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Reviews

Quantum Mechanics Curriculum: A Review

Madhu K. *

"Science is a culture of doubt ..." – Richard P. Feynman

A certain book on quantum mechanics, claimed to be popular across South Asia, explains the collapse of the state during a measurement of an observable as follows. The book claims that a measurement to find the value of an observable quantity for a physical system in a state $|\psi\rangle$, is described by the action of the associated operator $\hat{A}$ on that state as

$$\hat{A}|\psi\rangle = a_n|\psi_n\rangle$$

where $|\psi_n\rangle$ is the eigenstate to which state collapses. The shockingly absurd equation appears to invoke sorcery to decide which 'eigenstate' should appear on its right hand side. The process of measurement involving decoherence of the state during interaction with the measuring apparatus is explained with just the operators in the space of states of the system! That this is widely taught across our universities made it necessary to mention this in this article which is primarily on quantum mechanics in our university.

Physics has come a long way over last four centuries and a student who wants to get into research, experimental or theoretical, needs to be prepared on several foundational aspects. The student should be initiated to the ways of thinking about questions in many of these. Even for those who do not want to get into research, the ways of thinking about problems are the critical part of the formation of a graduate. Indeed the larger society needs such a graduate in many more ways than through research. Talking in the context of India, and specifically Kerala, our universities have clearly fallen short of achieving this goal. The problem lies beyond just the choice of books or university curriculum. Nevertheless it is important to identify the problems associated with both these in our limited attempts to cut a way forward.

Quantum mechanics today has evolved significantly from how it started off in the early decades of twentieth century and this has reflected in the pedagogical treatment of the subject at university level around the world. It is imperative to think loudly on the pedagogical approaches to the subject that suits the undergraduate and graduate programs in our universities.

The deeper the understanding of a subject, the simpler the means of communicating it to a student. Given the level of understanding achieved, quantum mechanics definitely

*Union Christian College, Aluva,

deserves to be communicated in simpler terms. This makes it possible to introduce almost all of its formalisms right at the undergraduate level. Currently, at least at undergraduate level, university syllabi tend to take a historical route by starting with a discussion of the experiments that led to the discovery of its principles. This is followed up by the old quantum theory with examples such as Sommerfeld quantization of hydrogen atom and so on before introducing wavefunction and the modern understanding to the students. Whereas at the Masters level, syllabi of various universities often do not take the syllabus of their own undergraduate course in quantum mechanics into cognizance and go on to introduce the subject afresh. Masters syllabi however seem to take a relatively modern deductive approach to motivate the quantum mechanics directly through Stern-Gerlach experiment or the Young's double slit experiments.

It is necessary bring a significant change to this approach. Across the world, a full course in quantum mechanics is considered an integral part of an undergraduate study. It may be harder in the Indian context to reach this standards in a single leap, given the resources available at the university or college level. Apart from the historical motivations that led to the formulation of quantum mechanics, an undergraduate syllabus of the day must necessarily include a discussion on the mathematical formulation of quantum mechanics in terms of linear vector space, exactly solvable problems including particle in infinite and finite square well, harmonic oscillator, angular momentum and its algebra as well as hydrogen atom. If time evolution of quantum systems and time-independent perturbation theory are also introduced this could serve as a foundation level course on which one could build up further. It is important to use a text which can, by all considerations, be continued for further study at Masters level. Books such as the ones by D.J. Griffiths, R. Shankar fits the bill, but older ones such as Merzbacher should also be given a consideration. Quantum mechanics courses for a Masters program should be the logical continuation of the introductory course at the undergraduate level. Retaining the current format of two courses at this level will help in updating the content to bring it in line with requirements of a modern Masters degree programme. Topics such as time-independent approximation techniques, Heisenberg and Dirac interaction formalisms, time-dependent perturbation theory and scattering theory could be discussed in the first course in quantum mechanics at the Masters level. This will ensure an adequate study of all topics in quantum mechanics in the current M.Sc syllabus. This would also allow us to design the second course in quantum mechanics at an advanced level without spending time on the preliminary ideas. Although books mentioned earlier would serve the purpose, students should be encouraged to look at the ones by L. Landau and E. M. Lifshitz, C. Cohen-Tannoudji et al. and S. Weinberg.

A modern masters syllabus in quantum mechanics must necessarily discuss foundational aspects including the questions of measurement and interpretations. Measurement in quantum mechanics is a concept that is, very often, cause of confusion. This is further compounded by the use of books such as the one mentioned in the beginning of this piece. Students of the day must certainly have a grasp of the above aspects such as decoherence and entanglement. The immense amount of wisdom gained on these have already brought in a complete change in the way quantum mechanics is conceived today. It is time we accept this paradigm and look ahead to reconfigure the syllabus to include aspects such as density operator, mixed states, Bell's inequality, entanglement and basics of quantum information. The topics are discussed well in the book by M. A. Nielsen and I. L. Chuang. There are several books and resources such as the lectures notes of J. Preskill available on the subject that are also accessible easily.

The practice of dealing quantum mechanics in two courses at Masters level helps to fill some glaring lacunae in the present syllabi. Atom interacting with radiation is an aspect that is missed out in the present university syllabi. A study of spontaneous and stimulated radiation is definitely gainful for the students doing a second course at masters level. Although a bit older, the book on Quantum Optics by R. Loudon deals with the subject in a lucid manner. The book is also handy in case one wishes to introduce ideas like coherent and squeezed states.

Study of many-body systems is a part that is missing from our Masters syllabi. Many-body physics is frequently associated with many phenomena in atomic and molecular level, condensed matter systems and nuclear systems. We must address this glaring gap by including an introductory level content on many-body theory. Essential aspects such as Hartree-Fock approximation and density functional theory should be present in the second course in quantum mechanics at the Masters level. Most of the older books such as L. I. Schiff had this at some level but instructive discussions are often found in books on atomic and molecular physics and nuclear physics.

Relativistic quantum mechanics has been a part of Masters syllabi for a while. Progressively it has been recognized that a relativistically invariant dynamical description of high energy particles is quantum field theory. As a consequence, books on quantum mechanics, since 1970s, started omitting relativistic quantum mechanics. Unfortunately, our universities have not come to accept this change in perception and they continue to the topic of relativistic quantum mechanics in their respective syllabus which is already jam packed without it. It is important to note that quantum field theory has now become a foundation for theoretical description in wide ranging areas in particle physics, condensed matter physics and statistical physics. An introduction to the tree-level perturbation theory with the interaction of scalar fields could go a long way in addressing this lacuna. Books on quantum field theory such as L. H. Ryder or D. Amit that are easily available could serve the purpose. A relatively recent book that is popular is the one by M. Srednicki.

A good measure of understanding of a subject would be the ability of the student to critically engage with the subject matter. Even if we are not able to device a metric to measure such an ability, encouraging students to point out non-trivial mistakes in a book would be one such activity that could prompt the students to tread this rather unpopular path. Apart from breaking the superstitious faith often placed on books and this can definitely elevate the transaction of physics at our universities.