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Why Quarks Are Unobservable

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Résumé : Cet article pose la question de savoir si les quarks — constituants élémentaires de la matière et dernières particules de la physique des hautes énergies à avoir été confirmées — peuvent être observés de manière directe ou indirecte. D'abord, des définitions antérieures de « l'observation » en physique seront examinées — en l'occurrence, celles proposées par Grover Maxwell, Bas van Fraassen et Dudley Shapere. Puis, leurs résultats seront comparés à une définition du concept d'observation et à une différenciation entre l'observation directe et indirecte.

Une possibilité de mettre en évidence les quarks de manière expérimentale est le phénomène des *jet-events*, qui représentent un type spécifique de désagrégation dans les détecteurs de particules. Ces *jet-events* contribuent à l'étude de cas ici centrale, puisqu'ils sont la preuve la plus convaincante à ce jour des quarks. L'examen de *jet-events* et leurs évaluations par des physiciens mènent à la conclusion que les quarks ne peuvent être observés, ni directement ni indirectement. Cette thèse sera comparée aux points de vue de Kristin Shrader-Frechette et Michela Massimi sur l'observabilité des quarks. On en tire la conclusion que les quarks ne sont pas observables, si l'on entend employer le terme « observation » dans un sens non métaphorique et en conservant une relation avec ses usages dans la vie quotidienne.

Abstract: This essay deals with the question whether quarks—the basic components of matter and one of the youngest confirmed particles in high energy physics—can be observed directly or indirectly. First, I shall discuss earlier definitions of "observation" in physics suggested by Grover Maxwell, Bas van Fraassen, and Dudely Shapere. Then, I shall compare their results with a new consideration of the idea of "observation" in physics and the distinction between direct and indirect observation.

One of the ways that quarks appear in experimental evidence is in *jet-events* which are special decay patterns in particle detectors. These *jet-events* are the central case study for this essay since they are the most convincing evidence of quarks so far. My inquiry into the physics behind jet-events and their treatment by physicists leads me to conclude that quarks are neither directly nor indirectly observed. I compare this thesis to other views on the observability of quarks, suggested by Kristin Shrader-Frechette and Michela Massimi. But in short, it seems to me that if the notion "observation" is to

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have a reasonable relation to an everyday life's concept of observation, and if it is meant literally instead of metaphorically, then quarks are not observable in any currently-known experimental context.

1 Introduction

Observation and observability are key concepts when philosophy of science and epistemology meet. Philosophy cannot predict which objects might be observable and which are not. It has to define "observability" as an epistemological term used to give meaning to scientists' sentences when they claim to have observed something.

In this paper, I shall discuss the observability of a special kind of elementary particle—quarks. Today, it is common in physics to deal with entities that are barely observable, entities which are in principle only indirectly observable or unobservable. Now, with quarks, because of some physical aspects, it is not quite clear whether they are observable or not, even though they are fully-established in theory and sufficient experimental evidence of them exists. This has provoked some comments in philosophy of science, mainly by Kristin Shrader-Frechette and Michela Massimi. They came to the conclusion that quarks are—even directly—observable. Their argument is based on seminal works on the concept of observability by Grover Maxwell, Bas van Fraassen, and Dudley Shapere. My approach to this debate has two directions. First, to search for metaphors used by scientists to describe their findings in quark physics. And to address whether quarks can be seen or only "seen" in a certain experimental context. It is logical that if they could only be "seen"—and this is my presupposition—then quarks are only "observable", i.e., metaphorically observable but not literally observable. Something only metaphorically observable could be anything from an entity that is directly observable in another context to unobservable in principle. The idea, that a physical entity is only "observable", leads us to question its real relation to the epistemological concept of observability.

Second, I would like to focus on the exact role *jet-events* play in experimental particle physics. I will show in detail what jet-events are, and what their unique decay pattern in particle detectors looks like. However, my working hypothesis is that jet-events should not to be used as simple images to predict what might go on at a microphysical scale. The explanatory power of such events is more subtle, particularly when considering their relevance to the alleged observation of quarks. My general conclusion is that quarks are neither directly nor indirectly observable. This conclusion is not based on any genuine physical statement or theory in particle physics, but it might have consequence for the ongoing philosophical debate of scientific realism, particularly as the real classification of entities like quarks becomes more difficult when they cannot literally be observed or indirectly observed. Though, this final thought is not addressed in this paper.

So my chief statement is that quarks are not observable. To come to this conclusion I will try to develop, in the following Section 2, a concept of observation and draw a distinction between direct and indirect observation. Anything that is able to fulfil the criteria of direct or indirect observation has to be called directly or indirectly observable—regardless of whether this actually has been done or not. In Section 3, I will give an introduction to jet-events that occur in certain conditions when highly accelerated particles collide inside particle detectors. Then I shall apply the concept of observation to jet-events (Section 4). In this context at least, quarks are not observed in jet-events, and thus, we have strong indications to believe that they will not be observed under any other experimental conditions either.

2 What is observation of objects in physics?

2.1 Earlier proposals

The challenge to define "observation" has a lengthy history in philosophy. It is also a common subject in the philosophy of science and has particular relevance to the debate on scientific realism. I would like to focus on the meaning of observation in relation to physical objects. The most famous thoughts on this subject came from Grover Maxwell, Bas van Fraassen, and Dudley Shapere. And these authors are repeatedly quoted by later philosophers writing on quarks. Maxwell argues for the broadest possible concept of observation in a 1962-paper *The Ontological Status of Theoretical Entities* [Maxwell 1962]. In this work, Maxwell calls some objects theoretical while we would describe them as physically motivated and call them sometimes indirectly observable. He is not interested in a distinction between direct and indirect observation, but in a distinction between observability and unobservability, or, in his terms, between observation and theory. His inquiry looks at microbes, molecules, and elementary particles. These are objects that existed in scientific thought long before any tools were invented to observe them. Maxwell's main thesis is that there can be no clear distinction between observation and theory:

> The point I am making is that there is, in principle, a continuous series [of observations] beginning with looking through a vacuum and containing these as members: looking through a window pane, looking through glasses, looking through binoculars, looking through a low-power microscope, looking through a high-power microscope, etc., in the order given. The important consequence is that, so far, we are left without criteria which would enable us to draw a non-arbitrary line between "observation" and "theory". [Maxwell 1962, 7]

By Maxwell's reasoning, deciding that an observation through a microscope is not an observation leads us to try and establish a reliable boundary between observation and non-observation. Maxwell argues that trying to fix this boundary at the point where tools like microscopes are used is a dead end, because window panes and glasses are in some way tools too and nobody would realistically claim that the observation of an object through glasses is an indirect observation. His conclusion is that everything called observation in science, is actually an observation. And that observability is changeable and depends on the scientific tools and theories available at the time.

> I conclude that our drawing of the observational-theoretical line at any given point is an accident and a function of our physiological make-up, our current state of knowledge, and the instruments we happen to have available and, therefore, that it has no ontological significance. [Maxwell 1962, 14–15]

To Maxwell, observation is more or less any reasonable inference that can be made from experimental data or examined entities. This concept is based on the obvious absence of a dividing line between observation and non-observation (or theory). According to Maxwell, we are even able to observe the gravitational field or it's metric tensor $G_{\mu\nu}$ "by sitting on a chair—and we do it *directly*" [Maxwell 1962, 14]. To me the advantage of Maxwell's concept is that it is intuitive and carefully avoids the problem of theoryladen observation and other epistemological inferences. It openly states that any observation is laden by presupposed knowledge, whether scientific or knowledge of other kinds. The problem of *theoryladeness* in science (i.e., that nature and result of an observation depends on certain presupposed theories) is discussed elsewhere [Hanson 1958], [Kuhn 1962], [Goodman 1978].

Possibly, one could say that theoryladeness is everywhere, and therefore harmless. But Maxwell's definition of observation stops being intuitive if entities are categorically unobservable in principle, like natural constants or pure mathematical objects (e.g., virtual particles). And it seems to me that some data from particle experiments that are called observations rely too heavily on theory, for example jet-events on which I will comment in Section 3.

In Bas van Fraassen, we find a sceptic concerned by the breadth of the concept "observable". He does not deal with the distinction between direct and indirect observation but tries to pin down the distinction between observable and unobservable. This is quite simple, especially from an empiricist's point of view. Van Fraassen's examples are archetypal—seeing a vapour trail in the sky is not the same as observing a jet, but the unaided perception of the jet itself is (we come back to this later). Similarly, the track of a particle is not to be treated as an observation of the particle itself [van Fraassen 1980, 17]. Van Fraassen challenges Maxwell's view and suggests a concept of observation that is aware of its vagueness and its anthropocentric quality. The vagueness follows, according to van Fraassen, from the fact that drawing the line between what is observable and what is only detectable is not possible without arbitrariness in Maxwell's sense [van Fraassen 1980, 16]. The anthropocentric quality derives from the "able"-part in "observable". If something is x-able, someone has to have the ability to x. Van Fraassen asks further whether it is possible for technical aids such as microscopes and telescopes to increase the number of observable objects. Van Fraassen reasons:

> This strikes me as a trick, a change in the subject of discussion. I have a mortar and pestle made of copper and weighing about a kilo. Should I call it breakable because a giant could break it? Should I call the Empire State Building portable? Is there no distinction between a portable and a console record player? The human organism is, from the point of view of physics, a certain kind of measuring apparatus. As such it has certain inherent limitations (...) It is these limitations to which the "able" in "observable" refers—our limitations, *qua* human beings. [van Fraassen 1980, 17]

Furthermore, van Fraassen disassociates the observable-question from questions about observable and unobservable objects. By ridding himself of the need to find a line between observable and unobservable, van Fraassen is able to discuss his specific view of scientific anti-realism without being hampered by examples of new pretended observations in microphysics.

This survey—although a reliable alternative—has much in common with Maxwell's and so my suggestions run along similar lines as before. There is, as argued above, no compelling arbitrariness in the demarcation, or any necessary reason, to restrict observability to the unaided human eye. Van Fraassen's rejection of technical aids to observe events leads to a statement like this:

> A look through a telescope at the moons of Jupiter seems to me a clear case of observation, since astronauts will no doubt be able to see them as well from close up. [van Fraassen 1980, 16]

Thus, as to van Fraassen, the observable-label depends on the circumstances of the observation. While I fully agree with this opinion, his example seems to be based on something still open to be demonstrated. Since nobody so far has been close to the moons of Jupiter, all we know about their existence and observability is based on research done from a great distance with the help of, e.g., optical means, namely telescopes. We have to discuss the view through a telescope *before* we travel to the discovered objects (if such journey will be undertaken at all). Van Fraassen seems implicitly to agree to the existence of the moons as solid spheres orbiting Jupiter and, therefore, he already uses a concept of observation being independent of astronauts facing an object in front of them.

Finally, it must be pointed out that van Fraassen, based on his treatment of "observation" and "observability", would presumably deny the observability of quarks. For him, quarks would be a theoretical ingredient to make quark-theory *adequate* to deal with such events. While I would agree that quarks are unobservable, I come to that conclusion for different reasons.

Next on the list is Dudley Shapere. He investigates an experiment designed to study the core of the sun by monitoring neutrinos from it with a subtle apparatus placed deep underground [Shapere 1982]. The resulting data details the frequency of each radioactive substance found in the apparatus. Originally, the experiment was arranged to test a theory about atomic fusion in the sun's centre, something the data successfully confirmed. But Shapere was more interested in deriving a concept of observation from the experiment. According to him, the experiment was a direct observation of the core of the sun. This direct observation was theoryladen, but the theoretical components could be systematised and explained. He reasoned that for there to be an observation situation there must be, in general, a flux of information from the observed object to the observer. There has to be: (a) a theory about the observed object that has to release some kind of physical signal as information; (b) a theory about the transmission of this information that makes sure that the information is not altered or tampered with; (c) a theory about the receptor of that information which must not be a biological or even human receptor. Any kind of measuring device can be taken as a receptor [Shapere 1982, 490ff.].

Shapere summarises:

> x is directly observed (observable) if: (1) information is received (can be received) by an appropriate receptor; and (2) that information is (can be) transmitted directly, i.e., without interference, to the receptor from the entity x (which is the source of the information). [Shapere 1982, 492]

He shows explicitly how, according to the theory of core fusion, the centre of the sun emits neutrinos radiation in all directions, even in the direction of the Earth. According to particle physics, most of the neutrinos pass the Earth unaltered, but some interact with matter. Physics can predict the frequency of interactions in a given amount of, say, perchloroethylene provided it is placed underground to protect it from other cosmic rays. An interaction of neutrinos with perchloroethylene produces a radioactive isotope which can be counted. The theories about the sun, the flux of neutrinos, and the events in perchloroethylene as well as in a device like a Geiger counter tell us, according to Shapere, that there is information being reliably transmitted from the sun's core to us. Thus, we would be able to observe the sun's core directly.

So far, this notion of direct observation is convincing and it has the advantage of making the search for a definition of indirect observation, obsolete. Nearly everything is directly observable if we only have enough physical knowledge. Shapere excludes consciously the realm of quantum physics where theories of the source and the transmission are not clearly separated. This and other "special complexities and difficulties of interpretation" prevent the application of Shapere's concept of direct observation to today's elementary particles [Shapere 1982, 512–513].

There is, however, another reason to abandon his proposal. In Shapere's view the same situation can be interpreted as a direct observation of several different things. Counting the amount of radioactive decays in the Geiger counter can be a direct observation of the centre of the sun, or of neutrinos interacting with perchloroethylene, or of a radioactive substance, or simply the Geiger counter sat in front of the scientist providing data. In that case, the notion of observation once again broadens out to approach the views of Maxwell, although it is restricted to entities capable of acting as a source of information. To me, any reasoning on "observation" has to allow for directness, indirectness and complete unobservability, even when considering entities that are somehow hidden from view. The correct definition of "observation" should help to decide if these objects exist due to direct or indirect observation or if they will perpetually remain theoretical entities.

By now we should have some idea of how the protagonists of philosophy of science deal with the problem of scientific observation and how these proposals might be flawed. There are, of course, other proposals from Ian Hacking and Paul Feyerabend to name a few, but they are less important to us since their focus is slightly different from ours. For example, both Hacking and Feyerabend treat observation as an ability of scientists, something one is able to learn and improve upon [Hacking 1983, 180–181]; [Feyerabend 1978, 40–47]. They therefore are discussing the term "observation" from a different point of view. My approach in direct comparison to Hacking and Feyerabend is asking: What is the definition of "observation" independent of abilities and scientific theories; what term of observation did we already develop when thinking about learned scientists who seem to observe more than others?

Feyerabend, moreover, focuses on the theoryladeness of observation and concludes pretty fast that every observation, even in everyday life, is theoryladen. According to him, at least three theories are involved when we, e.g., observe a simple table: a theory of the human eye, a theory of light, and a theory of the physiology of the whole observer. Even a table would be a theoretical notion hence. Feyerabend believes that the dichotomy between observable and unobservable breaks down [Feyerabend 1978, 46]. I think this is too broad a concept of theory. We reasonably discuss whether we observe a simple table without any use and need for scientific theories. This fact goes to show that observation (everyday and in scientific laboratories) does not have to be theoryladen.

2.2 The approach to the problem of observation

Before fully entering the discussion, I want to develop two basic premises. First, a definition of observation should be independent from all physical knowledge. The meaning of "observation" should not be influenced by changes in physics. Observing something in science is an epistemological undertaking that originates from an object's observation in daily life. It neither depends on contingent technical knowledge, nor on an exclusive ability possessed by only a few. Therefore, I would like to argue in another way, as Ian Hacking has done in *Representing and Intervening* [Hacking 1983, 180–181]. I think that statements like "in former times observation was to do x but today, in the era of quantum physics observation is to do y" or "an expert sees electrons in a certain picture while a layman just sees light lines in the dark" (no quotations!) fail to address the heart of the matter, although it must be emphasised that physical insights can alter the realm of the entity being observed. (I will return to this idea later when talking about telescopes and microscopes.)

My second premise is that a definition of observation should avoid metaphors. It is easy to classify something as observable, audible, sensible, calculable or whatever, if it is not meant literally. Surely we "observe" the law of gravity while watching the curve of a stone thrown in the sky or we "observe" the quantum physical property "spin" in a Stern-Gerlach experiment. Literally, though, we observe only the stone in the first example and a continuous beam splitting in a (non-observed) non-homogeneous magnet field in the second. This is unquestionably the case at least temporarily. Entities like gravity and spin cannot be observed, only their effects. This is admittedly a complete different path in comparison to Maxwell or Feyerabend. Furthermore, if metaphors are used to describe experiments in microphysics, quote marks should be used to alert the reader to the distinction.

Observation is always a kind of perception. But what criteria does a perception have to fulfil to be classed as an observation of an object? Every observation begins with the human senses. It may otherwise cause some philosophers to quibble whether an automatic camera was actually observing an object prior to a human being arriving and observing the photograph or the stored film. (One can consider the observation accomplished since the presence of a human being changes nothing of how the object and its environment are observed). However, since observation is related to human knowledge I would prefer to exclude such debates and exclude Shapere's approach at the same time, too. Thus, the challenge to define "observation" is restricted to what observation may be for a human being interested in empirical knowledge about the external world.

Next I want to set the precondition that any object observed has to be perceived as an independent, individual entity. Think of somebody delivering a speech in front of an audience. The speaker watches the audience while talking. The object observed is the group of hearers, and not the individual hearers themselves. And it could happen that an old friend of the speaker was in the audience, and surprises the speaker by saying hello to him privately *after* the speech. At that point, the speaker is obviously observing his friend, but it would be wrong to say that the speaker had previously observed his friend while he was in the audience. Accepting the above distinction rids us of several problems. It allows us to recognise that watching the moon is not the same as seeing each of its craters, or that observing a sugar cube is not the same as observing its grains, molecules, atoms or electrons. Thus, it should be noted that parts of a group may not be observable even if the whole group is. In this way, some misleading arguments about the separation of direct and indirect observation can be avoided from the start.

There are many everyday examples that illustrate the distinction between direct and indirect observation. Take again an aeroplane in the sky. Sometimes it is directly observable, sometimes we observe it indirectly because we see only the vapour trail caused be the aeroplane. But what makes this distinction? If the aeroplane is close enough we are able to distinguish it in space and time, i.e., to separate it from other planes or other phenomena in the sky. While there may be a lot of physical things between the aeroplane and our perception, like air, light-waves and our eyes, epistemologically-speaking there is nothing between the observing person and the aeroplane if the person can see that plane. Moreover, we are able to identify some important properties of the aeroplane—its colour, size or construction. It is without doubt directly observed. By watching only the vapour trail of a plane, we can still gain some information about an individual plane travelling through space and time. Since the plane is beyond our human sensory reach, we do not observe the plane directly, we only see the vapour, but relying on our personal knowledge or experience of how vapour trails form, we can infer from the directly observed vapour trail that we are indirectly observing an aeroplane. Other examples of direct and indirect observation are fire and its smoke or a skier and his tracks in the snow.

Indirect observation depends on causality and some understanding of the origin of vapour trails, smoke, and ski tracks, fairly using the Humean concept of causality. It therefore has to be described as a knowledge- or *experienceladen* process. In science, indirect observation is, by analogy, *theoryladen.* Whereas direct observation, whether in daily life or in science, is not.

The problem of theoryladeness (see Section 2.1) is not relevant here, since it is strongly related to the *experienceladeness* of indirect observation in everyday life, and in this instance *experienceladeness* does not stop us from making reliable judgments. Remember the thoughts of Maxwell. We are, in contrast to him, able to suggest both an observation/non-observation line and a direct/indirect line for observations. These distinctions are neither arbitrary nor a function of human physiological or psychological attributes because they are dealing conceptually with the differences between directness and indirectness. They would also allow most observations undertaken with scientific tools to be described as direct observations.

The next problem is to separate a directly observed object from a mere illusion. Sometimes, especially when new tools of observation are invented, it is not clear whether the visible result is an object or just its image. The best way to solve this dilemma is to do the same thing as we do in everyday life to separate between object and illusion—we try to find out more about that object, we need achieve *broader acquaintance* with it.

If we are, say, on a street, and uncertain whether a car is real or just a picture on an advertising hoarding, we change the angle of our view by moving our head or taking a few steps to the side because we know from experience that a 3D object will look different from a 2D image if our point of view changes.

Now, what is important for us here is that a difference between the phenomena is only gained by expanding our visual experience of the object in question. From a distance, a single view of a real car may not differ from a picture. Similarly, people who wear glasses are sometimes surprised by a new object, say, laying in front of them on a table. Is it an object or just a spot on the glasses? The answer is obvious when you turn your head. If the object moves as your head turns, then it is a spot on the glasses. If it does not move it must be an object independent of your movement and therefore lying on the table. This is what I mean by broader acquaintance and when observing an object. And this concept is inspired by preliminary thoughts of Berkeley and Leibniz.[1] This everyday epistemology may sound irrelevant to the subtle methods of today's physics but, at the end of this Section, I try to show otherwise.

There is one last important point about the definition of observation. To observe something directly you must observe the object individually, but an indirect observation needs the viewer only to witness a physical phenomenon caused by the hidden object. But what about the individuality of an indirectly observed object? Think of a skier-track in the snow, a single one yet caused and consolidated by a group of skiers. Considering this example I must emphasis that the individuality of an indirectly observed object must be preserved. Otherwise we only indirectly observe a cluster of objects.

Our definition of direct and indirect observation is now complete. To summarise:

- An object is directly observed if it is perceived as an individual entity within broader acquaintance. The observation does not depend upon physically-caused phenomenon. And the observation is not theoryladen, although it can take place with the assistance of technical devices as long (temporal) as individuality is preserved and broader acquaintance remains possible.
- An object is indirectly observed if the physical phenomenon created by the object is observed directly. The indirectly observed object has to retain its individuality. And an indirect observation is always either theoryladen or experienceladen, whether it be in science or in everyday life.

This definition shows from my point of view some advantages over earlier concepts: Maxwell was forced by his approach to deny a clear distinction be-

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[1] See Berkeley's *New Theory of Vision*, sect. CIII ff., and his *Principles of Human Knowledge*, sec. XVIII ff. [Berkley 1910]; and see Leibniz *Nouveaux Essais*, 4. book, chap. 11 [Leibniz 1966].

tween observation and theory; he did not include something like our notion of broader acquaintance in his discussion. Shapere's proposal lacks of determination: the same situation can be interpreted as a direct observation of several different things. It is once more the notion of broader acquaintance that enables us to get rid of such underdetermination since if we make acquaintance we make it only of one object at a time.

Van Fraassen alludes to the dependence of contingent human physiology to pin down what observable is. With our definition of direct and indirect observation, however, we are independent of human physiology as well as of contingent technical progress. In addition to microscopes and telescopes, other instruments could be invented without impairing the above definition.

To end this Section I would like to recount a few examples found in science. A view through a telescope is a direct observation. By moving the telescope to various places in the sky or on earth, we get a reasonable change in view. In the same way, astronomical objects can be seen from different perspectives in winter and in summer. A single glance does not confirm an observation but repeated viewings over time do. This was crucial to Galileo's discoveries and this could held to be the main reason why Galileo's critics got silent in the long run. No understanding of the laws of optics or theoretical knowledge of the functionality of telescopes is needed to recognise the event as a direct observation.

Likewise, the view through a light-microscope is a direct observation. Though the microscope itself cannot be moved, the object observed can be with a pipette or other small tool. The moving of the pipette, seen in the ocular, is logically associated with the movements of the viewer's fingertips. Anybody, even those unfamiliar with microscopes, can recognise cells and bacteria after a short period of experience and by expanding the context of the situation. Night-vision goggles or glasses work in a similar way. But images of atoms made by a scanning-tunnel microscope work differently however. They rely on collecting single measured points in a grid pattern. Currently, the devices for scanning the surface of a solid material on atomic scale are not fast enough to result in an exact visual image, instead the results are an approximate 3D graphical image. It is similar to a picture. But even though we can explore the context of the picture, it is not the same as getting into broader acquaintance with pictured objects.

A conventional photograph is not a direct observation. It is an indirect one. From our general knowledge of photography, we know that a picture is typically shot in a certain place at a certain, very short time. Therefore, the individuality of objects seen in the picture is preserved. In the same way, the picture of particle tracks is a two-fold indirect observation. We never see the particle, rather a photograph of the trail of the particle. Still, the individuality of the particle is carried over to the picture. And we can, for example, deduce the particle's charge from studying the photograph. Particle tracks, particularly in relation to these observations will be discussed in the following Section.

3 Quarks and jet-events

3.1 Jet-events in physics

Before applying our concept of observation to quarks, we need to review some experimental methods in high energy physics. To investigate elementary particles you must use detectors to record particle tracks as a kind of photograph. Particle detectors are basically a particle-sensitive material that interacts with particles pointwise as they pass the detector. The points of interaction are collected, listed, and graphically displayed in relation to their order in space and time. The result: pictures of particle tracks, or to be exact, of rows of points of interactions. The aim is to develop a particle detector sensitive enough, that the rows are so dense that they look like continuous tracks to the naked eye. Or so dense that a computer can calculate a continuous track as if the particle was a tiny object, literally flying through the detector.

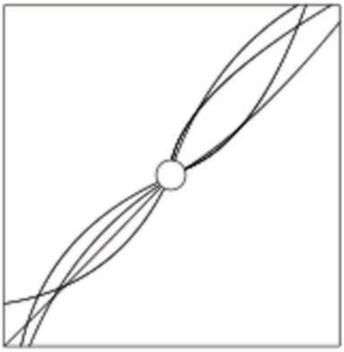
This model may not be consistent with some other aspects of quantum physics, but it is still useful in determining some properties of particles. Particles identified in this way are typically electrically charged like electrons, several mesons (on which I will comment soon), and protons. There are other types of particle detectors such as for photons and neutrons, but they are beyond the scope of this discussion.

Whatever particles like electrons are, it is fair to say that they are indirectly observed when they make a particle track. One individual track belongs for a short time to a single electron and by studying that track it is possible to identify some of the electron's permanent properties. The analogy of a skier's trail in the snow or a plane's trail in the sky holds true, though we have to accept that typical objects are directly observable in multiple situations whereas particles are not. You can shake hands with a skier at the bottom of a slope, but the closest you can get to an electron is its track. This might be worth philosophical consideration another time, but right now it is important to note that particle tracks are examples of indirect observation.

Now to quarks. The first thing to point out is that they cannot—in theory—cause single particle tracks like electrons or protons, despite the fact they are electrically charged. The physical explanation for this is based on the strong nuclear force between quarks. This force binds quarks together in *quark-confinement*. A phenomenon special to quarks that are thought to be the basic components of protons, neutrons (nucleons, or three-quark-systems), and mesons (two-quark-systems). Imagine the (slightly misleading) picture that quarks are small balls, quark-confinement is like a rubber band that holds them together and turns nucleons and mesons into stable particles. Trying to separate quarks from each other, by for instance shooting them through a particle detector, only serves to increase the force between them. If you try to split a bounded quark-system with energy it fails to break that rubber band.

Under the rules of quantum theory an unstable system of two quarks with a high level of energy converts to a system of four quarks with less energy. By adding energy to quark systems you do not isolate single quarks, but produce new ones that immediately combine to form two- or three-quark-systems. Although the initial system breaks up, the result is a new system of bounded, confined quarks. So quark-confinement stops any free, isolated quarks occurring in particle detectors. Ironically, the only place where quarks can move freely is inside the radius of its system that is bound by the energy force. (For other introductions to quarks, the confinement, and jet-events see, e.g., [Pickering 1984], [Galison 1991].) Nevertheless, the properties of quarks can be investigated either by probing a nucleus or by destroying it, and this is where jet-events come in.

Making particles collide at high energy and either destroy them and/or creating new particles is one way to test physical theories. Normally, collisions cause particles to scatter in all directions from the point of collision. A picture from a detector will show particle tracks spraying outwards from the point of collision. But under certain circumstances—defined by the type of colliding particles and their energy—a new kind of event can occur in particle detectors. On these occasions particle tracks tend to be bundled into two, three or four jets. The diagram below shows just such an event with two jets or jet-branches.[2]



The centre of the picture is the point of initial scattering. What happens there is, in theory, too small to detect. The events that occur take place on a scale far smaller than the core of an atom. But all the lines from the centre to the periphery of the diagram are particle tracks. In this example, they seem to be bundled into two jets. Quark physics explains why this pattern frequently occurs. The story goes as follows. When particles with high energy meet, the provided system decays and produces new particles. In several cases

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[2] For other pictures of jet-events see [Duinker & Luckey 1980, 127, 136], [Söding & Wolf 1981], [Banner *et al.* 1982], [Pickering 1984, 329].

two quarks are created that fly off from each other in opposite directions. To explain jet-events it is important to assume that quarks do exist as small chunks and have a state of motion. Due to the strong force, quarks cannot keep moving forward. When the deposited energy is great enough, the connection between the quarks breaks and some energy forms two new quarks. Each of the secondary quarks recombines with one of the primaries. Now we have two mesons flying away from each other, still in opposite directions. They are carrying too much energy to be stable and so decay into further particles—electrons, low energy mesons, protons, neutrons, whatever. These are the particles that reach the detector and make particle tracks. (Actually even neutrinos and photons can be produced and particle detectors can also record some particle's velocity, energy, and charge. Such evaluations occur during jet-event research too but shall not be part of this paper.) So, although nothing is left of the initial quarks and their secondary mesons, the resultant tracks indicate a common source and suggest that all particles are part of one of the bundles, and both bundles form jets that move in opposite directions (as shown in the diagram). It may be that particle tracks are ordered in this way by chance, but jet-events occur more frequently than probability would suggest. It makes sense that all particles are bundled into a branch of a jet-event because they all come from a single meson which itself comes from a single quark. So it seems plausible that the causal effects of an invisible object can produce an observable phenomenon, and that the data from the particles involved in an individual jet leads to the recognition of an individual quark. And this would make jet-events, an example of indirect quark observation. Yet by looking at the role jet-events actually play in high energy physics other issues arise.

3.2 Physicists on jet-events

If you look at the main publications on jet-events, it was not the fact that jet-events occur (and that they point to single quarks) that excited physicists, but that an ensemble of jet-events was collected. For example, there is one publication about the confirmation of the *jet-model* in a statistical counting omitting any emphasis of a single jet-event [Hanson *et al.* 1975]. See also this typical statement about jet-events:

> We have observed that events with a large transverse energy (. . .) have a dominant two-jet structure(. . .) A sample of two-jet-events has been studied and observed to feature properties characteristic of hard scattering of partons. [Banner *et al.* 1982, 210]

No leading physical publication brought up the discovery of an individual jet-event or a single quark. The experimental evidence for the validity of quantum chromodynamics in the context of jet-events consists mainly in the measurement of values like "transverse momentum distribution", "distribution of the Fox-Wolfram moment", and certain cross-sections [Söding & Wolf

1981, 265ff.]. This is crucial because it diminishes the value of single events and enhances the value of them collectively. Therefore we have to reconsider, whether an individual causation of a jet by a quark can be confirmed. Moreover, as mentioned in the introductory physical section, the reliability of a single jet-event is not certain. A physical comment on three-jet-events where one branch seems to stem from a radiated gluon instead of a third quark says:

> The observation of three-jet-events in high energy e^+e^- annihilation qualitatively confirms the prediction of hard gluon bremsstrahlung by leading order QCD [i.e., quantum chromodynamics]. It does not, of course, rule out other mechanisms as possible sources of these events. Therefore, detailed and quantitative tests are called for. [Söding & Wolf 1981, 276]; the quotation contains a reference to an acceding publication: [Preparata & Valenti 1981]

Hence, physicists argue quite careful when considering branches of jet-events. As if they were aware that the branches do not necessarily have to be produced by quarks. The power of the theory describing quarks—*quantum chromodynamics*—depends upon accurate predictions of the frequency of jet-events during numerous scattering events occurring under certain conditions. Predicting the number of jet-events is based on our ability to separate jet-events from other events. We need to acknowledge that jet-events do not have to be as neat as in the diagram above. A reliable separation can be done by computer programs [Duinker & Luckey 1980]. We must also remember that events that look like jets but are not can occur statistically (and depending on the quality of particle detectors) without any link to quark physics.

Taking another look at the seminal works on jet-events it continuously seems that jet-events are always collected statistically. Results of experiments do not depend on the qualitative discovery that jet-events exist, followed by an investigation of the properties of a single jet-event and its branches. Although results from single jet-events are collected, they are evaluated quantitatively. The following comment makes this quite clear:

> The observation of three-jet-events in high energy e^+e^- annihilation into hadrons may be considered a major triumph of the theory. QCD had predicted such events to occur as a result of hard gluon bremsstrahlung. Close examination of the details of the three-jet process at [the particle accelerator called] PETRA shows consistency with QCD and comfirms the vector nature of the gluon. From the rate of three-jet-events the events determine $a_s = 0.17 \pm 0.01$ (stastistic) $\pm$ 0.03 (systematic) at $Q^2 \approx 1000\ GeV^2$. [Söding & Wolf 1981, 289]

In the literature we find only these typical statements. There is no publication among the leading jet-articles presenting a single jet-event as an observation-situation of one or more certain quarks.

Figuring out what is actually a jet-event is a subtle process. The job falls to particle physicists. But they must rely to some extent on epistemology because it is not possible to single out an arbitrarily accurate jet-event from a jet branch and say it is caused by a single quark. This constraint is not important for quantum chromodynamics or the engineering of particle detectors. Quark theory and quark experiments are today breathtakingly well established.[3] To me it seems that actually physics is not particularly interested in single jet-events but philosophy is. This view is supported by the fact that several of the initial publications on jet-events do not display jet-events at all [Hanson *et al.* 1975]. Plenty of debates already exist on observation and quarks. These arguments reference plenty of experiments but say little about jet-events. The following comments make an interesting contrast to our discussion and deal with quark-confinement and its limiting influence on our epistemological access to quarks. Both appraisals come to the conclusion that quarks are indeed observable.

3.3 The observability of quarks in Shrader-Frechette and Massimi

Although Andrew Pickering does not address the question of the observability of quarks in his monograph *Constructing Quarks* [Pickering 1984], other scientific philosophers have discussed this topic. The first debate took place around 1982 and was initiated by an essay of Kristin Shrader-Frechette [Shrader-Frechette 1982a]:

> It is widely accepted that scattering data are a means of observing particles directly. The difficulty with quarks, of course, is that they are not detected directly in any experiments, although particles said to be composed of quarks are directly "observed". More precisely, although effects of some particles are directly observed, in scattering experiments quark effects are not directly observed as quark effects, but are said to affect the behaviour of particles which are directly observed. [Shrader-Frechette 1982a, 133–134]

Shrader-Frechette goes on to deal with experiments confirming the J/ψ-meson (1974) and decays of *charmed hadrons* (ca. 1976). Quantum chromodynamics contains six different types of quarks, including one called *charm*. Charmed quarks are thought to be constituents of mesons or hadrons, providing them with special properties that other mesons or hadrons do not have. Examples are the J/ψ (or *charmonium*) and charmed hadrons. Verifying these particles would also verify quantum chromodynamics, if no other theoretical explanation exists.

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[3] The signature of jet-events played a crucial role, among others, in the confirmation of the sixth and heaviest quark, the top quark [Abe *et al.* 1994, 1995]; [Abachi *et al.* 1995].

Shrader-Frechette infers that charmed quarks actually have been observed in tests on J/ψ-mesons and charmed hadrons. Of course, no single charmed quark interacts with a particle detector—both charmoniums and hadrons being too short-lived to reach detecting devices—but they do cause certain decay schemes which particle physics call detect. Shrader-Frechette points to an important difference between the J/ψ- and charmed hadrons. The decay pattern of the charmonium can be explained without charmed quark involvement but the decay of charmed hadrons cannot. This fact is related to the creation of *K-mesons* seen in the decay pattern of charmed hadrons.

> Although the "observation" of charmed particles was obviously theory-laden (...), this "observation" was not as theoretical, in a potentially damaging sense, as that of charmonium. This is because, while hypotheses other than charmonium could have explained the J/ψ detection, there was no other known means of accounting for the K meson. Thus, at least in this microphysical instance, observations of hadron decay provided a more overt, a more direct means of observation of charm (...) precisely because the theoretical context in which they occurred was more unique and admitted of more specific predictions. [Shrader-Frechette 1982a, 139]

Shrader-Frechette's investigation draws its weight from the detailed analysis of background and alternative theories explaining the data of particle scatterings. And it seems possible to distinguish between direct and indirect observation albeit that theoryladeness is ever present. At least the last statement of the quotation can be read this way. But in the end, the conclusion that charmed quarks are observable either follows Shapere's unsatisfying ideas on observation or it is meant metaphorically and thereby allows for nearly any interpretation. Shrader-Frechette ends with a little disclaiming summary:

> It should not be surprising that our observations are understood in a very abstract way, or that quark "observations" are quite different from everyday observations. [Shrader-Frechette 1982a, 141]

Participants of the ensuing debate—all printed in *Synthese* in 1982—depart from quarks to consider the more general question of what scientific observation is [Albright 1982], [Shrader-Frechette 1982b], [Gruender 1982]. J. R. Albright reasons that since a theoryladen observation needs a community of members to agree on any presupposed knowledge, then observing is not dissimilar to simply *believing.* Albright writes that a *consensus* is necessary in scientific observation if the observation is to be thought reliable. This proposal—touching on the territory of relativism—is criticised by Shrader-Frechette and David Gruender and is too far removed from our discussion of the concept of observation to warrant space here.

The observability of quarks concerns Michela Massimi, too [Massimi 2004]. Her start point is *experimental realism.* It is a position that originates from

Ian Hacking, who opted for entity realism backed up by experimental scientific methods. Hacking argues that since we are able to build devices that emit electrons of a certain energy which have particular properties, those emissions should be treated as part of our reality [Hacking 1982; 1983]. He puts it like this: "If you can spray them, they exist." Alternatively, if you can use electrons as tools to probe other material, electrons must exist. Or if they play a causal role in our model of microscopic events, they must exist [Hacking 1982; 1983, 23, 36].

Massimi's ideas combine Hacking's realism and Shapere's concept of observation and apply them to quarks. She particularly focuses on the experimental context of *scaling violation* found in the measurement of *structure functions* of nucleons. In this context the existence of quark physics and science's present model of nucleons is strongly confirmed. We do not have to go into the details of structure functions, but her point is that a statistical collection of scattering data results in a graphical curve—the structure function—that has a certain property. It shows an inclination. Were there no inclination, then there would be no relevance to quark theory. But the quantitatively-predicted value of inclination of the curve, using the theory of coloured quarks inside nucleons and exchanging gluons, was confirmed, and the structure of the nucleus can be said to be physically understood.

While collecting scattering data, neither was the nuclei destroyed nor the quarks isolated, but they were probed and manipulated. Thus, Massimi brings Hacking into her argument:

> "Seeing" quarks is not licensed by strong notion of manipulation (spraying), but by a weaker notion of manipulation (probing) that nonetheless still satisfies the engineering criterion of experimental realism (interfering/intervening). This way of "seeing" the nucleon's constituents presupposes a massive amount of theory. [Massimi 2004, 49]

The Shapere-part of her proposal acknowledges that such observation (or "observation", as Massimi prefers to put it) is theoryladen and that our state of knowledge changes our realm of observation:

> I believe with Shapere that in certain cases what counts as "observation" depends ultimately upon our current state of knowledge; and, most importantly for the rest of my argument, what kind of entities physicists can arguably claim to "see" in a lab turns out to be dependent on what kind of theory about *these very same entities* they endorse. [Massimi 2004, 49]

Massimi interestingly allies Hacking's experimental approach to Shapere's theory-focused concept of observability in quark physics, although Hacking's "if you can spray or manipulate them, they exist" raised suspicion in some people, and I am told it is a tautology. It is also possible that Massimi's concept of observation is nothing more than a metaphor for something else. For our purposes though, it is evident that studying structure functions represented as graphical curves on paper is neither a direct nor an indirect observation of quarks. Not that this effects our conclusion too much. Jet-events seem to be more intuitive and better direct evidence for quarks than structure functions could ever be.

My review of ideas on the observation problem generally (Maxwell, van Fraassen, and Shapere) and more specifically in relation to quarks (Shrader-Frechette, Massimi) has hopefully given you an insight into how deeply interwoven the discussion of observation and theoryladeness are. And how quickly accepting the idea of theoryladeness leads to the statement that "observable is anything". Jet-events could provide a viable go-between.

4 The interpretation of jet-events

First, from our look at direct and indirect observation, it follows that in particle physics only indirect observation applies. This is not because elementary particles are too small—many small things like cells and microbes are directly observable and can be seen with the help of a microscope and our knowledge of their context. But elementary particles withdraw from broader acquaintance. It well may be that the principles of quantum physics provide the constraints. Using indirect observation is nothing to worry about, many things in everyday life as well as in science and high energy physics are only indirectly observable, so we have no reason to exclude them from our ontology.

But the question remains are quarks indirectly observed in jet-events? To answer it, we have to take a single branch of a jet-event and try glean as much information from it as possible, just as we might if we took a single particle track to learn about the particle's charge-mass ratio, its energy and other properties. Again, I do not see whether other experimental contexts come closer to quarks than jet-events. As we have seen in Section 3.2, however, physicists do not take a single jet-event to get information that is causally linked with one or more distinct quarks. The criterion of indirect observation given in Section 2.2, therefore, is not fulfilled.

You could argue that there is physical significance in looking at single jet-events, and that it will make a nice task for a particle physicist sometime in the future. Alternatively, you could reconsider the origin of a jet-event branch in the quark physics model.

The indirectly observed particles that make tracks in a bundle, come from a short-living meson. This meson does not cause a trail itself but every trail from a jet-branch carries some properties of the original meson, like its electrical charge. The sum of the electrical charge carried by the secondary particles is equal to the charge of the initial meson. Although, such a meson is not observed directly in a jet-event, it can be identified by its charge that is carried by secondary particles. The condition of indirect observation, i.e., observing directly a physical phenomenon created by the object "meson" is fulfilled. The directly observed phenomenon is particle tracks. In this way, it is possible to say that the meson is indirectly observed. It is indirectly observed because it is identified in a decay pattern that itself consists of indirectly observed secondary particles.

Although the meson is thought to consist of two quarks, the quarks play no part in the decision of whether the meson is indirectly observable. According to the quark model, one of the quarks in the indirectly observed meson comes from the very centre of the particle collision that causes the jet-event. However, we cannot identify that individual quark by looking at the single jet-branch.

The electrical charge of a quark (which is always $-1/3$ or $+2/3$) is never conserved in a jet-branch since all detectable particles carry a charge of $+1$, -1 or zero. The distinction of whether the original particle was a quark or an anti-quark is also lost. Such information is not derivable from one single jet-branch. So, if indirect observation is meant literally, we do not observe quarks indirectly in a single jet-event.

Obviously, images of jet-events give an idea of a good, working particle detector but they are not crucial for the confirmation of theoretically-determined measuring values. By comparison, think of the discovery of the positron by Carl D. Anderson in 1932. In his publication, we see images of positron tracks. Since these images show that a single track is caused by a single positron, they were key to his claim that positrons are indirectly observable [Anderson 1932]. Getting even one image of a certain particle track means the discovery of a positron by indirect observation. And the charge-mass ratio typical for a positron can be determined by evaluating the curvature of that track. Remember our definition in Section 2.2. Anderson observed indirectly positrons in the same way as we observe indirectly an aeroplane by watching a vapour trail in the sky.

This type of investigation is impossible for quarks, although quark physics and quantum chromodynamics is none the worse for this. That quarks cannot be observed has little impact on the successful verification of the physical entity "quarks", if the term "entity" is understood in its most basic sense. Many entities are not observable—forces, natural constants, fields, virtual particles, resonance particles, as well as natural laws or terms of natural laws.

To end this investigation I would like to appraise the meaning of my conclusion. There is a strong consensus that some objects, which are not directly observable, might be indirectly observable. There are additionally entities that to us do not exist *because*, among other reasons, they are not indirectly observable.

In the case of quarks, we have seen that they cannot be indirectly observed, even in the comparatively evidential context of jet-events. This should be a strong hint that quarks are in principle unobservable, although, this is not yet proved. This brings us to the debate of scientific realism. And the indications are that quarks can only be treated as entities, similar to other unobservable entities in science.[4]

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