Philosophy of experiment: illustrations from the ultracold[#]

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1 SOME RADICAL THEMES

I shall explain the ultracold in a moment. It is good to begin by mentioning, and slightly exaggerating, some radical themes that will be illustrated:

- Theory and experiment merge
- In a quite different sense, the micro and the macro merge
- There are macroscopic quantum phenomena: we can "see" Schrödinger equations
- A return from big science to tabletop experiments
- The inauguration of 'analogical research'
- New kinds of conceptual change – in the very idea of the molecule
- The signature as a central concept of experimental physics
- Duhem's thesis generalized
- The deepest investigation into the only two kinds of things in the universe
- We shall create macroscopic Schrödinger cats: systems in two states at the same time and place

2 THE ULTRACOLD

In 1925, twenty years after the *annus mirabilis*, Einstein published a paper in the Proceedings of the Mathematics and Physics section of the Prussian Academy of Sciences (Einstein, 1924-1925).[1] Only in 1995 did it begin to yield an incredible cornucopia of experimental results. This was a radical break-through that won a Nobel Prize. Two groups, one in Boulder, Colorado, and one at MIT, one in June and one in September, 1995, produced their first *Bose-Einstein Condensates* about as close to absolute zero as one can meaningfully get.

Bose-Einstein condensates are so called because Einstein got the idea from a suggestion about photons sent him by the then unknown Indian physicist, Satyendra Nath Bose (1894-1974) (Bose, 1924). By 2002 about 30 teams had made BEC – as I shall call it from now on[2]. By now the number will exceed 200. It is still tricky, and it takes two or more years to set up the laboratory and get everything working right, but the process is becoming routine. I recently visited a laboratory in Taiwan where a single graduate student created the first BEC in that island which, in many ways, leads the world in industrial strength high-technology.

[#] The themes of this paper are developed at length in "Another new world is being constructed right now: the ultracold", Max-Planck-Institut für Wissenschaftsgeschichte, Berlin, Preprint 316. This paper was presented at the Conference "The shape of experiment", Berlin, 2-5 June 2005, <http://www.mpiwg-berlin.mpg.de/Preprints/P318.PDF>.

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[1] The manuscript of Einstein's paper turned up in Leiden in August, 2005, and is now on view on the Internet: <http://www.lorentz.leidenuniv.nl/history/Einstein_archive/Einstein_1925_manuscript/>

[2] BEC = Bose-Einstein Condensation or Bose-Einstein Condensate. One often says simply, Bose condensate.

Why all the excitement? Leave aside the delight in achieving a technical triumph, and the vindication of a seventy-year-old research programme. Bose-Einstein condensation occurs at very cold temperatures. At 10^{-9} degrees above zero – virtually zero – atoms are very unenergetic. They do not move much. Hence it is possible to observe them and to manipulate them quite easily. We are able to have a more intimate interaction with the microworld than ever before. This break-through in experimental physics enables us not only to plan a whole new range of investigations, but also to recommence a lot of theoretical modelling.

What follows is divided in (3) larger philosophical themes, (4) brief history, and (5) lesser philosophical themes.

3 LARGER PHILOSOPHICAL THEMES

3.1 The last dichotomy

If you are thinking about how to distribute a number of things into a number of classifications, there is exactly one intuitive way to think about it: you imagine all the distinct arrangements of the individual things into a number of distinct boxes. You can imagine variations on the theme: distribute balls into boxes without making distinctions among the balls. Or distribute balls into boxes allowing only one ball in any box. And so on, many games can be played, of which these three may seem the simplest. The statistics of the first case is the way in which Maxwell and Boltzman thought about ideal gases, and it is called Maxwell-Boltzmann statistics. The second case arose when Bose was thinking about photons, and he wrote to Einstein, who picked up on the idea. We speak of Bose-Einstein statistics. That was 1924/5. Soon after it was realized that a third model was needed, and so we have Fermi-Dirac statistics, named after the two fundamental thinkers who saw their physical significance.

The first great textbook of probability that I read was Feller. (Published almost sixty years ago, it is still an excellent place to start taking probability seriously.) There, in 1962, I first encountered Bose-Einstein "statistics":

> The appropriate, or 'natural', probability distribution seemed perfectly clear to everyone and had been accepted without hesitation by physicists. It turned out, however, that physical particles are not trained in human common sense, and the 'natural' (or Boltzmann) distribution had to be given up for the Einstein-Bose distribution in some cases, for the Fermi-Dirac distribution in others. (Feller, 1950, vol. 1, p. 5)

There are two basic kinds of things in the world, and they satisfy the two post-Boltzmannian statistics, after which we call them *bosons* and *fermions*. By now we know they are constituted by aspects that seem more fundamental than their probability distributions, namely their spin, a concept invented after Bose statistics were devised. Nevertheless, just from the statistics, one sees that fermions are solitary – no two of them can ever go into the same energy state. That is a consequence of the Pauli Exclusion Principle, also a contribution later than Bose's. Bosons are gregarious; when they are cold enough – have low enough energy – lots of them can all go into the same lowest energy state.

It is a historical accident that the statistics started everything off. The fundamental concept of a boson, and of the spin that distinguishes them, came after the statistics. But even today it has seemed natural for experimenters whose lives have been forged by bosons to say that they find the statistical difference utterly mysterious (Cornell & Wieman, 2002).

In the last accounting, the world has exactly two kinds of things in it, bosons and fermions.

3.2 Recollect Eddington's two tables: and then turn to macroscopic quantum phenomena

Perhaps the only two things that we recall about Arthur Eddington is that he supervised the international observations in 1919 that were the public confirmation of Einstein's general theory of relativity, and that he said there were two tables in front of him, the table of common sense, and the table of physics. He began his introduction to his Gifford Lectures (on philosophy and religion) with these words:

> I have settled down to the task of writing these lectures and have drawn up my chairs to the two tables. Two tables! Yes, there are duplicates of every object about me – two tables, two chairs, two pens. […]
>
> One of them has been familiar to me from earliest years. It is the commonplace object of that environment I call the world. How shall I describe it? It has extension; it is comparatively permanent; it is coloured; above all it is substantial. […]
>
> Table No. 2 is my scientific table. […] My scientific table is mostly emptiness. Sparsely scattered in that emptiness are numerous electric charges rushing abut with great speed; but their combined bulk amounts to less than a billionth of the bulk of the table itself. (Eddington, 1928, pp. xii-xiii)

Most philosophers have thought that Eddington's worry is to be met by philosophical analysis. No. There is a lot more physics now than there was in 1927. We understand more about of the layers that lie between the microscopic table (as I shall call it) and the macroscopic one. Here is how these two terms are defined in Messiah's classic exposition of quantum mechanics:

> We define the 'microscopic' scale as the one of atomic or subatomic phenomena, where the lengths which enter into consideration are at most of the order of several angstroms (1Å $=10^{-8}$ cm). The 'macroscopic' scale is the one of phenomena observable with the naked eye or with the ordinary microscope, i.e. a resolution of the order of one micron (10^{-4} cm) at best. (Messiah, 1958, vol. 1, p. 3)

Eddington gave his lectures 1926-27, just when the second quantum theory came into being. At that time and for a long time to come, the macroscopic and the microscopic were worlds apart – two worlds, in fact. Eddington's two tables were not some confusion caused by bad philosophical grammar. They were the state of physics.

No longer. In recent years there has evolved an entire field called *mesoscopic* physics, the physics of what goes on between these two edges, between 10^{-8} cm and 10^{-4} cm. Not much exists in an ordinary 'material' way in that gap between 10^{-8} and 10^{-4}. Mesophysics builds objects that fill it. It is synthetic physics. It is a way to engage in nanoengineering. Unlike nanoengineers, mesophysicists are less in the business of moving atoms around than of making new ones.

Eddington quite rightly felt a gap between the microscopic world, which we could only infer, and the macroscopic world, which we touch and press, as when we lean on table 1. But now there is now an amazing domain of human interaction and construction that lies between the two.

We nevertheless have a sense that quantum phenomena are essentially in the world of Table 2, both because they are microscopic, and because they need two descriptions, one particulate, and one in terms of waves. This is where Bose condensates come in. One of the more common phrases I encounter in conversation in the lab is, *macroscopic quantum phenomena*. This might seem to be a contradiction in terms, but it arises in the following way. Cold condensed atoms are ones that can all go into the same ground state. Normally a cloud of atoms consists of atoms in a great many states, each of which is itself a superposition. But in a Bose condensate, all the atoms are in the same state, so an observation on their average wave function is a macroscopic look at the quantum wave function, because it is the average of a lot of identical functions. I asked one central experimenter in the BEC field: What do you *mean* by a macroscopic quantum phenomenon? – A long pause, then – It is when I can *see* it.

Here is a new question for philosophical analysis: Do we now, in certain circumstances, "see" quantum phenomena? I do not mean, do we see phenomena that can be explained only by quantum mechanics, for which the answer is plainly yes. I ask, can we now observe veritable quantum wave functions? Many physicists are now prepared to say, Yes!

3.3 Tabletop experiments

Return to ordinary tables. In the 1970s, the most visible physics was still Big Science, the label coined by Derek de Solla Price, and whose epitome was the Manhattan project. The work I am now describing is a return to an earlier world, where experiments are done on the tops of tables, Eddington's tables type 1, *very* solid tables. These are optical tables, poised on cushioned legs to guard against vibration. They are inscribed with high precision threaded holes at precisely regular intervals for screwing in lasers, lenses, split mirrors, and other bits of equipment. Many labs often have two, one with the lasers and lenses, a work of art that could well stand in any gallery of contemporary art – exquisite colours, too. On the second table are the atom trap, and various tools for inducing electrical and magnetic fields, more lasers, cameras, and so forth. The two will be connected by fibre optics that carries the coherent light made on the first table to the actual experiment on the second table. There will be other incomparably more messy tables, for the computers, coffee cups, note pads, pencils and doodles.

The two men in Boulder who shared the 2001 Nobel Prize for making BEC were Carl Wieman and Eric Cornell. Describing one of his early experiences when he moved to Boulder, Cornell writes, "In contrast to the other laser cooling experiments I had seen, which took up the better part of a room, Carl [Wieman]'s experiment could have fit on a card table".[3] A typical BEC lab will have 6 people working in it – a director, one or two postdocs, one or two graduate students, one or two undergraduates, and the ever essential technical person who may share his skills with several labs in a larger unit.

The exciting physics of today has, then, returned to the table top, where small is amazing, and tabletop is 'in'. In a related field, Gérard Mourou has devised techniques to produce very high intensity lasers which, for a very short time, can produce energies at the level of CERN, on top of a table. He published a semi-popular paper a few years ago subtitled 'Physics of the Extreme on the Tabletop'. *Le Monde* ran a story headlined "The intensity of the laser will make matter gush out of the vacuum" (Alberganti, 2005). Well, yes and no. He will get matter by having two beams of coherent light hit each other at enormous energy in a vacuum, and in that sense he will produce matter out of nothing (a quantum rabbit out of an empty hat, as it were). Until recently one needed all the majesty of CERN or of SLAC to produce those energies. Now it is done on the top of a table.

4 A BRIEF HISTORY OF BOSE-EINSTEIN CONDENSATION

The following two tables may be useful for reference.

Absolute zero	0 Kelvin	–273.15° Celsius
A millikelvin	1/1000 of a degree Celsius above 0 K	
A microkelvin	1/1,000,000 of a degree Celsius above 0 K	1 μK
A nanokelvin	1/1,000,000,000 K (10^{-9} K)	1 nK

A short historical summary of low temperature research:

1. Low temperature: below 4 K.
   A century ago the Dutch physicist Kamerlingh Onnes (1853-1926) was able to produce such temperatures during his manufacture of liquid helium. In 1911, he showed that at these temperatures mercury has no electric resistance: It becomes

[3] Eric A. Cornell, 'Autobiography', < http://nobelprize.org/nobel_prizes/physics/laureates/2001/cornellautobio.html>

	a superconductor. (In 1986 Bednorz and Müller created ceramic near-crystals which were superconducting at 150 K, or 123ºC.)
2.	Very low temperature: Below 2.174 K. The Russian physicist Pyotr Kapitsa (1894-1984) showed in 1937 that Helium-4 is superfluid at this temperature. NB : The He-4 atom is a *boson*.
3.	Extreme cold: Below 0.005 K. At this temperature Helium-3, a *fermion*, becomes superfluid. This superfluidity is a phenomenon very different from the superfluidity of He-4.
4.	Ultracold: around 1 nanokelvin. Bose-Einstein condensation occurred in the ultracold – in 1995.

4.1 Bose-Einstein condensate in the mind: Bose and Einstein 1924-5

In 1905 Einstein had proposed quantized little 'grains of matter' to explain the photoelectric effect. In 1924 Bose was trying to explain the concept of the photon to his students at the newly founded and poorly funded University of Dacca. By that time, every physicist had some conception of a photon, but no one could explain the black-body radiation of photons. Bose thought he could see how to do so. I shall recall only one element that connects with the statistics mentioned in § 3.1.

Fifty years earlier, Boltzmann had described the probability with which a molecule of an ideal gas assumes a given state of energy. He took for granted that the molecules of the gas are always distinguishable. In particular, when two particles hit each other, it is always possible to say which one is which after the collision. That is the Maxwell-Boltzmann statistics. Bose proposed that photons do not satisfy this law. They are numerically distinct but indiscernible, violating Leibniz's principle of the identity of indiscernibles. Using this model he could deduce the black-body spectrum for photons.

Einstein was impressed by the idea, and with characteristic imagination, went on to ask what would happen if the atoms of an ideal gas obeyed the same statistics. He saw that something very weird would happen to such a gas at very low temperatures. When cooled, a gas becomes liquid and then solid: steam, water, ice, in our most familiar experience. But we get a different phase transition with a gas of cold bosons. A great many of the atoms will go into the same state of lowest energy, while the rest behave like an ideal gas whose distribution of energies is Gaussian.

Many of the concepts of modern physics did not exist yet in 1925. Two years later, George Uhlenbeck (1900-1988) introduced the essential concept of *spin*. In the beginning he really did think of the electron as spinning in one direction or another, and hence as having an additional degree of freedom. We have come to see the concept as far more rich and far more abstract. Spin is a quantum number that determines the kinetic energy of a particle. It can have only integral values (0, 1, or e.g. -3) or half integral values (½ or e.g. 2 ½). Bosons, the gregarious entities that satisfy Bose-Einstein statistics, have integral spin, while fermions, the solitary ones, have half-integral spin. Very light particles like electrons tend to be fermions, while heavier ones such as protons are mostly bosons. But photons are bosons. Atoms in a gas also have spin which varies according to isotopes. Except Beryllium, every element has an isotope with integral spin, atoms of which are therefore bosons. The other isotopes have integral spin and are therefore fermions. Hence my conceit that everything in the world is either a boson or a fermion. Or: half the things in the world disobey a weak form of Leibniz's principle of the *Identity of Indiscernibles*, and the other half obey a very strong form, the Pauli exclusion principle.

4.2 Theory and Experiment : BEC and superfluidity

Sometimes theory precedes experiment, and sometimes experiments come before theory. In this respect two kinds of low temperature phenomena present a remarkable contrast. The theory of BEC preceded its experimental confirmation for 70 years. In contrast superconductivity was experimentally demonstrated by Kammerlingh Onnes in 1911, with no theory to predict or explain it. When Pyotr Kapitsa established the superfluidity of Helium-4 in 1937, there was no theory to predict that either. The history of superconductivity and superfluidity is a history of experiment before theory from 1911 to 1957.

Fritz London (1900-1954) did have a profound phenomenology of superconduction and superfluiditity. He had a remarkable comprehension of superfluidity as a macroscopic effect produced by the quantum theory. He is a hero for students of BEC, because he saw from the beginning that Helium-4 was a boson, and that its superfluidity was connected with a Bose condensation phenomenon. But only in 1957 did John Bardeen, Leon Cooper, and John Schrieffer provide a microtheory of superfluidity, now called BCS after their initials.

Such absences continue: No theory explains a phenomenon known since 1986, high temperature superconductivity. But in the case of BEC, there was only theory. It was a rich history of theorizing, especially in the Soviet Union, with men such as Lev Landau (1908-1968) and Nikolai Bogoliubov (1909-1992). We only got a Bose condensate in 1995. That required radical advances in cooling atoms, and the laser was the tool.

4.3 Laser cooling: the 1980s

A hot bath gets cold because the most energetic water molecules evaporate, and so carry energy away with them. That is the cheap way to cool atoms. They can be confined in a trap, using electric and magnetic fields; the warmer ones escape, thereby reducing the energy of the remaining trapped atoms. Trapping technologies improved enormously in the 1970s. Tricks to speed up evaporative cooling followed suit. Very crudely, laser light is produced in a range of suitable frequencies, and this will excite some atoms to the point where they leave the trap, thereby cooling the remaining trapped atoms. Hydrogen was often the preferred element, and a number of teams were producing very cold hydrogen by evaporative cooling. Unfortunately, although this produced a whole range of new experimental skills, the apparatus became more and more complex. Increasingly attention was focussed on bosons of alkali metals, such as potassium, lithium, and, in the first successful experiment, rubidium. This was a choice encouraged by nature and society. Nature, because alkali metals have a single electron in the outer shell, and so they are easier to interfere with in a systematic way by using laser light of a frequency corresponding to the spectrum of the metal. Rubidium became the metal of choice, in many start-up labs, for a wholly social reason. The cheap mass-produced lasers that are used in CD players and the like use dark red light, so one could buy cheap off-the-shelf lasers.

In the mid 1980s there was a fundamental breakthrough: slowing atoms travelling in one direction by a beam of laser light of the right frequency, travelling in the opposite direction. This produced a variation on the Doppler Effect, whereby the relative velocity of the atoms was lowered, and hence they had less energy. Three laboratories shared the Nobel Prize of 1997 for their successful laser cooling: those of Claude Cohen-Tannoudji in Paris, Steven Chu in Stanford, and William Phillips at NIST in Gaithersburg. (NIST, the National Institute of Standards and Technology, is the former Bureau of Standards, of which there was always one main centre in Gaithersburg near Washington D.C. NIST now a second centre, in Boulder, Colorado, in close collaboration with physicists at the University of Colorado.)

The story of laser cooling provides a philosophical lesson. Paris and Stanford got Doppler cooling to work exactly as theoretical analysis had predicted. But the NIST group – part of an institution whose mission had always been the most precise measurement possible – was sceptical. They did not get values that agreed well with calculation. One thing that they noticed was that it made a difference where one placed the detector with which one observed the expanding cloud of atoms after the trap had been switched off. It is no mean feat to get all one's equipment in the neighbourhood of a tabletop. For convenience we humans tend to stack things up, so that we put the detector above the trap. These are very cold, lethargic, atoms. They have very little energy. Normally gravity has no discernible effect on the motion of an atom. But never forget Galileo: very cold atoms will fall, just like cannon balls. It will make a difference to your measurements whether you put your detector above or below the expanding cloud of atoms, because the atoms below a detector will be accelerating away from it, and those below one will be accelerating towards it – all in almost free fall.

The upshot was a surprise: experimenters routinely assume that their apparatus is not going to work as well as it ought to. But Doppler cooling worked much better than it should have. The groups of Chu and Cohen-Tannoudji had been content with results that pretty well fit predictions, but more delicate measuring showed that the cooling was much better than predicted. This is not a story one finds presented in this way in the printed record; I owe it to Paul Lett of NIST, who worked in Phillips' team.[4] Back to the drawing board: Cohen-Tannoudji and others realized there was another phenomenon at work, Sisyphus cooling. The name is apt. One has the picture of the beam of coherent light being like a washboard or other corrugated surface. An atom confronting the beam has to go up each corrugation, expending energy, and then do it all over again and again. That is the crude explanation of why laser cooling is so effective.

4.4 Bose-Einstein condensation in the laboratory: Boulder and MIT, 1995

All the pieces were in place, and yet Steven Chu, just mentioned, said in 1994: "I'm betting on nature to hide Bose condensation from us. The last 15 years she has been doing a great job". Nature unveiled herself a few months later. Victory went to the team with the simplest experiment and the simplest apparatus – that of Carl Wieman and Eric Cornell, in June 1995, using rubidium-87 (Anderson *et al.*, 1995). This was published in *Science* with the note: received 26 June 1995, accepted 29 June 1995. Evidently the community was impatiently waiting! All simplicity is relative, but the Boulder group really did reverse the ever-increasing complexity of the hydrogen experiments.

> Previous laser traps involved expensive massive laser systems and large vacuum chambers for atomic beam precooling. […] However in the first JILA [Boulder] magnetic trap experiment our lasers were simple diode lasers, the vacuum system was a small glass vapor cell, and the magnetic trap was just a few turns of wire wrapped around it. […] If we wanted to modify our magnetic trap it only required a few hours winding and installing a new coil of wires. This was a dramatic contrast with the hydrogen experiments that, like all state of the art cyrogenic experiments, required an apparatus that was the better part of two stories, and the time to modify it was measured in (large) fractions of a year. (Cornell & Wieman, 2002, pp. 83, 87)

A few months later Wolfgang Ketterle's group at MIT succeeded with Sodium. There are now excellent summaries of the innumerable tricks of the trade, of which the most useful may be Ketterle's (Ketterle, Durfee & Stamper-Kurn, 1999).[5]

4.5 The present

A new continent has been created, the ultracold, and we can only speculate what will be found there. To begin with there are variations on the original theme, even with the workhorse isotope, Rubidium-

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[4] One of the published papers on the NIST work is Lett *et al.*, 1988

[5] Available in the on-line archive of all condensed matter papers since April 1992, <http://arxiv.org/archive/cond-mat/9904034>. For an entertaining popular explanation of the field, see the 'Atomic Lab' on-line at <http://www.colorado.edu/physics/2000/bec>.

87. Try to make a more long-lived condensate, with a far greater density of cold atoms, or on the other hand with very few. The Boulder condensates began with about 2000 atoms. Now rubidium condensates are ten thousand times larger. But also one plays with extremely dilute gases, what is called number-squeezing. This leads to the thought that we will soon be able to produce macroscopic Schrödinger cats.

That will fascinate philosophers, but other issues are central to the future of physics. One very active field is cold fermions, partly because of the analogy with Cooper pairs (of electrons, which are fermions) that are at the heart of the BCS theory of superfluidity. Fermions have half-integral spin. You cannot make a BEC of Fermions, but a pair of fermions is a boson, since spins are additive. So a gas of paired fermions should turn into a Bose condensate. Deborah Jin, a former student of Cornell's, was able to do this in 2003 (Greiner, Regal & Jin, 2003).

Is a condensate of fermion-pairs a superfluid? Everyone thought so, but the proof was left to MIT, using Lithium-6, in June, 2005. Because there is no friction, a superfluid condensate should produce a regular lattice of vortices on its surface (Zwierlein *et al.*, 2005). Rudolf Grimm, director of the BEC laboratories at Innsbruck, hailed this result as a quantum revolution, comparable to the first production of Bose condensate in 1995.

> The spectacular observation of vortices in a Fermi gas heralds the advent of a new era of research reaching far beyond Bose-Einstein condensation. As an immediate experimental step, interfering light fields can be used to simulate a crystal lattice, providing a unique tool for solving problems in condensed matter physics. And the amazing level of control demonstrated in the work [at MIT] can be extended to more sophisticated systems – mixed Fermi systems could be used to simulate a nucleus of protons and neutrons, or exotic semiconductors. This final proof of superfluidity in a Fermi system opens fantastic new prospects for many different fields of many-body quantum physics. (Grimm, 2005)

At present one speaks of two regimes, BEC and BCS, and of the BEC-BCS crossover as the material conditions in which one is produced, become close to those in which the other is produced. The standard conjecture is that the same physics is involved in both cases. The analogies between Cooper pairs and pairs of fermionic atoms leads many investigators to think we are getting closer to understanding the foundation and nature of both types of phenomena.

Those matters touch the present heart of our subject. But there is no lack of more speculative work. I shall mention four examples, not because they are the most important, but because they are rather varied, and range from the relatively routine clearing up of old problems to bizarre investigations of new topics.

(a) What happens when light passes through glass? As soon as there were photons in physical theory – 1905 – there were accounts of what happens when a photon passes through a dielectric. The trouble is that there have been two competing models in circulation ever since the first decade of the twentieth century. One is due to Einstein's teacher, Hermann Minkowski (1864-1909) and the other to Max Abraham (1875-1902). The latter is in effect more complex than the former, and adds an extra physical effect. It has been proposed for some time that on Minkowski's account, a beam of photons passing through glass should produce a force acting against the direction of the beam, while if Abraham is right, the force should be in the direction of the beam. This has the virtue of being a qualitative effect, even if it is a subtle one that has thus far never been detected. Is the glass nudged to the left or the right? Paul Lett is undertaking an experiment at NIST using a Bose condensate as the dielectric. A positive outcome may be hoped for in a couple of years.

(b) Cold atoms have almost no energy so, as we have said, they fall just like cannon balls. If only we could free them from the effects of gravity, we could study them with less effect from that external influence. Their wave function would be even more readily observable, and we would have a more 'macroscopic' quantum phenomenon than ever before. So, why not try to make *BEC in a laboratory in space*? Such a programme is envisaged. The first step is to make more robust lasers that stand up well to free fall. So they are now being dropped 146 metres from the Bremen *ZARM-Fallturm*, where they are in a controlled and measured state of free fall for 4.7 seconds. The dropping tower in Bremen can do three drops a day if the experimenter's measuring equipment is up to it. One likes to think of it as being admired by Galileo's ghost.

(c) One of the most dramatic of quantum effects is quantum tunnelling. Electrons cross an energy barrier, now they are on one side of it, now they are on the other. It is a well-established phenomenon that follows directly from theory, and yet it remains in a way wholly mysterious. What *does* happen in that instant when something 'tunnels' through a barrier? It is not obvious that the question makes sense, for we may be simply making a macroscopic demand – asking a question that makes macroscopic sense – in a domain for which it is in principle inappropriate. But everything happens so slowly in the ultracold, that one can ask what *ultracold quantum tunnelling* looks like. This is a project that Aephraim Steinberg hopes to undertake in the quantum optics laboratory at the University of Toronto.

(d) To conclude with something more mainstream, the laser produces an intense beam of coherent light which is an extraordinary tool for endless applications. For some years now there have been what, by a dubious analogy, are often called '*atom lasers*'. These produce beams of cold atoms going in exactly the same direction with exactly the same energy. These are developed at NIST for its traditional role, metrology. One envisages exact measurements based on interference patterns using these highly collimated beams of atoms.

5 LESSER PHILOSOPHICAL THEMES

5.1 Experiment and theory

BEC and superfluidity between them illustrate opposite side of what philosophers have sometimes called the inductivist/deductivist divide. Deductivists think that theory always comes first, inductivists that observation and experiment always come first. BEC is a fine case for deductivism: seventy years of rich theorizing before any experimental confirmation worked. Superfluidity and superconductivity are great examples for the inductivist: decades of phenomena and phenomenology before the BCS theory of 1957, and even now high-temperature superconductivity is a fact of the laboratory and potentially of industry, that no theory well explains.

Philosophers of science tend to write as if 'the' relation between theory and experiment was a timeless aspect of the scientific endeavour. In *Representing and Intervening* I recall Humphry Davy's lovely invocation of analogy in 1812 (Hacking, 1983, p. 152). Fifty years later an equally great chemist, Justus Liebig was a Popper ahead of his time, "in science, all investigation is deductive or *a priori*. Experiment is only an aid to thought, like a calculation: the thought must always necessarily precede it if it is to have any meaning" (*ibid*., p. 153). Popper merely furnished the epitome of all future deductivisms: "the theoretician must long before have done his work […] It is he who shows the experiment the way" (*ibid*., p. 155).

These are the standard examples, yet the entire contrast between theory and experiment may be fading before our eyes. In the great BEC labs one regularly hears the following from experimenters. We are so lucky – we have a theory group on the 5th floor who understand exactly what we do, and we need them to work out what to look for. Go to the 5th floor, and one hears: We are so lucky – we have an experimental group in the basement who understand exactly what we do, and we need them to give us some numbers to use as parameters in our models. (Labs are usually in the basement to minimize vibration and building sway in high winds.)

Here is a conjecture for our times: We have moved to a regime where, in physics, they are mutually inextricable. You cannot do experiment without detailed theoretical plotting of the possible outcomes. But also you cannot do theory without experiment telling you numerical values to incorporate in models.

5.2 A thesis due to Pierre Duhem made general

A century ago, in the course of his masterpiece on the philosophy of physics, Pierre Duhem presented his famous argument that an observation made with instruments can never refute a theory (Duhem, 1906; Duhem, 1956). An astronomical theory predicts that a celestial phenomenon will be observed at a certain place and time. Using an appropriate telescope one sees nothing. Refutation! It is time to revise the theory? Not necessarily, one can always modify the current theory of how the telescope works.

Philosophers who appear not to have read Duhem now write about the Quine-Duhem thesis, but that is a confusion. Quine wrote about holism and the revisability of any part of a conceptual scheme in the light of a recalcitrant experience. He wrote about the *logical* possibility of saving any belief whatsoever. Duhem wrote about the possibility in real-life experimental physics of saving a hypothesis challenged by observations made using instruments.

Andrew Pickering and I have generalised Duhem's thesis (Hacking, 1992; Pickering, 1995). You can modify the theory of how a particular type of telescope works, but you can also modify the instrument itself. The history of laser cooling just described affords a splendid example. We begin with an arrangement of atom traps, lasers and so forth, but after the work of William Phillips, Paul Lett, and their team at NIST, we modified both the apparatus (moving the detectors around) *and* the theory of how it worked (the Sisyphus effect).

5.3 On conceptual change: what is a molecule?

We all learned that molecules are groups of atoms held together by the chemical bond (to mimic the title of Linus Pauling's famous textbook). I always thought that was one handy fixed point in the sciences. Not so. Recall cold fermions. There is a strong analogy with Cooper pairs of another type of fermion, namely electrons. The bond in Cooper pairs is very weak, compared with the chemical bond. So too is the bond between pairs of fermions that form a boson – indeed the nature of this bond is not well understood yet. It has become increasingly common for ultracold atomic physicists refer to Cooper pairs as molecules, and likewise for fermion pairs. Far from this being a merely extended usage, one hears the proposal that it is time to rethink the nature of the chemical bond. In 2003 Deborah Jin and her colleagues wrote that fermion pairs are molecules "in the ordinary sense of the word" (Greiner, Regal & Jin, 2003).

Ever since Kuhn and Feyerabend, philosophers have debated whether theory change produces meaning change. Science in action gives us a richer perspective. We may at the moment be rethinking what molecules are. Yes, this may produce a new or revised concept of the molecule, if you prefer to talk that way. Such linguistic or logical playfulness should not deflect from the more complex issues of rethinking the molecule. What holds items of a certain size together? Answers will be influenced by and influence such profound concepts as the strong and weak forces in subatomic physics.

5.4 Signatures of BEC: written by nature or chosen by society?

Since 1995 there has been a standard 'signature' of Bose-Einstein condensate. A cloud of bosons is trapped. Has condensation occurred? Turn off the traps and photograph the gas as it expands. Deduce the energy of the atoms from the rate of adiabatic expansion. If Bose-Einstein condensation has occurred, some of the gas will be a condensate in lowest energy state, and the rest will be thermal with an ordinary Gaussian distribution of energies. The Boulder laboratory transformed the state into a vivid picture. A sequence of three images in false colours of atomic velocity distribution is produced. The height of the graph indicates density, colours indicate velocities. We 'see' the very cold gas (a) just before BEC appears, a pretty Gaussian looking curve, then (b) with a peak appearing above the curve, just as the condensation is starting, and (c) after a lot more evaporative cooling, when there is a peak of low velocities, surrounded by a Gaussian-looking distribution of higher velocities. The 'Three Peaks' have become the standard image for a lab to display, often on-line, in order to announce that it has succeeded in making BEC.

To what extent is the choice of this image a historical accident? To what extent is it imposed by 'natural' constraints? The question is fairly general. Phenomena or what we call effects are often associated with characteristic signatures. To take an even more current example, when fermion pairs condense, the (presumed) superfluidity will cause vortices to appear on straightforward photographs of the gas. This is called the *smoking gun* that establishes what is happening.[6]

It appears that the choice of a signal as definitive for a phenomenon is partly social, partly natural. We choose a signal, and a way of formatting the signal (the colourful Three Peaks, the pretty symmetric arrays of vortices) so that it strikes the human eye. Between social and natural are also the choices of instruments, their history, their relative cost. That is partly a history of the evolution of the subject, but also a contingent history of particular laboratories with their own instrumental traditions.

In his masterly study of high-energy physics, Peter Galison wrote of "the 'golden event': the single picture of such clarity and distinctness that it commands acceptance" (Galison, 1997, p. 22). He lists some famous ones, from Anderson's picture of the positron in 1932 to the 1970s picture of the single-electron neutral-current event in the 1970s. Note that golden events, in this way of speaking, are *pictures*. But increasingly images are malleable. The old confidence that a photographic record tells it as it is has gone forever. The Boulder team translated their data into a striking series of images where one can see the peak (high density) of very unenergetic atoms (the part of the graph coloured blue). This image, the Three Peaks, becomes cemented in the mind of the community. This is a remarkable collaboration of the social and the physical. That in itself gives no incentive to anti-realism about the phenomenon of BEC. The phenomenon is real, and it produces the signal by which we recognize it. But the form in which that signal is made present to us, the extended community, is somewhat contingent on a tradition that is only a few years old, and which was inaugurated during 1995. A tradition that in retrospect seems inevitable. Thus we are furnished with a clear example of the contingent assuming the guise of the necessary.

5.5 On analogical research: From the cold laboratory to the cold star

During the twentieth century, analogy almost disappeared from the philosophy of science, with the notable exception of Mary Hesse, who connected analogy with modelling, and thereby presaged the subsequent attention to models as opposed to theories (Hesse, 1963). Analogy has meant different things in different eras, but there is the core idea of similarity in some structural respects between things that are otherwise dissimilar, suggesting that they may be alike in other structural respects as well.

Here is a first use of what I shall call *analogical research* in the BEC field. There is the thought that fermion pairs in the ultracold laboratory have a remarkable interest for nuclear astrophysics. 'Ordinary' luminous stars like our sun are mostly made up of protons – hydrogen atoms – that are burned into helium by nuclear fusion. The heat of the fusion stops these stars from collapsing: the thermal expansion and the gravitation attraction balance. Neutron stars such as white dwarfs are composed mainly of neutrons. Neutrons are fermions. Fermions resist being compressed too tightly. There is a rather cute reason for this. According to the Heisenberg uncertainty principle, severely constrained position entails great uncertainty in momentum. So the locally constrained fermions move around very fast, which produces what is called the degeneracy pressure. This counteracts gravity and keeps the blob of neutrons from collapsing. Since we cannot experiment on white dwarfs, we have little direct evidence telling us how to model fermions under these conditions, but it is now widely speculated that they exist as fermion pairs forming a superfluid. In the laboratory we shall be able to determine experimentally, by manipulation of conditions, a great many of the properties of fermion pairs that we

[6] Referring to the research in Boulder, *Physics World*, March 2004, writes under the headline, 'Fermionic first for condensates': '[…] the JILA result is the "smoking gun" of a fermionic condensate'.

have hitherto been unable to model. Thus by analogical reasoning we may pass from a more thorough knowledge of the ultracold to an understanding of how and why neutron stars exist. And perhaps I was wrong about the phenomenon of BEC existing only in labs. Maybe there are pockets of Bose-Einstein condensate in neutron stars!

5.6 On analogical research: From crystals to optical lattices and back again

To take another example of analogical research, I quoted Rudolf Grimm: "interfering light fields can be used to simulate a crystal lattice, providing a unique tool for solving problems in condensed matter physics" (Grimm, 2005). Here is what he had in mind. A crystal is a solid with a well defined geometrical form, characterised by a regular three-dimensional arrangement of atoms. A typical form is a three-dimensional lattice. An optical lattice can be thought of as an artificial 'crystal', composed not of atoms but, in a sense, of light. If you send two beams of laser light having the same frequency against each other in opposite directions, interference produces periodic dark and bright bands, which have half the wave length of the laser beam. Hence with three pairs of opposed lasers one can produce a lattice in three dimensions. Such a lattice can be used to trap atoms of cold quantum gases. The mathematics of such a lattice is simply taken over from a standard crystal lattice.

But now we can reverse the learning process. We took our knowledge of crystal mathematics and applied it to optical lattices. We can use easily manipulated optical lattices to investigate the structural properties of crystals that we cannot manipulate. This is really interesting. There is no good theory about high temperature superconductivity of certain artificial crystals, and no easy way to interfere with those crystals to find out more about them. So we can now by analogy transfer questions about these remarkable crystals to laboratory work on optical lattices.

There is a remarkable feature shared by both these cases, but it is more apparent in the case of crystals than in the case of neutron stars. We are no longer in the realm of *argument by analogy*. We have turned to what might be called *analogical research*, we investigate X, which is not susceptible to laboratory purification and manipulation, by an analogical substance Y, which is easily investigated in the laboratory. The essence of the laboratory is controlled interference and the production of new phenomena. When we cannot conveniently create a laboratory for asking one set of questions, we may be able to create the analogical laboratory where we pose parallel questions, and then see if the answers, by analogy, do not transfer back to the subject that in the first instance aroused our interest: neutron stars or high temperature superconductivity.

5.7 Macro and micro merged?

Do we see quantum phenomena? My colleague Serge Haroche insists that atoms and ions have ceased to be merely theoretical entities since he and his colleagues see small numbers of them in his ultracold laboratory (Haroche, 2003). We may go even further. Have we changed forever the gap between the microscopic and the macroscopic? Have we ended the dichotomy between Eddington's two tables? I think this is happening in many domains. There is mesophysics and nanotechnology. Most astonishing of all, to my mind, are the macroscopic quantum phenomena induced by Bose-Einstein condensation.

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