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The nature of science: a didactical issue

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ABSTRACT. The paper discusses the communication issue on the nature of science for scholars. After making explicit the author's position on the structure of scientific knowledge with regard to the relation theory/experiment/technology, three case studies are presented which focus different aspects of the relationship. In all cases (thermodynamics, superfluid helium, phase transitions) the combination between theories and experimental data differs in development from one case to another.

Key words: philosophy of science, nature of science, didactics of science, science education, scientific knowledge.

RESUMO. A natureza da ciência: uma questão didática. O presente artigo discute as conseqüências da comunicação para os estudantes de idéias sobre a natureza da ciência. Depois de explicitar a posição do autor acerca da estrutura do conhecimento científico no que concerne à relação teoria/experimento/tecnologia, são apresentados três casos focalizando diferentes aspectos dessa relação. Em todos os casos (termondinâmica, hélio superfluído, transições de fase) o jogo entre teorias e dados experimentais diferem em seu desenvolvimento de um caso para outro.

Palavras-chave: filosofia da ciência, natureza da ciência, didática da ciência, educação científica, conhecimento científico.

In literature on education we are witnessing a growing concern on the need to communicate not only the contents of scientific disciplines but also the epistemological aspects so that scientific literacy could be attained[1]. When reading the literature I often feel a sense of uneasiness with regard to the overlapping of different aspects of the problem. The first aspect is related to the knowledge of "science". This implies the understanding and learning of the contents agreed upon by the scientific community on the basis of observation and experimentation in natural phenomena. Or rather, the theoretical framework which accounts for the empirical data and some procedures for the collection and analysis of data and of formal mathematical treatment.

The second aspect is related to the knowledge "about science" and has different facets. First there is the meta-reflection on the production and evolution of the contents of science. This boils down to the procedural methodology of making observations, planning experiments, developing theories and models, comparing theoretical analysis with empirical data. Further, there are the social aspects of making science for what concerns the internal organisation of the scientific community, i.e. research groups, organisation and interactions, publication procedures, role of conferences and symposia, scientific debates. There is also a socio-political aspect based on the relationship between the scientific community and society as a whole (for instance, criteria and sources of financial support; also popularisation efforts and ethical problems). "Knowing science" and "knowing about science" thus seem to stand at two different cognitive levels. While it is possible to learn science without a meta-reflection on "what is science", the reverse is not true: the meta-reflection is possible only if there is some knowledge to act on at a meta-level.

An example of the difference between the two levels may be found in the relationship between theories and experimental data: at the level of

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[1] See also: Interchange, v.28, n.2-3, 1997. Special Issue on History and Philosophy of Science and Science Education. Journal of Research in Science Teaching, v.35, n.2, 1998. Special Issue on Epistemological and Ontological Underpinnings in Science Education. Science and Education, v.6/7, 1997/1998. Special issues about the nature of Science and Science Education.

"knowing science" the understanding of the relation is restricted to general information on experiments and data that form the empirical basis of the theories to be learned and to the procedures of data evaluation and processing. At the level of "knowing about science" the understanding involves the knowledge of how experiments are planned and carried out, how procedures for taking and analysing data are developed and justified, how technology contributes to scientific research, how theoretical and experimental researchers react to problematic or unexpected experimental evidence[1].

In research literature one may find many articles concerning the ideas or misconceptions held by students (and different tools have been proposed to detect them), but the same questions stayed on: a) Why should a student develop a "correct" image of science while studying science? b) Anyway which one is the "correct image of science"? Researchers seldom makes this explicit.

This brings me to focus still another question: To which kind of experts should a researcher in education or a science teacher recur for developing a reasonable idea about science and for planning the ways of communicating it to students?

The answer seems simple: the expertise that is required may be found in part in the work of philosophers, epistemologists and sociologists and in part in the work of scientists. However, the two parts focus different aspects of the problem to science educators and teachers. Moreover I often have the impression that science educators recognise the competence of philosophers, epistemologists and sociologists on the issue, while scientists are often assumed not to be reliable in talking about "what is science" as they are so involved in "doing science" that they do not have the time and the competence to argue about what they are doing[2].

In fact, I seldom find references to the outstanding scientists who have written about science: Duhem and Poincaré are examples from the past, De Gennes (1994), Jacob (1997), Gellmann (1994), Cini (1994), Levy Leblond (1996) are more recent examples. Of course, epistemologists and philosophers have this competence since they have studied the work of the scientists in historical records. Nevertheless, little has been done on the "science in the making". Latour (1998) says that "there is a philosophy of science, but unfortunately there is no philosophy of research. There are many representations and clichés for grasping science and its myths; yet very little has been done to illuminate research".

Something is available on the relation theory-data-reality, on the interactions among scientists in a laboratory set up (Latour 1979, Giere 1988 are examples) and on the role of technology (Gallison 1997). However, we must note that scientists do not publish the detailed history of the planning and definition of an experiment, together with the reasons for choices in technology and the dead ends of trial measurements.

In the articles one finds the final apparatus, with the indication of measurement instruments and, eventually, procedures and experimental results. It may sometimes happen that, from the planning of an experiment, the design of a new instrument or a calibration procedure are produced. However, these technical details are generally published in the appropriate technical journals without any reference to the experiments that prompted their development.

Research articles therefore present a tale of the experimental research not as it has been developed but as it could have been developed in an ideal world in which no accidental effects interfere in the story.

Coming then back to my questions, my answer to the first is that students will not develop a correct image of science unless explicitly taught. This teaching must be strongly connected with examples of true research activities.

The answer to the second is that a lively debate about what may possibly be a "correct" image of science should be acknowledged.

Such a debate involves philosophers, science educators and scientists. However, while philosophers and science educators are exchanging ideas in conferences (see the periodic meetings of the "History, Philosophy and Science Teaching" International Group: Tallahassee, Kingston, Minneapolis) and in the literature of Education, scientists are more often discussing within their community. As a rule, the latter is reluctant to hold discussions with philosophers and is only very rarely engaged in the connected educational problems. The communication gap between scientists and researchers in Education is quite symmetrical as the latter seem to prefer to listen to what philosophers

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[1] It may be noted that often the experiments used for understanding science are didactical experiments, which have no place in the evolution of scientific knowledge. Compare the "air-track" experiments for Newtonian Mechanics with Galileo's thought experiments for imagining a world without friction.

[2] Implicitly this is a recognition that learning science and learning about sciencelies lie at different levels.

say about the work of a scientist than to scientists speaking of what they are actually doing.

In any case, we are convinced that, in order to facilitate communication, researchers in science education should make explicit the image of science that guides their work.

Therefore, in the next section I will discuss our understanding of the structure and evolution of scientific knowledge which will frame the case studies reported in section 3 as possible themes for a didactical communication of the relation theory-experiments-technology.

What is science?[3]

I will give a possible answer to this question with regard to a) the aims of scientific work, b) the structure of scientific knowledge, c) science as a social enterprise.

The aims of scientific work. Notwithstanding the fact that knowledge of the natural world is a product of the human cognitive ability with roots in the prehistory of mankind, essentially important for surviving, we ask ourselves what are the aims of the kind of work we call nowadays "science".

If we look at the history of modern western science, we see that, since the beginnings of the so called "scientific revolution", scientists themselves have been engaged in a lively debate on the aims and the scope of the new "Philosophy of Nature" (think, for instance, about the debate between Cartesians, Leibnizians and Newtonians). The "modern" epistemological debate arose probably from the well-known "crisis" of the mechanical world picture at the end of the last century (Duhem wrote his famous book to show that the aim of Physics is not to "explain" but to "describe" and "classify" phenomena). At present military applications, ecological and bioethical debates have given rise to the problem of social control on the aims of scientific activity.

We may look for a definition of the aims of science from the inside and from the outside of the scientific community. Epistemologists look at science from outside, doing research on problems that have become part of the traditional problems of their community, but are not often shared by professional scientists. On the other hand, professional scientists are part of a "scientific community" which states the rules for scientific behaviour. We should then take into account not only the aims but also the "rules of the game" of the scientific community.

Every member of this community will easily agree that the aims of his work are (1) to increase the understanding of the world we live in; (2) to develop knowledge aimed at a better control and prediction of phenomena and events, to make this knowledge "useful" for the development of new technologies.

To reach these aims, scientific research results are "public". Each individual contribution - which obviously may incorporate opinions, styles, tenets of individual scientists, restricted groups, etc. - is subject to the scrutiny of a wider scientific community (for instance, the "referees" of scientific reviews). Therefore, scientific ideas or experimental results are always exposed to criticism and may give rise to debates among different scientists, research teams, etc. A difference may be encountered between theoretical and experimental research, since the latter is more aimed at reaching an intersubjective agreement based on the reliability of data.

Instruments for the confrontation of ideas are scientific reviews, conferences and symposia (where new ideas may be debated and eventually accepted or rejected), scientific societies (which may stimulate new lines of research), workshops, etc. Therefore the terms of the confrontation are, on one hand, the natural world of phenomena (which includes the experimental outcomes of laboratory practice) and, on the other, the different points of view of different scientists and the exercise of accurate criticism. Thus, the development of science requires both an "intersubjective" agreement on rules, criteria, models of explanation, background knowledge etc. and the competition of different point of view, via scientific debates and criticism.

The structure of scientific knowledge. Currently science is organised in different fields, each one characterised by a common shared set of theories, models, empirical laws, methodologies of research. This common shared knowledge is, as we have already pointed out, the knowledge obtained about that part of the world which pertains to the field of research by the intersubjective agreement among different scientists who have the competence for comparing models and theories with natural phenomena, experimental outcomes, technological products.

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[3] What is reported in this section is the shared agreement reached, after a very lively debate, by our group while working on the European project Laboratory in Science Education (Bandiera et al, 1998)

Since each subfield has its own specificity, scientists of different fields may have difficulties in communication. However, the interrelations between theories, models, experimental outcomes, technological products cross over the different fields of the experimental sciences.

We will show this structure in the two conceptual maps (Figure 1 and 2). Figure 1 shows the relation between the "real world" of facts/events/phenomena and the "ideal world" of models and theories. Figure 2 tries to explain the relation between theories (theoretical research) and experimental data (experimental research), while pointing out the importance of technology and suggesting a possible evolution of shared knowledge.

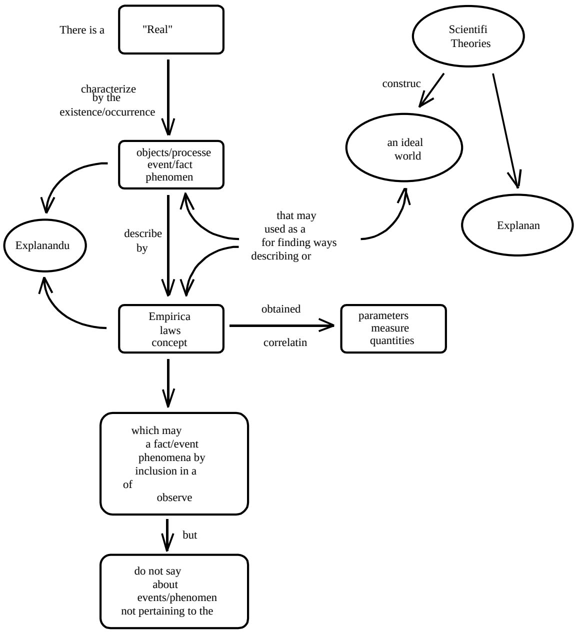

Figure 1. Conceptual map of the relation between the "real world" of phenomena and the "ideal world" of theories

Some commentaries.

- The statement "data are theory-laden" should be changed into "any research project, either theoretical or experimental, is laden by all the shared knowledge, at a given time, in the three aspects of theories/models, experimental outcomes, technological artefacts".
- Problems that may be solved by scientific research are contextually defined at any given time and change in the course of time along with the evolution of the shared knowledge and with changes in the social context.
- There is a difference between theories and empirical laws. Empirical laws maintain their validity in correlating experimental data (in the accuracy range defined by the measurements), even if the theory supposed to explain them changes or is rejected.
- There is a difference in the kind of explanation given to a phenomenon by an empirical law or a theory: an empirical law "explains" only in the sense of including the phenomenon in a family of phenomena (if you want, an empirical law "explains" a fact by defining the "sameness" with other facts). A theory tries to explain it by the use of concepts and variables which are not defined at the level of the empirical laws and which are invoked as "the reason why" of the relations among measured quantities.
- Any kind of scientific experimental work requires the acquisition of competence in the knowledge shared by the community. A necessary step before planning an experiment and collecting new data involves the analysis of the experimental data already available.
- Research may develop in various directions:
  a) development of theoretical aspects related to new or anomalous data;
  b) logical organisation of theoretical aspects;
  c) technological development;
  d) experimental verification/falsification of theoretical hypothesis;
  e) experimental exploration of fields opened by theoretical or technological developments;
  f) analysis of experimental data in search of empirical correlations/generalizations;
  g) analysis of experimental data in the light of new theoretical hypothesis;
  h) collection of observational information and correlations.
- As empirical laws unify different sets of experimental data and theories unify different sets of empirical laws, one gains an obvious advantage of economicity of representation and communication in reaching a more and more unified scientific knowledge (the overarching framework that scientists aim to construct). In a given field, at a given time, the degree of possible unification is often known to the scientists. However, it is more practical to use the knowledge at a lower level of unification for the solution of well-defined problems.

Science as a social enterprise. The scientific community judges the validity of a (theoretical or experimental) research with arguments that may be both theoretical and experimental. Its aim is to reach an "objective" judgement, devoid of personal biases or opinions. However, a "subjective" component cannot be completely avoided. Biases and systems of beliefs may be particularly relevant when experts have to make decisions on the financial support of research projects.

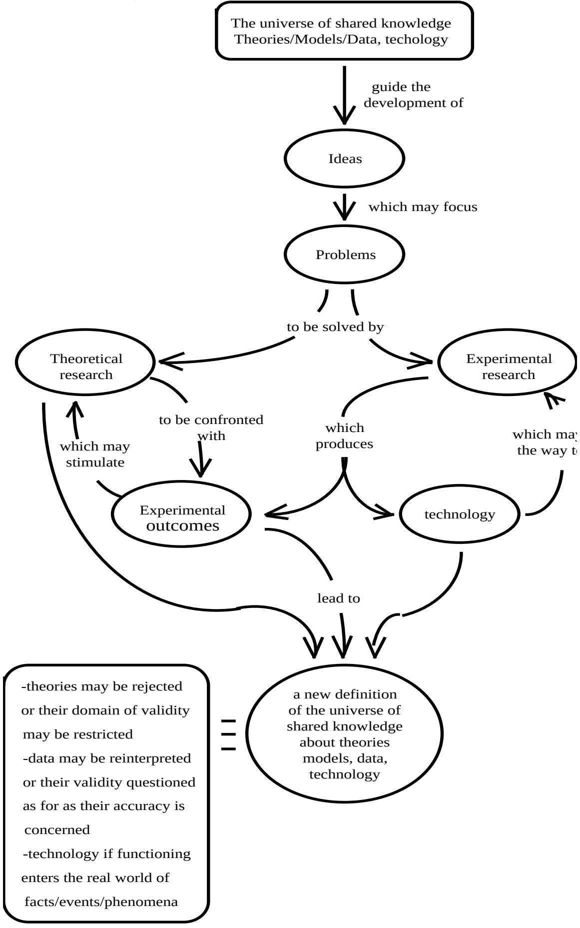

Figure 2. Conceptual map of the structure of scientific knowledge

Experimental work is nowadays organised in work groups in which every scientist contributes according to his particular competence and capacities. Scientists who are able to contribute to all aspects of a scientific enterprise are very few. The dimension of a group of experimental research may include several hundred persons: this is typical of the so-called "big science", such as in High Energy Physics or Genoma Project. Requesting a financial support, any research project is conditioned by its socio-economic-political context.

Case studies for didactical communication

I will present three examples for a didactical activity aimed at conveying ideas on the epistemological aspects of Physics as an experimental science. The three examples have roots in my personal research activity and I apologise if I will not give good references to philosophical work.

Thermodynamics. This is an interesting case of the "freezing" of didactic communication at the theoretical frame developed at the end of the nineteenth century. Moreover, the phenomenological and technological aspects on which the definition of the theoretical frame was based are often forgotten (for an extensive discussion see Tarsitani 1996). I may summarise them synthetically:

- The first point concerns the definition and measurement of the intensive variables temperature and pressure. The building and calibration of accurate thermometers was a major concern for good empirical data collection.
- The phenomenology of transport phenomena and of some equations of state was well known since 1820-1850 (Fourier, Fick).
- The technology of heat engines poses problems for efficiency (see Carnot).
- The importance of friction-dissipation for the reaching of equilibrium is known in different fields (see Joule).
- The analogy of the relation Δh/fluid flow (h is the intensive variable conjugated to the extensive flow variable) and ΔT/heat flow is well known, but the focus of the second principle is only on ΔT.
- The atomic model is but a hypothesis. The two problems of defining the equilibrium properties (connected with the need of a non-conservative variable, the entropy) and of proving the validity of the atomic hypothesis, contemporary present, require debates.

At the beginning of this century entropy S fully entered the theoretical frame with the establishment of Gibbs relations

$$dU = TdS - pdV + \mu dN$$
$$0 = SdT - Vdp + Nd\mu$$

The road is thus open to the theoretical development achieved during the twentieth century, which I may summarise as follows:

- Research is devoted to organise logically the theoretical frame. Attempts to axiomatise the theory are advanced (Caratheodory, Gibbs).
- A theoretical frame for transport phenomena is proposed for the steady state case. The production of entropy in a real process may be calculated by using the phenomenological relations. There are problems in the prediction of the behaviour of signal transmission.
- A fluid model is largely used in a thermodynamic process, while statistical thermodynamics is a growing field.
- A mesoscopic approach needs to be developed when the limits of validity of the macroscopic approach become evident (fluctuations at the critical point, the limit of OK temperature).
- The generalisation towards a complex system is accomplished.
- Proposals for treating general processes are being developed as extensions of the theoretical frame of the equilibrium case (see Extended TD).

Low temperature physics. At the beginning of the twentieth century the phenomenological frame of equations on fluid state and on the conduction properties of metals was well established. In both cases a theoretical frame (thermodynamics for the first and electromagnetism for the second) was also available.

The development of the technology of producing low temperature was developed and the properties of fluids and metals could be studied. No strange behaviour was predicted by the theoretical frame.

"Every substance will solidify at low enough temperature" and "the resistibility of metals will change with continuity" were reasonable predictions. Problems were raised when it was discovered that helium did not become solid by just lowering the temperature but showed strange properties of "superfluidity". Further, some metals showed an abrupt disappearance of the resistibility at a definite critical temperature (superconductivity).

As soon as the phenomena were judged empirically, the search for a theoretical explanation raised the interest of scientists. Much more interest was devoted to superconductivity than to superfluidity because of the possible technological applications. The first theory of superconductivity (BCS theory), however, limited the phenomena to metallic materials. The field of high temperature superconductivity has been mainly driven by interests in the technological applications and still lacks a good theoretical explanation.

I will here present the case of superfluid helium (Atkins 1959, London 1964), a liquid with strange macroscopic properties which attracted the interest of many famous scientists but remains practically unknown to students. At the beginning of the century the University of Leyden in the Netherlands was a very good centre of research for the properties of fluids. Kamerlingh Onnes first succeeded in reaching the critical point of helium (5,2 K) in 1908. It was, of course, assumed that the phase diagram of helium would correspond to the well-known diagram of Figure 3 with the reaching of the ordered solid phase for low pressures and zero temperature. However, in exploring the liquid phase, another sort of critical point appeared at the temperature of 2,19 K, below which the liquid behaved differently from ordinary liquids.

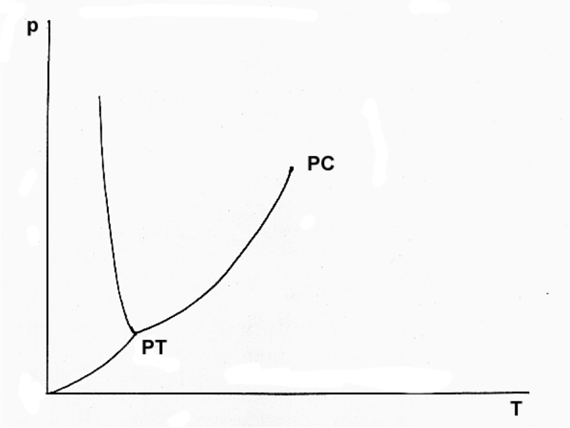

Figure 3. Phase diagram of ordinary substances

Approximately 30 years were needed to reach a reasonable phenomenological account of the properties of this new liquid phase. We may quote London:

> *"In 1908 Kamerlingh Onnes succeeded in liquefying helium (critical temperature 5.2 K). Yet almost thirty years passed before it became apparent that liquid helium, if cooled below 2.19 K, transforms [itself] into a substance which is entirely different from all other liquids. Though numerous observations of strange behaviour of liquid helium had been made over a period of years, not until 1937 did it become clear that* new differential equations *were required to describe the mass flow and the heat flow of*

> *"superfluid" helium, i.e., liquid helium below 2.19 K....*
>
> *That something strange happens to liquid helium at about 2.2 K was noticed by Kamerlingh Onnes as early as 1911. He found that when the liquid is cooled below that temperature it starts expanding instead of continuing to contract, thus deviating from the behaviour of most substances. Later, in 1924, Kamerlingh Onnes and Boks made more elaborate measurements and found that the density-temperature function has a sharp maximum with a* discontinuity of its slope *(discontinuous thermal expansion coefficient) at that temperature. In 1928 Keesom and Wolfke, comparing the discontinuity with a phase transition, were first to use the terminology "helium I" and "helium II", suggesting the idea of a kind of allotropic modification, helium II being the low temperature form. From the beginning it seemed very odd to imagine that a kind of allotropy could exist in a liquid, especially if the liquid consisted of such extremely simple spherically symmetric monatomic molecules as He. In fact, in contrast to ordinary phase transitions, the transition from helium II to helium I is not accompanied by a latent heat. Specific heat measurements by Keesom and Clusius in 1932 showed a singularity of the specific heat curve whose characteristic profile, resembling the shape of the letter λ has given rise to the name "λ–point" for this kind of singularity. Lambda-points occur in many substances and are characterised by vanishing latent heat and the above-mentioned sort of singularity of the specific heat" (London 1969, p.1-2; Figure 4).*

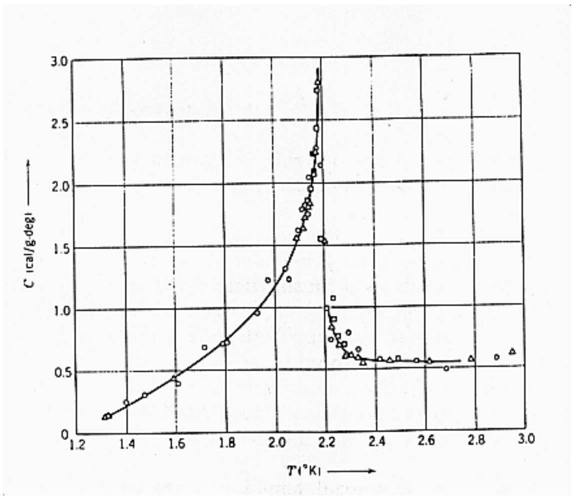

Figure 4. The λ discontinuity in specific heat

The phase diagram of liquid helium (Figure 5) shows two peculiarities:

a) instead of one triple point between the solid, liquid and gaseous states, there are two triple points at the end of the λ line which separates liquid helium I from liquid helium II.

b) The melting curve is practically horizontal and approaches the zero temperature at a pressure of about 25 atm: liquid helium is a substance that cannot be solidified under its own vapour pressure merely by cooling.

The strange behaviour of liquid helium II particularly concerns the flow and heat conduction properties.

Starting from heat conduction, a first hint of the difference from ordinary liquids may be visually observed when pumping over a helium bath in order to decrease the temperature following the vapour pressure line: the liquid boils vigorously until the temperature of 2.19 K is reached; suddenly the boiling stops and the liquid remains quiescent while the temperature continues to decrease.

Further investigations on heat conduction showed a marked dependence on geometrical properties and a very high heat conductivity compared with that of normal liquids.

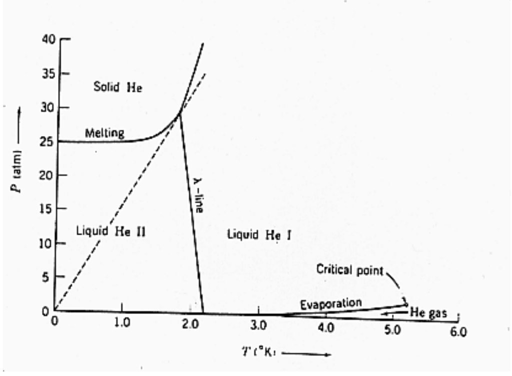

Figure 5. The phase diagram of Helium 4

Moreover, it was shown that a temperature difference gave rise to a pressure difference (mechanic-caloric effect) which produced the spectacular "fountain effect" with vessels connected by a very thin capillary (Figure 6). This indicates that flow properties were enhanced when diminishing the cross section of the connecting tube.

Flow properties lead to viscosity measurement. In this case one observed a strong discrepancy with ordinary liquids. The two experimental procedures (capillary flow and rotating disk damping), which were acknowledged reliable as leading to values for the viscosity coefficient η within experimental accuracy, reported values of η which differed by orders of magnitude. The value of η from the capillary flow measurement was very low (even lower that the value for gaseous helium) while the value from the rotating disk experiments, although decreasing with decreasing temperature, was not very different from the viscosity of He I.

Which experimental value should be taken as correct? More questions however came when the "supersurface film" was discovered quite accidentally in 1922 by Kamerlingh Onnes. He had observed the transfer of helium, at a very striking speed, between two disconnected vessels if there was a difference in the level of liquid. The transfer stopped when the levels reached the same height. The effect was successively explained by assuming the existence of a peculiar film of helium of an anomalously large heat conductivity covering all walls that are in contact with the liquid. The presence of the film was then verified (1938) by independent groups who determined the film thickness ($\cong 3\ 10^{-6}$ cm).

One had thus quite a large amount of empirical data that could not be explained by existing theoretical frameworks. The connection between heat conduction and flow behaviour indicates that some of the usual differential equations of macroscopic Physics do not apply to liquid helium II.

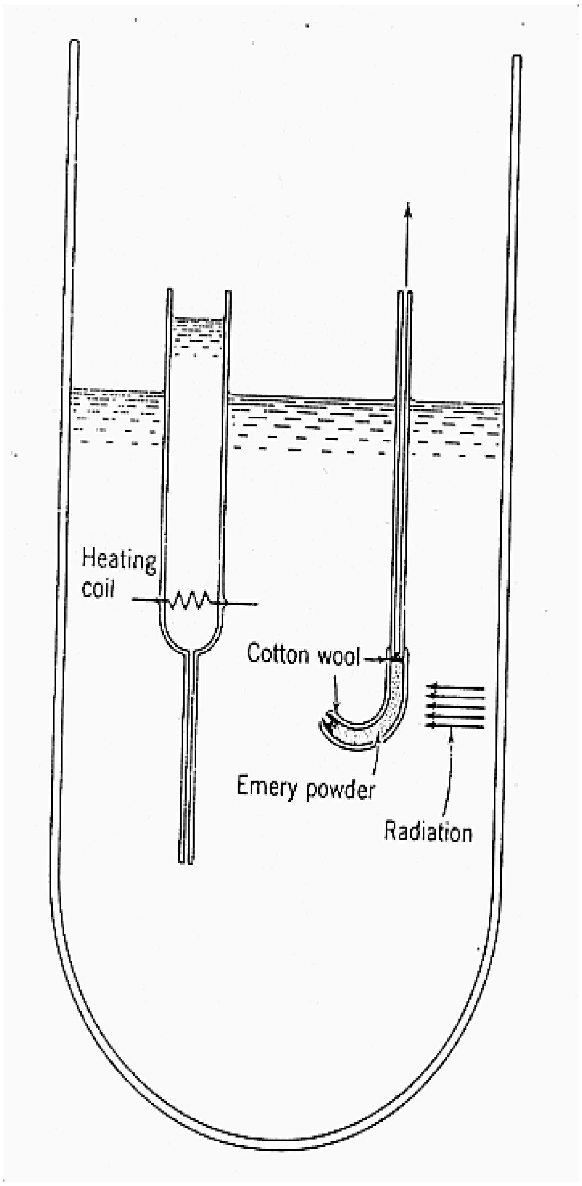

Figure 6. The fountain effect

The λ discontinuity in specific heat suggests that the λ transition is a second order phase transition in the Ehrenfest classification. The persistence of the liquid state up to OK suggests the existence of some kind of order in the momentum space at the expense of order in ordinary space. Anyway, the stability of the liquid state at low temperature is well explained by a thermodynamic reasoning which, correlating macroscopic properties, shows that the energy of the system in the liquid phase is lower than that in the solid one. Also it is well know that an ideal Bose-Einstein gas has a critical temperature for condensation in the lowest quantum state.

All this theoretical items lead to the development of a model (the two fluid model) which correlate many of the most striking phenomena of liquid helium on a common theoretical basis and, moreover, of predicting new properties.

The model employs the qualitative features of a degenerating Bose-Einstein gas and discrepancy in viscosity measurements to put forward the hypothesis that liquid helium II behaves "as if" it were composed by two interpenetrating fluids, the normal and the superfluid [the "as if" underlines the model nature of the mixture of fluids: normal and superfluid cannot be separated as ordinary fluid mixtures].

The superfluid (corresponding to the condensed phase of the Bose-Einstein liquid) is characterized by a density ρ_s that increases from 0 at the λ temperature to the total density ρ of the liquid at OK. It does not contribute to entropy and to viscosity:

$$S_s = 0 \qquad \eta_s = 0$$

The normal fluid (the carrier of the entire thermal excitations) is characterised by a density ρ_n which decreases from the density ρ at the λ temperature to zero at OK. It contributes to entropy and viscosity:

$$\rho S = \rho_n S_n$$

η_n of the order of the viscosity of liquid helium I at the λ τemperature.

Each of the two fluids has its own velocity field (v_n, v_s) such that

$$\rho_s + \rho_n = \rho$$
$$\rho v = \rho_s v_s + \rho_n v_n$$

The discrepancy in the viscosity measurement is easily explained by the fact that the normal fluid, in a capillary apparatus, is held back by its viscosity. The flow is mainly due to the superfluid. On the other hand, in a rotating disk apparatus, the disk is not affected by the superfluid and damping is totally due to the normal fluid.

A first check of the validity of the model was obtained by the experiments by Andronikashvili who used a pack of disks made of aluminium sheets. Such an oscillating disk system provides two sets of information at the same time: damping is connected to the viscosity ($\eta_n\rho_n/\rho$), while the frequency gives the mass ratio (ρ_n/ρ). The results of the experiments are shown in Figure 7.

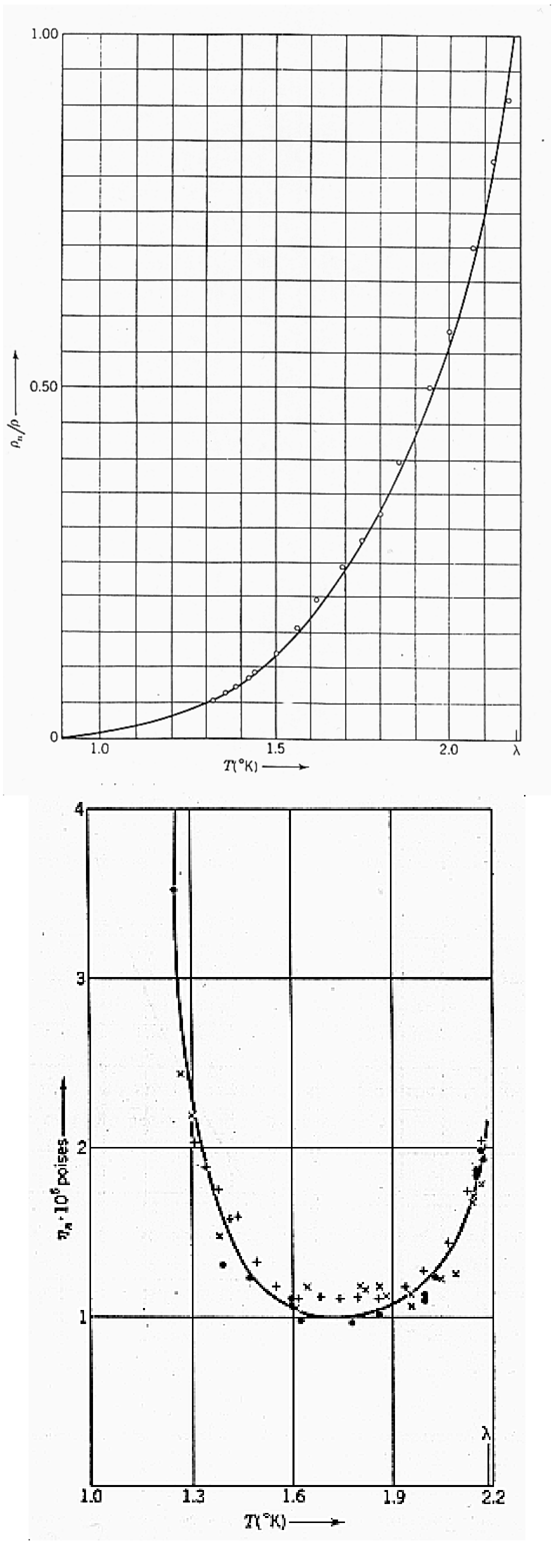

Figure 7. Density and viscosity of the normal fluid

An interesting prediction may be derived from the two-fluid model concerning the possibility of propagation of thermal waves (then called *second sound*). It is analogous to the derivation of the ordinary sound equation (pressure waves) in that it assumes Euler equation of hydrodynamics for the liquid as a whole, the continuity equations for mass and entropy in the form

$$\frac{\partial p}{\partial t} + div\rho v = 0$$

$$\frac{\partial ps}{\partial t} + div(\rho s v_n) = 0$$

Two separate equations may be written for the flow of the normal and the superfluid. It is assumed that a temperature gradient besides the pressure gradient may contribute to the flow (that's why they are called "thermohydrodinamical equations").

I will not go into more details in the calculations, but only give the results. A wave equation for temperature is obtained with a velocity

$$u_{II}^2 = \frac{\rho_s}{\rho_n}\left(\frac{s^2 T}{c_p}\right)$$

The experimental data obtained by Peshkov in 1944 (Figure 8) show the agreement of the measured data with the predicted value. Needless to say the history of superfluidity does not end at this point. However, I think that its beginnings are a nice opportunity to discuss the issues with students:

a) the role and importance of technological developments for experimental inquiries,
b) the role of experiments planned not for answering a specific theoretical question but driven by a position of the kind "Let's see what happens if (temperature is lowered) now that we have the technical possibility of undertaking the condition (lowering the temperature)",
c) the changing role of empirical data as inputs for developing theories into theories as input for producing empirical data.

Phase transitions

On one hand this is an interesting case for the relation theory/data/technology; on the other hand, it is interesting for the convergence of different fields of research. The well-known Van der Waals equation of state predicts the existence of a critical point for the transition liquid-vapour and the qualitative behaviour of fluids at this point.

The experimental data, however, show a lack of reproducibility which stimulates the search for more accurate thermostats and instruments and for procedures to purify the material systems in investigations. The values of the critical pressures and temperatures require high pressure, high temperature apparatus and measuring devices.

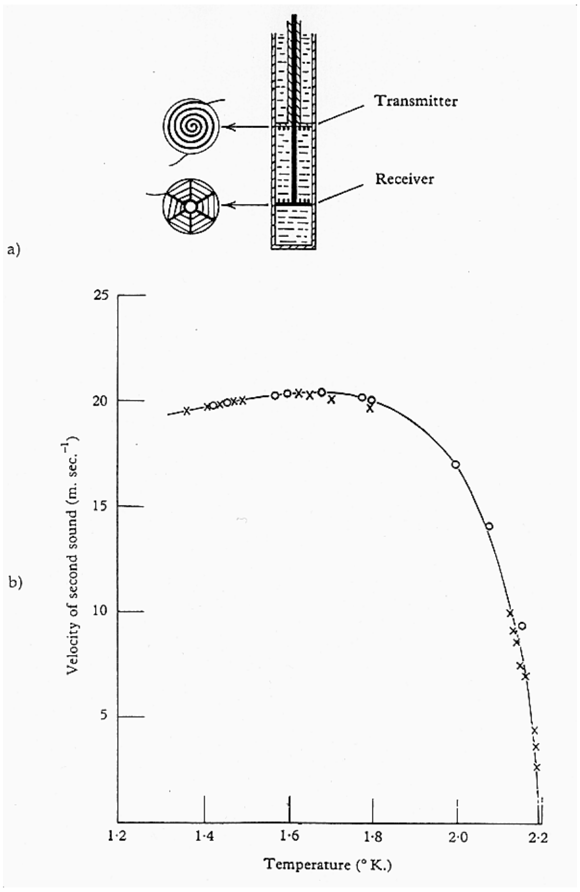

Figure 8. Second sound velocity

In the 1930 the Michels' Dutch group published a large set of isotherms of $C0_2$ in the critical region. The quantitative disagreement with Van der Waals equation was clear. The presence of a systematic error due to the gravity field was also established and the data closest to the critical point were excluded from the empirical validity.

In a different field, the transition from paramagnetic to ferromagnetic behaviour had found a theoretical description (the Curie-Weiss law) which showed an analogous quantitative disagreement with the experimental data produced by Weiss during the same period. The magnetic case raised the interest of theoreticians who proposed a microscopic model for the transition (Ising model). Since an analogous model (the lattice-gas model) was derived for fluids, it began to be recognised that critical point behaviour in different fields could have the same explanation.

However, the quantitative disagreement with the theoretical description (Van der Waals - Curie-Weiss) focused the attention of both theoreticians and experimentalists on the singularities in the thermodynamic variables along particular curves. An example: Van der Waals predicts a divergence to infinity of the compressibility on the critical isochore as $K \alpha \tau^{-1}$ which is not followed by the empirical data. It may be described by a power law $K \alpha \tau^{-\gamma}$ with $\gamma \sim 1.2$. The experimental focus was on the determination of the “critical exponents”, describing the singularities of thermodynamic variables in the approach to the critical point.

It may be noticed that a strong belief in the continuity features of our representation of the world raised some resistance to the acceptance of non-rational values for the exponents: all sorts of possible flaws in the experimental procedures were then analysed.

When a new theoretical hypothesis (the scaling law hypothesis) in the 1950-60 suggested the use of experimental data in the whole critical region and not just on particular curves, data were not available for any substance. While experimentalists devised new measuring systems with the possibility of high accuracy, the old data by Michels and Weiss were reanalysed in the light of the new hypothesis and with the empirical support needed (for a more detailed historical account, see Domb 1996). The lesson is that theories do change but experimental data, when good, maintain their empirical value.

Conclusions

The three cases show that the aim of didactical communication on science is that “Classical science is a conversation between theory and experiments. A scientist can start at either end - with theory or experiment - but progress usually demands the union of both theory to make sense of the experiment and data to verify the theory” (Kelly 1998). However, we must also show that the development of the conversation is strongly related to the context. Conversation may run smoothly or give raise to hot debates, while stimuli may come from other conversations…

At first in thermodynamics the debate was hot with regards to the convergence of two theoretical issues. On one hand, the appropriate state variables (energy and entropy) had to be defined in accordance with existing experimental evidence and devising new experiments for comparing quantitatively different approaches to the same equilibrium state.

On the other hand, the atomic hypothesis was in need of validation. Once the two problems were solved the theoretical basis was laid and the subsequent development of the theories was a quite smooth process of adaptation of the basis to embrace the experimental process phenomenology (mostly already known empirically).

In low temperature Physics the evidence of the unexpected phenomenology (permitted by advanced technology) showed the inadequacy of the previous theoretical partner in the conversation. New theories were needed for the conversation to continue. The debate is still open towards technological applications.

In the case of phase transitions the theoretical and the experimental side need to readjust themselves to new theoretical ideas and new approaches for the experimental part. We also perceive the pieces of different conversations coming in and contributing towards the solution of the problem.

I am convinced that a full appreciation of the complex relation theory/experiment/technology cannot be reached by students if the problem is treated only in general terms. Of course, the need for contextualising in case studies forces the presentation of the epistemological aspects in a strong interrelation with disciplinary contents.

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