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ORIGINAL PAPER

"Shut up and calculate": the available discursive positions in quantum physics courses

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Abstract Educating new generations of physicists is often seen as a matter of attracting good students, teaching them physics and making sure that they stay at the university. Sometimes, questions are also raised about what could be done to increase diversity in recruitment. Using a discursive perspective, in this study of three introductory quantum physics courses at two Swedish universities, we instead ask what it means to become a physicist, and whether certain ways of becoming a physicist and doing physics is privileged in this process. Asking the question of what *discursive positions* are made accessible to students, we use observations of lectures and problem solving sessions together with interviews with students to characterize the discourse in the courses. Many students seem to have high expectations for the quantum physics course and generally express that they appreciate the course more than other courses. Nevertheless, our analysis shows that the ways of being a "good quantum physics student" are limited by the dominating focus on *calculating quantum physics* in the courses. We argue that this could have negative consequences both for the education of future physicists and the discipline of physics itself, in that it may reproduce an instrumental "shut up and calculate"-culture of physics, as well as an elitist physics education. Additionally, many students who take the courses are not future physicists, and the limitation of discursive positions may also affect these students significantly.

Keywords Physics · Higher education · Quantum physics · Discourse · Identity

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”Räkna, räkna, räkna”: diskursiva positioner i kvantfysik

I diskussioner om att utbilda nya generationer av fysiker beskrivs ofta möjlig problematik i termer av svårigheten att attrahera kompetenta studenter och få dem att stanna kvar vid universitetet. Ibland diskuteras också snedrekryteringen vad gäller kön och andra sociala kategorier, då fysik är en av akademins mer numerärt ojämställda discipliner. I den här studien av diskursen i tre kurser i kvantfysik på två svenska universitet vänder vi på perspektivet. Vi frågar vad det innebär att bli fysiker och om vissa sätt att bli fysiker och att göra fysik på privilegieras i denna process.

Ett stort fokus inom fysikdidaktisk forskning (physics education research) har varit på hur studenter bäst kan lära sig fysik, till exempel genom att få dem att tänka mer som experter. Dessa studier handlar alltså om hur studenter ska bli fysiker, men vad det innebär att bli fysiker problematiseras sällan. Studier som gjorts av forskare med genus- och kulturperspektiv pekar på hur fysikens kultur är könad på flera sätt och hur detta medför flera problem, som exempelvis ett begränsat utrymme för alla uttryck av”stereotyp femininitet”. Framförallt pekar denna forskning på hur ett identitetsperspektiv på fysikutbildning hjälper oss att ställa kritiska frågor kring deltagande och lärande i fysik.

I denna studie använder vi ett diskursanalytiskt angreppssätt för att fråga vilka diskursiva positioner som görs tillgängliga i universitetskurser i kvantfysik. I våra intervjuer och observationer framkommer att många studenter såg fram emot kursen i kvantfysik och tycker att den i allmänhet är roligare än många tidigare kurser. Vår analys pekar trots detta på flera hinder för att kunna inta en position som en “god kvantfysikstudent”. Den praktik som genom kursernas diskurs kommuniceras som mest central har vi karakteriserat som att”plugga kvantfysik”, vilket innebär att prioritera kvantformalism och att lösa typtal, snarare än att uppnå en konceptuell förståelse. Även om också”utforskande” och”tillämpning” av kvantfysik kommuniceras i klassrummet är”pluggande” i fokus. Detta medför att andra möjliga förhållningssätt till kvantfysiken än att”hålla tyst och räkna” blir närmast omöjliga i utbildningens kontext, även när andra sätt från början motiverat studenter att läsa kvantfysik. Samtidigt som huvudfokus ligger på att räkna uppmanas studenter implicit och explicit att angripa kvantfysiken på ett utforskande och nyfiket sätt. Detta leder till en paradoxal situation där en “god kvantfysikstudent” inte bara behöver kunna”räkna” kvantfysik, utan också sätta sig in i en bredare kontext som varken förekommer eller ges utrymme i kurserna.

Våra resultat pekar på flera möjliga negativa följder både för utbildningen av framtida fysiker och för fysiksamhället.”Plugga”-diskursen riskerar att reproducera en instrumentell och elitistisk fysikkultur, där en mångfald av möjliga förhållningssätt till fysik utesluts. Ett ytterligare problem är att många av de studenter som läser kvantfysik inte siktar på att arbeta som fysiker, utan ska använda den kvantmekaniska kompetensen i andra kontexter. Kanske drabbas dessa studenter extra hårt av uteslutningen av diskursiva positioner.

Studying quantum physics is a vital step for university students aiming at becoming physicists. Quantum physics is not only a requirement for getting a physics degree but also an important and emblematic part of contemporary physics: As a major theoretical development and paradigm shift in physics, as the basis for many technological innovations, and as a symbol of “cool science” in popular culture. Aiming to discuss how a physicist is “made” and how the culture of physics is reproduced, we investigate what possibilities for achieving a position as a “good quantum physics student” are available to students in introductory quantum physics courses. We believe that this could provide valuable insights into discussions of equity in science, where physics is often seen as a field that fails in recruiting women and minorities.

Equity issues in science and science education are often discussed in terms of inclusion and exclusion. Who is represented in science? What can we do to increase diversity? This is evident in national and international policy reports, where calls for increasing the participation of women and minorities in science are made both for reasons of justice and for increasing competitiveness or economic growth (European Commission 2004; OECD 2008; President's Council of Advisors on Science and Technology 2012). Similarly, much research on equity in science education is focused on differences in achievement and participation between women and men, and on measures for bridging these specific "gender gaps". This is especially the case in physics education research (PER), which has primarily been studying "the subject matter and reasoning patterns of physics" (Heron and Meltzer 2005, p. 390).

In our study, we want to move the formulation of the problem from that of the people coming into and staying in science, to that of science itself. We ask not only how the culture of science includes or excludes certain kinds of people, but also what kind of scientists are "made" in science education and training, and what kind of scientific culture is reproduced in this process.

Inclusion, social identity, and physics culture

In studies of physics education at the university level, the culture of physics has not been discussed to any large extent. In the mainstream of PER, "physics" is mostly taken for granted. This is not surprising given that PER is an example of disciplinary-based education research (DBER), which can be defined as: "DBER investigates learning and teaching in a discipline using a range of methods with deep grounding in the discipline's priorities, worldview, knowledge, and practices." (National Research Council 2012, p. 9). One example from PER is the notion of teaching students to "think like a physicist", that was developed from research on physics problem solving (Van Heuvelen 1991). This has had a large impact on both research and development where "expert-like thinking", that is, "thinking like a physicist", is often sought after in students, but seldom problematized. Another field of study focuses on assessing students' attitudes towards physics and evaluating different measures for aligning them more with physicists' attitudes. Generally, there seems to be an implicit idea about what a physicist is, and that becoming like a physicist is something good. If students fail at achieving this, it is often seen as a result of inadequate instruction that could be improved. Several survey tools have been developed for assessing students' attitudes, such as Maryland Physics Expectations Survey ("MPEX", Redish 1998) and Colorado Learning Attitudes about Science Survey ("CLASS", Adams et al. 2006). However, few studies in PER have adapted any of the identity perspectives that are often used for example in discussions on attitudes to science today (Tytler 2014), and those who do tend not to problematize the value of becoming a physicist (see for example Irving and Sayre 2015).

In the wider literature of studies in university science education an identity perspective is often used, particularly in studies inspired by feminist theory. For example, pathways of successful minority women in science have been discussed in terms of the possibilities of achieving a "science identity" (Carlone and Johnson 2007). Several other studies have shown that certain ways of being a science or physics student are privileged and that these ways are often gendered. Cathrine Hasse (2002), in her ethnographic study of physics students, found that having a playful approach towards physics and experiments was appreciated by instructors even though it disturbed the teaching. However, this approach was only exhibited by some male students. Karin Due (2012) studied problem solving in groups of high school students and found that the position as a "competent physics student" in high school is more readily available to men. Carolyn Jackson and Anne-Sofie Nyström (2015) have discussed the position of "effortless achiever" as an important ideal for men in an educational environment premiering the gendered notion of geniality.

Studies in the culture of physics have shown how the idea of objectivity constructs physics culture as neutral, or as Sharon Traweek describes it in her ethnographic study of high-energy physicists, as a "culture of no culture" (1988, p. 162). However, this neutrality is connected to masculinity in several ways, and this is clear for example in Alison Gonsalves' (2012) study of physics doctoral students. In the contradictory discourses about who a physicist should be, most expressions of "stereotypical femininity" were posed as deviant, and difficult to reconcile with the image of a "competent physicist". Similar patterns have been described by Anna Danielsson (2009) in her study on physics students' conceptualization of physicists, although she shows that there is space for negotiations as well. Nevertheless, the culture of physics is not the same everywhere and important national differences in the possibilities of participation for men and women, mainly due to the relative importance of class in different countries, have been described by the European UPGEM project (Hasse et al. 2008). Traweek described some of the differences between the cultures in American and Japanese labs, where women were believed to be less suited to careers in physics either due to them being too uncompetitive or too competitive, respectively (1988, p. 104). Another trait that is often expected of physicists is a kind of "authentic intelligence" or "smartness" which is generally perceived as male. The distribution of these expectations across disciplines has been shown to correspond to the proportion of women in the discipline, with women being more under-represented in disciplines where beliefs about the necessity of "raw intelligence" is stronger (Leslie, Cimpian, Meyer, and Freeland 2015). In particular, as Traweek argues, the image of the "physics genius" is an essentially male Fig. (1988, p. 102).

The major part of the studies described above examine physics culture as conditioning participation in physics for different people, but few of them discuss how this culture influences the science being conducted. One example of this, which discusses the intellectual culture and values of quantum physics explicitly, is David Kaiser's historical studies of the training of quantum physicists in cold war-era USA. He argues, for instance, that the large increase in the number of physics students during the cold war aligned teaching of quantum physics with an instrumental view of physics, suitable for military applications but excluding discussions about the foundational and interpretational issues of quantum physics:

> The goal of physics became to train "quantum mechanics": students were to be less like otherworldly philosophers and more like engineers or mechanics of the atomic domain. (Kaiser 2007, p. 28)

This attitude is captured in the well-known phrase, "shut up and calculate" (Kaiser 2014), which has been attributed to several notable physicists (Mermin 2004).

The culture of physics can be argued to contain certain ideologies and ideas about which "styles of doing science" are right, where "shut up and calculate" is just one example. Kristina Rolin (2008) describes two male-coded styles of doing physics: Margaret Wertheim's (1995) discussion of the "quasi-religious" framing that some physicists give to the quest for a "theory of everything" and the "playful physicist" notion from Cathrine Hasse (2002). Rolin argues that widening the possible styles of doing physics would not only help increasing diversity in participation but also be good for physics itself, as different styles can lead to different kinds of valuable research.

There are some examples of science education studies which explicitly discuss the reproduction of scientific cultures or communities, and the possible consequences of this. For example, a recent study by Anne Solli and colleagues show that in the discourse of the undergraduate education of biotechnologists, certain styles of thinking about certain subjects are excluded from an identity as a biotechnologist. Specifically, political-economic rationales for opposing GMO are excluded from the discourse, presenting GMO opposition as mostly irrational and unavailable to students supposedly striving to be scientific, rational and objective biotechnologists. Thereby the culture of biotechnologists is reproduced as narrowly scientific (Solli, Bach, and Åkerman 2014). This is a clear example of how a culture or community with specific values is reproduced in the identities made available through discourse.

Our study is an attempt at taking this discursive view of the reproduction of scientific cultures and communities and applying it to physics education, in that way giving new insights on issues of equity and disciplinary culture in physics.

The role of introductory quantum physics

Taking the first course in quantum physics is an important step towards being included in physics culture for several reasons. First, quantum physics serves as an important symbol for the discoveries and enigmas of physics explored in the beginning of the twentieth century by some of the greatest "heroes" of science. This, along with the apparently counterintuitive results of quantum physics, has resulted in numerous popular books and documentaries describing these mysteries and discoveries. Some of the well-known symbols of quantum physics, such as the Schrödinger equation, used to calculate particle probabilities, and Schrödinger's cat, a thought experiment demonstrating the seemingly unintuitive aspects of quantum indeterminacy, are referenced in everything from t-shirts to TV-shows. Quantum physics is even taken as the ground for pseudo-scientific claims like the direct influence of "positive thinking" on the universe, popularized in books like *The Secret* (Byrne 2006) or ideas such as *Quantum Healing* (Chopra 1989, see Burwell 2013 for a critical discussion). Second, quantum physics is one of the first encounters students have with the modern forms of physics used in many physicists' daily work. Third, a quantum physics course is taken mainly by students who are aiming at a career as "physicists". These are, in the Swedish context, primarily students on the three-year Bachelor of Physics program or on the five-year Master of Engineering Physics program, along with pre-service physics teachers. European guidelines for physics bachelor degrees list Quantum physics as one of three essential knowledge areas for a future physicist, besides *Mechanics and Thermodynamics* and *Optics and Electromagnetism* (Ferdinande 2009).

Quantum physics is generally regarded as a difficult subject (see e.g. Singh and Marshman 2015). Because of the conceptual difficulties in the coursework, this first encounter with modern physics may demand some conceptual leaps as some of the classical "facts" students have learned earlier have to be revised, but also because of the mathematical formalism that is needed for quantum physics that students generally have not encountered before. This is made even more difficult when quantum physics is taught in a "minimal instrumentalist" way that leaves out many of the difficulties of interpretation to focus on only the formalism. Ileana Greca and Olival Freire Jr. (2014) argue that this often happens in quantum physics courses and that this has several negative consequences as students have a hard time connecting the abstract calculations to a solid conceptual understanding. Some "semi-popular" quantum physics courses have tried to bridge the gap between incomprehensible calculations and over-simplified models. For regular physics undergraduate courses Charles Baily and Noah Finkelstein (2015) show how it is possible to help students to develop both conceptual understanding and learn the things generally viewed as important by making interpretational issues explicit.

Discourse and identity

Identity and culture are often studied through the notion of discourse, which in James Gee's terms can be viewed as "how we use language to say things, do things, and be things" (2011, p. 3). This means that language and other means of communication do not only serve to "communicate" an independent reality but also construct human reality by structuring our perceptions. Gee, like other discourse analysts, uses a broad view of discourse which does not only encompass language but also "socially accepted associations among ways of using language, of thinking, valuing, acting, and interacting, in the 'right' places and at the 'right' times with the 'right' objects" (2011, p. 34). In this study, our analysis will include both linguistic and "other" parts of discourse.

In discussing how identity is constructed in discourse, we draw on Gee's tools for discourse analysis and Judith Butler's theory of subjection. Butler is well known for her theory of how identity, in particular gender identity, is constituted *performatively* in discourse through repeated acts of construction (Butler 1990). Along with this comes the notion of *subjection* (or *subjectification*), which asks questions of how intelligible human subjects come into being through a mastering of, and submission to, prevailing discourses (Butler 1997). This paradoxical process of subjection means that the possibilities of being recognized as a person hinges on whether one manages to occupy an intelligible subject position in discourse. Bronwyn Davies (2006), taking up Butler's notion of subjection, discusses how "mastery" in educational situations can be understood as an achievement of a subject position as an "appropriate student". She argues that a threat to students in the discourse of school is that they "are constantly at risk of being recognized as inappropriate and incompetent" (p. 434). At the same time, there is the even more profound risk of not being represented in discourse at all:

> Subjects, and this includes school students, who are constituted as lying outside intelligibility are faced with the constitutive force of a language that grants them no intelligible space. (Davies 2006, p. 434)

Using Butler's and Davies's discussions, we view the process of subjection and intelligibility as taking place on different levels. At a more fundamental level it refers to the becoming of an intelligible person with expected gendered, sexual (etc.) identities; and at a more contextual level it means achieving intelligibility in certain contexts, e.g. becoming "a 'good student,' a 'good cook,' a 'gang member,' a 'competent lawyer,' a 'real basketball fan,' or a 'real Catholic'" (Gee 2011, p. 34). We inquire into the contextual level of "becoming a physicist" and ask questions about what positions as a physicist are made intelligible in the local discourses of physics courses. For this reason we will not be using either of the terms "identity" or "subject position", but rather use *discursive positions* or just *positions*. The positions we talk about in this study are abstracted or idealized and made available in the local discourse in physics courses. These positions are not necessarily what students personally would identify with, especially not in any long-term perspective. At the same time, we view these positions as structuring the ways of becoming an intelligible physics student in the context of quantum physics.

We study the discourse in quantum physics courses with the help of discourse analysis. This means doing qualitative research in an interpretative tradition where results are always open to reinterpretation and where the quality criteria involve trustworthiness rather than objectivity (Taylor 2014, p. 44). In studying discourses with a social constructionist perspective we can never properly be "outside" the discourses we study and observe them in an "objective way". Rather, the goal we, as discourse analysts, aim for is methodically distancing ourselves from the material and trying to reflexively analyze "taken-for-granted" meanings (Jorgensen and Phillips 2002, p. 21).

In the concrete discourse analysis, we will use Gee's tools for discourse analysis, and particularly his notion of "building tasks of discourse" (2011, p. 15). According to Gee "[w]e make or build things in the world through language", and he delineates seven "building tasks of language" for which different discourse analytic questions can be asked (2011, p. 17). The building tasks in Gee's system are: *Significance*, *practices*, *identities, relationships*, *politics*, *connections*, and *sign systems and knowledge*. In our analysis, *practices* and *identities* (*discursive positions* in our terminology) will be foregrounded.

Aims and questions

The aim of this study is to explore what discursive positions are made available in the educational practice of introductory undergraduate courses in quantum physics. We want to explore how the culture of physics is reproduced, how new generations of physicists are trained, and what consequences for participation in physics and for the diversity of both physicists and physics this might have. In order to do this we ask: How is the discourse in quantum physics courses making different positions more or less accessible and attractive to students?

Studying quantum physics courses

Quantum physics is taken by a more limited population of students than more basic physics courses in Sweden, which are taken by most engineering students. In the three courses we studied, the majority of the students were enrolled in programs aimed towards a Master in Engineering Physics (one course, about 100 students) or a Bachelor Degree in Physics (two different courses, both about 30 students). The Physics Bachelor programs in Sweden contain a few students studying specializations such as astronomy and meteorology, apart from the specialization of "general physics". Some of the Engineering Physics students will choose a specialization where they study significantly more physics than others after the quantum physics course. There were also a few students aiming for a Physics Teacher Degree taking the courses. On the whole, this means that the student populations taking the courses have rather diverse physics interests, although the majority of students can be viewed as aiming to become "physicists" in some sense. The courses are given in the end of the second year or the beginning of the third year on the three programs.

Although given at different universities for different programs, the structure of the courses is rather similar. The learning goals of the courses as stated in the syllabi are mainly focused on the basic formalism of quantum mechanics, but the historical background and the societal importance of quantum physics are also mentioned. Two of the courses have a length of 10 ECTS credits and contain three laboratory exercises. One course, taken by bachelor program students, has a length of 7.5 ECTS credits and does not include laboratory exercises. The courses largely follow a “traditional, instructor-centered structure”; lectures demonstrating new material are combined with problem solving sessions, where a Ph.D. student serving as teaching assistant (TA) demonstrates problems on the blackboard (Redish 2003, p. 18). The lecturers at times used active teaching techniques, like “clickers”, but this was not the rule. Even though the observations showed that there was some variation in how much dialogue the lecturers or TAs engaged the students in, the structure nevertheless was instructor-centered in the sense that the instructor for the most part stood by the blackboard, showing new material or solving problems in front of the students.

The observed instructors in the courses consisted of three lecturers who were professors at their respective physics departments, three teaching assistants (TAs) who were all Ph.D. students and two laboratory instructors who were also Ph.D. students. In the larger course for engineering students the lecturer and some other TAs also held problem solving sessions, but only one of the TAs classes were observed. One of the lecturers and one of laboratory instructors were women and the rest of the instructors were men. Most of the students spoke Swedish but except for the lectures held by one of the lecturers, the language used in class was primarily English. This was either due to exchange students taking the course or the instructors’ insufficient proficiency in Swedish, or both. In this paper, all Swedish quotes are translated into English, and in order to maintain confidentiality no notes will be given of the original language.

To study the discursive positions made intelligible in the courses, we used participant observation combined with focus group interviews. As our aim was to study the “enacted” discourse in courses, that is, how the discourse about learning quantum physics played out in concrete interaction in the studied contexts, we needed first-hand observations of these interactions. To further capture some of the negotiations of students in this discourse, group interviews that allowed students to reflect on their practice were used.

The first author attended lectures and problem solving sessions in all three courses and labs in one of them, took notes and compiled these into field notes containing descriptions of events and environments as well as many quotes of spoken language, some verbatim and some more in summary. In this article, some of these quotes and descriptions are used for illustrating the discourse in the classrooms. Some informal conversations with students, mainly from one of the bachelor courses, were also recorded in the field notes. The project started out with observation of one of the bachelor courses, where more than a third of lectures (8/18) and a quarter of the problem solving sessions (6/24) were observed. This course also included labs, and the first author participated in 2 out of 8 sessions. To get comparative material from other settings and teachers, the two other courses were added to the study. A preliminary analysis indicated that the first few lectures and problem solving sessions set the stage for how quantum physics should be approached so observations of the last two courses focused on these sessions with 5 of 16 lectures and 4 of 15 problem solving sessions observed in the bachelor course, and 4 of 19 lectures and 2 of 40 problem solving sessions observed in the engineering course. No labs were observed in these courses, as we found the labs to present a rather “separate” setting with teachers and tasks different from lectures and problem solving sessions.

In addition to observations, the first author held three group interviews with three to five participants from each of the courses. These interviews focused on students' experiences of the course, of studying physics and becoming/being a physicist. The interviews were digitally recorded and partly transcribed for analysis along with the field notes. In the interviews, the participants were five bachelor students of which one studied meteorology in one of the bachelor courses; two bachelor students and a medical physics student in the other bachelor course; and four Engineering Physics and one bachelor student in the engineering course. All students present in class were informed about the project and given the choice of not participating through not being recorded in the notes. Interviewees were recruited by asking the whole class for volunteers.

Drawing from interpretative and critical research traditions, we have used the mixed material from observations and interviews in an interpretative discourse analysis. The field notes and interview transcripts were studied by all authors and coded thematically by the first author. This initial analysis suggested that focusing on the relationship between the building tasks of *practice* and *identity* would be a viable way forward. As explained above, we will not be using identity as a term here, although the term we use, "discursive positions", lies close to what Gee describes as a "who-doing-what" in discourse (2011, p. 44). Discerning what *practices* are made intelligible in the discourse also relates to what discursive positions are made intelligible. Gee, in describing the building task *practices* bids us to ask the question: "What practice (activity) or practices (activities) is this piece of language being used to enact (i.e. get others to recognize as going on)?" (2011, p. 18). A second round of analysis asked this question of the material and this, along with the participating author's observations are the basis for the conclusions in this paper.

Findings

This section will describe our findings from analyzing the discourse through the observations and interviews in the three quantum physics courses. Students' expectations of quantum physics courses, as expressed in the interviews, were generally high. This is commonly related to popular images of quantum physics and its centrality in modern physics. A variety of positions as a quantum physics student can be imagined, as students come in with different expectations. However, we argue that the practices made intelligible in the, mostly similar, discourse of the courses limit the available positions. We will outline the analytically discerned practices *calculating quantum physics*, *exploring quantum physics*, and *applying quantum physics* and argue that the overwhelming focus on "calculating" narrows the possibilities for finding a position as a "good quantum physics student".

A long-expected course

Most of the students we communicated with seemed to have been looking forward to their course in quantum physics. Students may relate the course to quantum physics in popular physics books, or expect the course to be an opportunity to finally engage with some "real physics". At an introductory lecture in one of the courses a student uttered to his deskmate: "This could be the most exciting course in our program, and then it's all downhill from here." Although these views were particularly explicit at the start of the courses, all students the first author talked to, irrespective of study direction, referred to their quantum physics course as more fun than earlier courses throughout.

The physics bachelor students in one of the interviews describe how they expected the course to be a kind of climax in their education:

Erik: It was mostly like, ok now [snaps fingers], now it starts for real, kind of

Glenn: […] I might be speaking for myself but you have been waiting to come to this real physics, the one you read about in popular science [others hum in agreement], but never get to calculate on. So now it feels like, now we are starting for real, now we start to use everything we have learned the first two [others say "yes" in agreement] it feels like it has kind of culminated.

Bob: Yeah, it feels like quantum physics is one of those things you have heard about and thought about as something very advanced and you have wanted to come there in some way and now you are finally there.

We found this enthusiastic attitude explicitly encouraged by one of the lecturers, who opened the first lecture with the words: "Welcome to the first lecture in quantum physics. I hope you're psyched up." Several students happily confirmed that they were and that they had waited for this by exclaiming "yes". This lecturer also informed the students that "quantum physics was one of the courses that got me enjoying physics." These were the only such explicit examples observed though, the other instructors usually started just by going into what the course (or their part of it) would look like. Nevertheless, a similar hype for quantum physics was built up when another lecturer ended the first lecture with a video of electrons in a double-slit experiment slowly building up an interference pattern set to dramatic music.

While several students seemed to eagerly look forward to the course and had great expectations for it, some claimed that they did not really know what to expect from the course and that they had not heard that much about quantum physics before either. Frida and Linn, who study meteorology, said that some older students and their classmates had described the course as important and interesting, but that in contrast to themselves, those people were more interested in physics and had read lots of popular science books.

In general, these expectations can be said to represent a rather broad spectrum of positions taken towards the course. Quantum physics can be a way of doing "real physics" or "exploring the universe" but for some it is only a required part of their education, a course among others, that they do not have any specific expectations about. However, the available space for the position as a good quantum physics student is narrowed in the classroom discourse. The practices made recognizable as going on in the classroom do not make room for everything. We will continue with detailing these practices and their consequences in the following sections.

Calculating quantum physics

Calculating quantum physics, the most prevalent practice, is strongly situated in a context of studying physics. In this practice, students are expected to listen to instructors, read the literature and solve problems the same way as it is done in all previous physics course. The novelty of quantum physics is expressed primarily as new ways to calculate, not new ways of modeling or understanding reality. Here, doing quantum physics consists in learning a new formalism and applying it to example problems, mainly solving the Schrödinger equation "in the usual way" in different systems.

One characteristic part of *calculating quantum physics* is instructors' insistence that students have to understand the formalism to understand quantum physics, here expressed by one of the TAs:

> This course is intensively mathematical. It will seem more like mathematics than physics at times. But this is how quantum physics is. You have to be able to operate on the equations before understanding the physical meaning of them.

Similarly, the lecturer in the same course, when recounting the evaluations from previous years, told the students that some complaints had been raised about the course containing too little physics and too much mathematics. This criticism was brushed away with: "Well, what should I say? There's a lot of mathematics in quantum mechanics! A few of you will think there's too much math in this course."

Understanding the mathematical formalism in the context of these courses to a large extent involves solving problems, and this is evidenced by the advice another lecturer gave the students at the start of the first lecture:

> I have a piece of advice for you: calculate, calculate, calculate. To grasp quantum mechanics you have to calculate […] do it from the start.

Specifically, solving problems mostly means solving the Schrödinger equation. Students will "soon learn it by heart" but "it will be a little frustrating in this course, because I will just put the Schrödinger equation out there" (one of the lecturers in the first lecture). Another lecturer talked in a similar way and specifically told the students that they would be going through lots of solutions to the Schrödinger equation during the course. Additionally, in learning the formalism, there are many things the students just have to take at face value. A lecturer told the students that "when I learned quantum mechanics, the Hamiltonian was just this combination of operators."

Physics courses generally have a recommended textbook for reading alongside the lectures, but how it is used in courses varies. In the courses we studied, one lecturer told the students to make sure to read the book in time, another to focus on reading the terser homemade compendium before class and the third that the students could certainly complete the course without buying a book if they wanted to. As the textbooks can provide extra context and different views, completing the course without a book means putting a larger focus on only the content of lectures and problem solving sessions.

As the goal of the courses was primarily understanding the formalism and solving problems, the main practice enacted in lectures and problem solving sessions was focused on getting through the material. Often, lecturers and TAs complained about not getting through all the material scheduled for today, or hurried to squeeze something into the last minutes of the lecture and said things like: "One more thing and I'll let you go." Sometimes the last minutes were not enough either, as exemplified by one of the lecturers after a problem solving session: "I'm happy it's only five minutes delay and we've completed all problems." Even with an ambition to give the students "some minutes to think" the main goal of problem solving sessions seemed to be getting through the assigned problems as exemplified by this extract from the field notes:

> "The format of these exercises is very similar to what you have experienced so far." The TA tells the students that he will "read out" the problems and give the students "some minutes to think."
> "Unfortunately, I won't give you so much time for that, because we have 7–8 problems to go through every time. I will need the time to demonstrate them."

In interviews, students voiced their concern over not having enough time to think, write or realize what they did not understand in lectures and problem solving sessions. For example, David, when asked whether the course is difficult, said that one can often be "three blackboards behind" when the lecturer asks a questions. In class, there might be a negotiation over the position as a student who manages the tempo:

> The lecturer writes an expression on the blackboard and asks: "Is this right?" One of the girls in the back says: "Could you wait a few seconds when you're done?" "Am I writing to quickly?", the lecturer asks. Oliver says "no" and someone else answers him: "That's easy for you to say, who are not taking notes." (Oliver is mostly sitting with his computer and not taking notes there or on paper) The lecturer says: "Should I continue?" Oliver again: "Just go on." Another student says: "It's kind of hard to write that much and think at the same time." "Yes, that's true", the lecturer says and continues.

These negotiations may also be played out in a jocular manner as the students verbally oppose the high tempo. In one of the problem solving sessions, the TA signaled a break by saying: "So we will have five minutes break before we continue. Of course normal time is fifteen minutes. If you need fifteen minutes it's ok." This was answered by a student who said "it's good that you're ambitious", which brought down some laughs from others. Nevertheless, most students in this problem solving session were back within 5 min for the second half of the class.

The focus on getting through the material meant that there was not much time for questions or reflection from the students, who were put in a kind of pedagogical double-bind as they were simultaneously urged to ask questions, as this quote from a first lecture for bachelor students illustrates:

> You should also ask questions. If you don't ask questions, that means you are either a) bored, b) don't get it or c) you're both bored and don't get it. [At this, a student in the back laughs a little]

Statements like these, even though they are delivered in a humorous way, may put students in a position where only "smart" questions can be asked, that is, if asking questions would imply "getting it". Additionally, coming up with a "smart" question is probably also made difficult, if many students are "three blackboards behind" or if the openings for questions are given like this lecturer often does: After going through some material, asking if anyone has any questions but continuing with new material after just a few seconds. A few other instructors usually stopped to ask questions in a similar quick way, but this varied among instructors and classes. For example, one of the TAs often waited 10–15 s for questions to pop up and the dialogue between the lecturer and the students in one bachelor course was often more extensive than between the lecturer and the students in the other bachelor course. However, this extensive dialogue was viewed as exceptional by the students who describe how they "have never been livelier than in this course" (Robin) even though "it is a tradition in our class that no one answers questions" (Hugo).

Exploring and applying quantum physics

Apart from the dominating practice of "calculating physics", we discern two peripheral practices made recognizable as going on in the courses. We choose to call these *exploring quantum physics* and *applying quantum physics*.

At times throughout the lectures, lecturers talked about how results or theories currently discussed were "discovered." Typical examples of utterances in this genre are: "Planck came along and he postulated that energy comes in discrete quanta" (lecturer in bachelor course) or that "Bohr came up with it [the formula for the energy levels of hydrogen] in 1913, long before the Schrödinger equation" (lecturer in other bachelor course). We view these kinds of statements as part of making the practice *exploring quantum physics* recognizable. This practice was seldom construed as occurring "here", in the classroom and is not necessarily offering a discursive position available to students. Rather, these statements serve as descriptions of something that "has happened", actions performed by absent actors, being retold in the context of the classroom.

Instructors used historical accounts in different ways and for different purposes, but the historical material was in general disconnected from the main course material, and this was done in several ways. In the problem solving sessions, where the focus was almost exclusively on solving problems, history was seldom mentioned at all. In lectures the historical material was often separated in a clear way from the main material, both by placing most of it in its own lecture and in the way it was presented. In the first lecture, one of the lecturers used a digital presentation to give an overview of the historical development of quantum mechanics. The lecturer told the students that this would not be happening much in the coming lectures, where the blackboard would be used. During this lecture, when the lecturer turned to the blackboard to write some derivations, most of the students, who had earlier watched the presentation in a leaned-back position (with some exceptions) immediately grabbed pen and paper and leaned forward to note what the lecturer wrote. Suddenly, the practice of the lecturer was mirrored by the students and something that they also *did*. The historical content was thus, in contrast to the main material, presented in a way that engaged students less.

The lecturer in the course for engineering students used a slightly different approach to lecturing than the others, with relatively more material presented in slide presentations (this lecturer spent maybe half of the time with slides, whereas the others only used them occasionally). This lecturer also included more descriptions of the "discoveries" of quantum physics, and separated it less from the main content than the lecturers in the other courses. The engineering students on this course brought this up in the interview, and contrasted it to other courses they had taken earlier, which used a more "math-focused" approach. The students argued that the lecturer, by going through the experiments, allowed them to participate in something that can be characterized as a practice of exploring physics:

Rikard: Like this, [the lecturer] has often started with an experiment like black body radiation [Magnus: yes] and then: "this is how it should have been, that didn't work *at all* and then they had to do like this and no one really got why" like this, I don't know, I mean it was quite good to then start with an experiment, why didn't what we had believed about it work? What do we have to do to make it work? Kind of…

Magnus: Yes, it feels kind of like we are doing the same thing that they did a hundred years ago [laughs and several inaudible utterances]

Here, Magnus expressed this experience as "doing the same thing that they did a hundred years ago," which perhaps appeared as an exaggeration to the others, who laughed. At the same time, another student, Lena, argued that even more could be made out of it. Particularly, when the discussion continued, she asked for more integration of the mathematical and the popular/historical accounts of quantum physics, even though she appreciated the "histories" told by the lecturer. Although the lecturer in this course invited the students to think more about the "exploration" of quantum physics, the final focus of the course and its exam, as in the other courses, was on understanding the concepts and formalism and solving problems. Thus, even though students appreciate what they may pose as "doing the same thing that they did a hundred years ago", these practices are constructed mainly as something someone else does, something that is being retold but placed outside of the lecture and the course.

This means that, even though "the history and philosophy of quantum physics" is treated in different ways by different lecturers, the practices implied in these descriptions (which we gather under the title "exploring") are mainly outside of the available discursive positions for students in the courses. In other words, the people pictured as doing them are not the students. However, there were a few occasions where something like an exploration of quantum physics beyond the formalism was enacted in a practice that included the students. One of these was in a lab where students several times got into discussions of "how does this work". Two similar occasions of more conceptual or "philosophical" discussions of how things work involving students were observed during classes as well. The first was when one of the lecturers let the students reflect over a "thought experiment" during the break in the first lecture: "Suppose we measure the position of the particle at time t and get the value c. Where was the particle a short moment before that?" Discussing this, the students and the lecturer got into a dialogue that for a moment brought some of the more intricate questions in quantum physics to the fore. This only lasted for a short while though, and all students did not seem to participate as much in the discussion as the ones on the first rows, who were usually those who answered most questions. This first lecture nevertheless set the stage for the relatively dialogical style of lecturing that this lecturer used throughout the course, even though it mainly concerned the formalism and solving the Schrödinger equation in the rest of the lectures.

The second occasion of these kinds of discussions was in a problem solving session held by another lecturer. When the lecturer talked about measurements and eigenvalues, exemplifying it with Schrödinger's cat, a student asked "do we get an eigenvalue if we measure an eigenstate," which started a discussion between the lecturer and several students about the nature of measurements. It ended with the same student concluding with the interpretation "Is it like if we toss a coin and in the air it can be both sides but when it lands only one?" The lecturer affirmed this with "One can think of it like that, that is actually good." After this discussion, students in this class asked many more questions than earlier.

Another minor practice of quantum physics that is communicated through the discourse of the courses, is that of *applying quantum physics*. This was hinted at in the, relatively few, instances when instructors talked about the possible applications of the current material. This again seemed to be done more often by the lecturer in the engineering course, who sometimes explicitly referred to technical applications that could be important for engineering students:

> This is important, especially for civil [i.e. Master of] engineering programs, because it's a big industry […] if you want to design materials, for the last 20 years, you don't go to the lab […] if for instance you want to study corrosion. Instead you use parallel computing to solve the Schrödinger equation […] it's very accurate.

A similar hint about the practical use of quantum physics was given when another lecturer told the students that "what I usually do is trying to solve the Schrödinger equation for different molecules". However, these kinds of statements are even more rare than stories about discoveries in quantum physics. Some of the interviewed bachelor students put forward the labs that they do as a "motivation boost" that would be good to do earlier in the course because then "you can really see this real-life connection and then still study a and $a^\dagger$ and everything" (Erik). The others agreed, and this possible connection of labs to "real life" may also be an example of when students can get a glimpse of *applying quantum physics*.

We understand the practices of *exploring* and *applying* quantum physics described above, even though they are at times made recognizable in the discourse and some "exploratory" activities do occur, as secondary, and in particular, as something that is largely portrayed as enacted by actors outside the classroom. The practice of *calculating physics* remains dominant in the classroom. Nevertheless, students are given many different, sometimes conflicting, signals about what being a good quantum physics student means.

Being a good quantum physics student

Some of the many expectations for quantum physics can be interpreted as aiming at positions of "being a physicist" in different ways. The hopes of "doing real physics" or getting to know "cool physics" are of this kind. Not all students taking the courses have these aspirations, though. In this section we will outline what positions as "a good student" are made intelligible in the courses and show that these may pose different but equally important problems for most of the students.

Being intelligible as a "student", or as a "good student," means mastering the discourse of one's education (Davies 2006). This entails being recognized as engaging in certain activities or practices, being recognized as a "who-doing-what" (Gee 2011). The discursive practices made intelligible as going on in the quantum physics courses thus have consequences for the positions as "good students" that are available. The practices are part of a linguistic and non-linguistic discourse in the sense that they involve both "actions" and the interpretations of actions. Certainly, studying quantum physics means doing some specific things while taking the course. These things and how they are interpreted set the stage for what positions students can take, and for who might be a "good" quantum physics student. In this study, lectures and problem solving sessions mostly followed a traditional pattern, where students were expected to listen and take note of the information conveyed by the instructors, and then solve problems and read books on their own. This practical structure sends signals of what should be seen as important and less important in the courses and what kind of knowledge students are expected to "learn by doing."

A telling episode of the conveying of messages about what "good student practice" is was observed in one of the courses. Students had heard that they would have some "group work problem solving sessions". Just before the first problem solving session, a few students expressed expectations of solving problems on pen and paper and discussing them together. When it turned out that this session was a more traditional problem solving session, where the TA solved problems on the blackboard and where he additionally had printed out notes with all solutions, most students sat back and watched. The end of this TAs sessions usually involved some shorter problems, which the students could solve themselves and hand in (voluntarily). When the students learned this at the end of the first session, most of them immediately seemed stressed and switched focus to solving problems themselves. Someone made a joke about possibly losing points on the exam if you would fail on this assignment. Here, being a good student meant both listening carefully and applying what you had heard to your own problem solving.

The students were sometimes told directly by instructors what was appropriate behavior. As mentioned above, students were told to "calculate" and "do exercises" but also to "read the literature", things which could certainly be sorted under the practice of *calculating quantum physics*. Doing these things and doing them well is valued student behavior. This is clearly communicated as one of the TAs thanks Stephen, one of the most active and visible students in the class, for presenting the solution to a problem on the blackboard:

> That was very good. This shows the value of solving problems before class. […] How many solve problems before class? Because if you don't, I think you will have problems.

However, at times students are also asked to be active and curious and do things that are outside the normal practice. For example, another TA recommended his students to read up on the emblematic quantum physics experiments in a book he himself read outside class when he was a student.

These instructions to be active and for instance ask questions possibly create the kind of a double-bind that was discussed in the section on *calculating quantum physics*. Students are expected to be smart and ask questions in no time. In a lecture that is strongly dominated by the lecturer talking, this is of course hard. The lecturer who joked about the virtues of question-asking, just before the break in another lecture asked if there were any questions and said: "Some brave soul wants to raise a hand? … come on" and asked the students to think about it during the break.

Part of the dynamics of this general reluctance of students to ask questions in lectures can be explained by the fear of asking "dumb questions":

> Hugo: I mean, I like to try and come up with it myself, if I have any question, before I ask, and then it gets kind of late to raise your hand and interrupt something, when some time has passed. Then I get very annoyed with some people who ask very stupid questions very often.
>
> Paul: Yeah, and you don't want to be one of them, do you?

A few times during class, lecturers used interactive techniques to survey student understanding, for example by posing multiple-choice questions. In relation to this, one of the interviewed students said that sometimes "you have to do hand raising and then it's really embarrassing if you are alone." This further exemplifies that enacting the expected behavior of active asking and answering of questions is not only difficult in the dominating practice of *calculating quantum physics* because it is hard to catch up and ask something, but also because it is associated with risk, the risk of failure.

Being a good quantum physics student is also a position that can be argued to be opposed to being a "physicist" in some ways. Some of the interviewed bachelor students, when asked about what makes a "typical physicist" objected that there is not really such a thing as a typical physicist. Instead they claimed that for instance the variations among the students on the program are much bigger than they perhaps had expected when they started. Nevertheless they go on and claim that features such as playfulness and curiosity are important traits for a physicist.

The interviewed engineering students, when asked about what makes a good "physics or engineering physics student" talked about "studying continuously" and not being "bound up by problems with solutions included" but rather "just take a starred [difficult] exercise without possibilities of control and sit and experiment", even though they knew that it means risking to "waste" a lot of time. However, the best strategy for getting good grades, they agreed, was to study hard and do test exams a week before the final exam. Among these students, who had earlier complained about too few conceptual discussions, the position of a good student seemed hard to negotiate. In the end, their strategies usually came down to performing well on exams, even though they recognized this might not really be what a "good student" should do. Similarly, in a discussion about whether they appreciate labs, Glenn, one of the bachelor students said:

> And then you get to test different things and see what happens, well kind of letting out the physicist [the others laugh]. I mean, the merry [referring to the earlier discussion of playfulness and curiosity] physicist [others laugh again]. So the labs as such are often much fun but then, yeah, the lab reports can destroy that joy at times, especially when it gets too stressful.

The position as a playful and curious physicist is thus often opposed to the position of a good student performing the *calculating quantum physics* practice. Additionally, most of the possibly attractive positions associated with students' expectations of learning quantum physics, some of which could be interpreted as *exploring* or *applying* quantum physics and being more of a "physicist", are difficult to attain for students in the dominating understanding of "doing quantum physics" as equal to *calculating quantum physics*.

The negotiations that the students have to do about these practices and positions can seem to take the form of disillusionment or acceptance of the more or less boring side of studying physics, like for Bob:

> It can seem very cool and magnificent when you talk about it in a popular science way, but when you are really there and should do quantum physics and sort of calculate your raising-, lowering-operators, then it's not that, what should I say, glorious. So, there is a certain difference. I still think it is fun to do it, but you have a completely different idea about what quantum physics is now when you've been doing it yourself than you had before.

Discussion

The primary finding in this study is a dissonance between different expectations on and of students taking quantum physics courses. First, some students have high expectations for the course going beyond the dominating *calculating quantum physics* practice, which they are expected to participate in. Second, while the instructors expect students to be active and curious, to achieve such a position would partly mean overcoming the focus on calculating that is imposed by the courses. Striving to be recognized as a "good student" means that some other possible discursive positions are excluded.

Being into *calculating quantum physics* means being into learning quantum formalism for its own sake. This is a position and attitude that can be deemed to be differentially available to students with varying interests and backgrounds. Those who expect to "explore" fascinating scientific and philosophical issues during the course may be disappointed by the prevailing focus on calculating. Similarly, those who view their main reason for learning quantum physics as learning to use it in some kind of application (technical or scientific) will rarely find explicit connections to those things during the course. Last but not least, those who take quantum physics as part of their required courses, as "general knowledge," but do not expect to use its formalism and calculations explicitly, will probably find it hard to achieve a recognizable progressive learner position in courses focused mainly on calculating. This is evidenced by the accounts from meteorology students and a pre-service teacher student who claimed to not really know what the course was supposed to give them.

For the students going on towards a physics degree, there is not only the problem of being disappointed if the course does not contain that much “fun”. After all, that is not necessarily the purpose of higher education, even though keeping students’ interest up is a good idea for retention and learning. We recognize as equally problematic the issue that the discourse in quantum physics courses may reproduce an instrumental and elitist physics culture, where the ways of being a physicist and doing physics are limited.

The discourses and methods of teaching quantum physics in our context can be connected to the developments of American physics teaching during the Cold War. A “pedagogical emphasis upon efficient, repeatable—and thereby trainable—techniques of calculation” (Kaiser 2002, p. 153) can be recognized in the common way introductory quantum physics is taught today, also in Sweden. The problem with this is, that it “reinforce[s] a particular instrumentalist approach to physics” (Kaiser 2002, p. 156). So, a kind of teaching that focuses too much on calculation risks reproducing a culture of physics where the only thing that matters is getting results, a “shut up and calculate”-culture, perhaps (as in the American case) aligned with military and industrial interests. This kind of culture does not only foreclose “[e]pistemological musings or the striving for ultimate theoretical foundations” (Kaiser 2002, p. 154), but also discussions of the social aspects of science and the role of science in society. The possibilities for other “styles of doing physics” (Rolin 2008) seem to be reduced.

If the practice of physics courses is focused on calculations, and this is embedded in an instrumentalist physics culture, we could guess that this selects and forms the students who continue with physics. In the context of courses, this is related to the question of competence, “who is seen as a competent physics student?”, raised in earlier studies (Due 2012; Gonsalves 2012). At first consideration, as the practice of courses seem to encourage a “shut up and calculate”-attitude, we could guess that the students who manage the calculations and “get” the mathematical formalism get the position as “bright” or “competent” students, and other competencies (like critical thinking, curiosity, etc.) get under-valued. This is not all there is to it though. Students are explicitly asked to “ask questions” and implicitly expected to be able to grasp a lot more of the context and connections of the material than is taught. This pedagogical double-bind mirrors the similarly paradoxical situations described by Hasse, where a playful attitude in physics was appreciated by some instructors as characteristic of scientists-to-be, even when it was not part of the expected disciplined classroom behavior and disturbed the regular teaching (Hasse 2002).

As our material shows, it is important to appear “smart”, or rather “not stupid”, in the classroom, for instance by avoiding asking “stupid questions.” Due’s results from high school show that the position as a smart or competent physics student is often more readily available to men than women, similar to the position as a playful physicist (Due 2012; Hasse 2002). This structure can be related to the common view of successful students in science as “naturally bright” versus “hard-working” depending on whether they are male or female (Jackson and Nyström 2015). As the idea of “natural intellect” or “being a genius” is connected to (white) masculinity (Traweek 1988), this works in excluding women (and other “others”) from academic disciplines where a belief in the necessity of “innate talent” is strong (Leslie et al. 2015).

In the quantum physics classroom, with its overwhelming focus on calculating, the position as really “smart” and “curious” will only be available to those students who manage to "get it" and still keep up their interest in the wider context. This is part of building an elitist physics education, where getting into "real" physics is most available to those who succeed in both calculating and being curious. Managing this could demand a heightened belief in one's abilities that is generally more common for men (Ehrlinger and Dunning 2003) who perhaps are more easily judged as "bright" or "a genius". Certain other positions as a physicist are also excluded or discouraged when this transcendence of only calculating is privileged: Being curious and interested without being a genius, being a hard-working learner, or being a "bright female student" are all positions that are difficult to achieve in an elitist physics education culture. Having a difficult and excluding physics education is sometimes viewed as a way of "weeding out" unsuitable candidates, but this becomes very problematic when for instance self-confidence or definitions of "smartness" are gendered.

We have argued that a classroom discourse focused on "calculating physics" risks reproducing an instrumental approach to physics, which is likely to exclude some students. In addition, students who aim for a position as "scientifically bright" are placed in a paradoxical situation where this position cannot be achieved by doing only the prescribed activities. This limits the possible ways of being a physicist and means that the courses mainly cater for those students who will benefit the most from doing all the calculations, mainly theoretical or mathematical physicists. In a way, these results point to several obstacles to getting students to "think like," or rather "become," physicists, that have been speculated about in the PER-literature. The question then is: What could be done differently, for a more inclusive quantum physics teaching? Evidently, we believe that in the interest of recruiting, sustaining, and producing a broad population of physics students, positions related to the other practices found in the quantum physics courses, exploring and applying, and possibly others as well, should not be closed off. In educating future physicists, physics teachers and engineers, a broad spectrum of ways of relating to the content needs to be made available to the students. For quantum physics, this would mean bringing out many more aspects in the teaching.

A starting point would be having more explicit discussions on the interpretations and philosophy of quantum mechanics (Greca and Freire 2014) and in that way allowing more of an "exploration side" to the courses. This could be argued to lie outside of the expected core content of quantum physics, but defining what is the core content, or, for that matter, what is "proper" science, is not an easy thing. The foundational questions of quantum physics that were deemed metaphysics during several decades turned out to generate testable hypotheses and may very well be important parts of physics in the future. As Kaiser argues:

> Strangely enough, many of the philosophical issues surrounding quantum mechanics are today being used to entice potential students into physics. As quantum computing and quantum communication become a commercial reality, tomorrow's students may find themselves routinely grappling with the same philosophical questions that challenged their forebears almost a century ago. (Kaiser 2007 p. 33)

In line with this, Baily and Finkelstein argue that it is certainly "possible to make these developments accessible to introductory physics students" (2015, p. 13).

Additionally, together with Greca and Freire we argue that the practices in the courses to a greater extent should mirror the practices students might be doing in the future, in different physics contexts. As they state it, "the inclusion of applications of quantum mechanics into real (although simplified) problems is not only important for the understanding of quantum mechanics, but will also motivate students to continue their studies in this subject" (Greca and Freire 2014, p. 293).

Our results show the value of approaching physics education from a cultural viewpoint, with a focus on discourse and the reproduction of physics culture in university teaching, and examining the positions made available to students in this culture. Further research could involve delving deeper into the concrete negotiations made by students, relating this to the discourse(s) of the education and students' backgrounds or goals. Another direction would be to widen the scope and study the discursive positions made intelligible in physics courses in different subjects, levels, and national contexts.

Conclusions

This study has given examples of how the discourse in quantum physics courses, some of the vital steps for becoming a physicist, can narrow the possible ways of figuring one's future in physics or related fields. We have discussed how this might lead to a narrow instrumentalist or elitist physics culture, where the expectations of what a physicist should be may serve to exclude both a diversity of people and questions from physics. In such a physics culture future physicists are molded in a certain form, where certain styles of doing physics are dominant and others left out. As quantum physics has a central role both as inspiration and qualification for physics students it is vital that it gives room for more approaches than "shut up and calculate".

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