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Prof. Jan Tobochnik, Editor
American Journal of Physics
Kalamazoo College
1200 Academy Street
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Dear Jan:

After an amiable, extensive and instructive email exchange with Travis Norsen, I would like to submit the following Letter to the Editor. The particular content of this Letter relevant to Norsen's AJP article is stated in the next-to-last paragraph, and in the PostScript.

Expressions of discomfort with quantum theory by Einstein, de Broglie, Schrödinger, Bohm, Bell and others often obscure their points with excess verbiage and somewhat nonstandard nomenclature. The recent article "Einstein's boxes" by Travis Norsen [Am. J. Phys. **73**, 164 (2005)] follows this trend, while reminding us of some issues that I attempt here to summarize more succinctly. (Defenders of quantum theory are often subject to the same criticism. This Letter presents an expression of support for quantum theory, similar to that of Shimony, Am. J. Phys. **73**, 177 (2005), but in a simplified form.)

In his later years Einstein codified his unease with quantum theory in the phrase "God does not play dice", which I interpret as discomfort that Nature is (according to our best understanding of extensive experimental data) intrinsically probabilistic. I therefore read efforts inspired by Einstein to show that quantum theory is "incomplete" as efforts to show that a better theory would not involve intrinsic randomness in individual systems (in contrast to randomness in statistical ensembles, with which Einstein was very comfortable).

Norsen has reminded us that Einstein's discussion of 1927 can be simplified to consideration of a single particle that could be observed in two spacelike-separated regions, 1 and 2. Following Einstein and Bell, he argues that if the observations are governed by a probability distribution P(1,2), then the lesson of special relativity appears to be that we should expect the probability distribution to factorize: P(1,2) = P(1) P(2). If the probability distribution does not factorize when regions 1 and 2 are spacelike separated, it is considered to be "nonlocal".

Factorization has the immediate consequence that there is nonzero probability of observing the particle in both regions 1 and 2 "at the same time". Surely Einstein and Bell would agree that such observations are not possible in Nature. The "locality" requirement that a particle can only be observed at one place at a time is not consistent with those observations being governed by a probability distribution P(1,2) that has no correlation between spacelike-separated regions. A probability distribution P(1,2) must be “nonlocal” for its predictions to be “local”.

Some people, apparently including Einstein, conclude from this that Nature cannot be intrinsically probabilistic (at the level of individual systems). But Einstein noted that observations of only a single particle are not sufficient to settle the issue, because it cannot be excluded that the particle already had a definite trajectory prior to its observation, and the probability distribution merely represents the ignorance of physicists. This led to discussions of two-particle systems in “entangled” states (“EPR” states or “Bell” states), experiments on which make it clear that the need for a probabilistic description of individual systems in Nature is not simply due to ignorance, but is intrinsic to Nature.

I conclude from this that it is poor use of language to label as “nonlocal” the correlated probability distributions P(1,2) of quantum theory for phenomena in spacelike-separated regions whose merit is to insure that their predictions are always “local”.

I come away from Norsen’s article with renewed appreciation of the subtlety of Nature and of the quantum theory that describes it so well. And, with a better understanding of how Einstein’s phrase “God does not play dice” summarizes the core objection of some people to that theory.

Kirk T McDonald

PS It is likely that the origin of Einstein's 1927 argument summarized in the article "Einstein's boxes" was a talk by Georg Joos that was attended in Einstein in 1923. This talk, and a following discussion session, are reported in the Physikalische Zeitshrift **24**, 469 (1923).

Joos describes an experiment that is essentially the same as Norsen's Figure 2, with the addition that the phosphor screen is viewed through a binocular microscope that includes a beam splitter. Joos comments on classical and quantum interpretations of observations of light from impacts of alpha particles on the screen as seen through the microscope.

The following discussion included comments by Born, Einstein and Wien. "Herr Einstein: Die Stichhaltigkeit der statistischen Kriterien kann ich nicht so schnell beurteilen. Aber sicher kann ich von theoretischen Standpunkt sage, daß bei partieller Reflexion zufällige Verteilung ganzer Quanten über die beiden Wege erfolgen muss."

My translation: "I cannot judge so quickly the validity of the statistical criterion (of Joos' semi-classical analysis). But I can certainly say from a theoretical standpoint that partial reflection must cause a random distribution of whole quanta over the two paths."

In 1923, Einstein appears to have held the view that a quantum particle has a definite path, although the paths of similar particles may be statistically distributed. Many of his later writings suggest that he never changed his view on this topic.

It took two years for Max Born, who also heard Joos' 1923 talk, to come up with a new interpretation of what was going on in Joos' microscope, namely that a quantum particle does not have a definite path prior to its observation, which interpretation has stood the test of time.