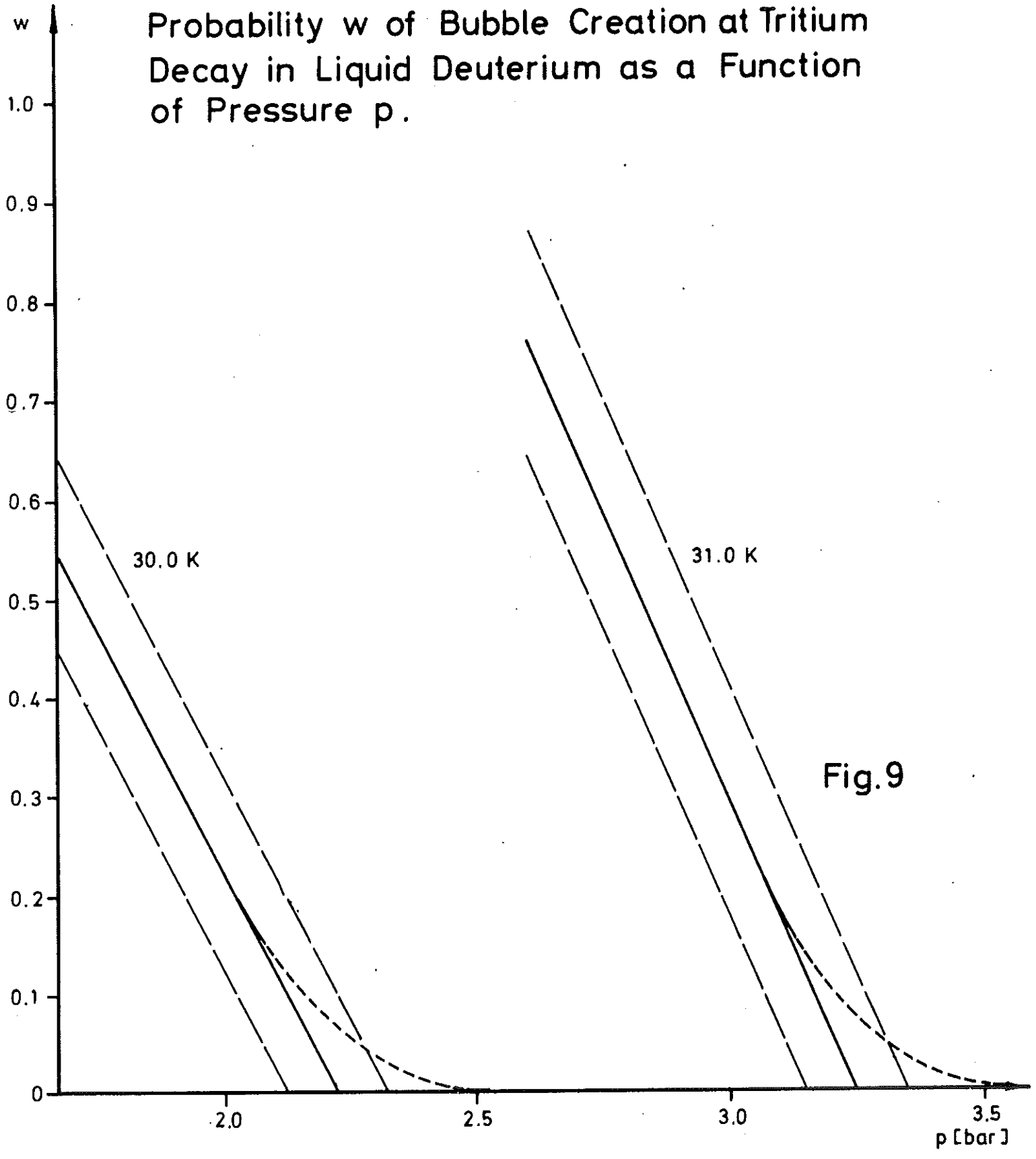
Probability w of Bubble Creation at Tritium Decay in Liquid Deuterium as a Function of Pressure p.
w
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
30.0 K
31.0 K
2.0
2.5
3.0
3.5
p [bar]

Fig.9