SUMMHAMMER'S EXPERIMENTAL TEST OF THE NON–ERGODIC INTERPRETATION OF QUANTUM MECHANICS

Vincent Buonomano

RELATÓRIO TÉCNICO Nº 06/89

ABSTRACT: The object of this work is to analyze Summhammer's recent experimental test of the Non–Ergodic Interpretation of Quantum Mechanics using neutron interferometry.

We conclude that the experiment presents clear and concrete evidence that the ergodic type assumption, that must be made in virtually all the well known interpretations of quantum mechanics, is valid. That is, the physical assumption that particles which consecutively pass through an interference apparatus will be independent as long as they pass through the apparatus alone, now has experimental confirmation. The Non–Ergodic Interpretation had been calling attention to the fact that hitherto there was no experimental evidence for this assumption.

Universidade Estadual de Campinas
Instituto de Matemática, Estatística e Ciência da Computação
IMECC – UNICAMP
Caixa Postal 6065
13.081 – Campinas, SP
BRASIL

Março – 1989

INTRODUCTION

The object of this letter is to analyze Summhammer's recent experimental test[1] of the Non-Ergodic Interpretation (NEI) of Quantum Mechanics using neutron interferometry (We will refer to Reference 1 as JS in the rest of this work.). NEI has been presented and studied in a series of works[2-12]. It uses the same Hilbert space formalism that the usual interpretations[1] of quantum mechanics do. However it differs from them all fundamentally in that it applies the formalism to a laboratory *time average* instead of a laboratory *ensemble average*. We recall that the conceptually correct (and only truly correct way) to perform an experiment on a one particle system[2] which gives a completely valid ensemble average[3] is to use many absolutely identical and independent apparatus. Each apparatues must measure exactly one particle which were all prepared in the same identical state. The ensemble average (for a one object system) embodies the idea of making absolutely independent measurements on essentially copies of a single object. It is impossible to perform such an average, both for economic reasons and due to problems associated with independently reproducing the same state preparation[4]. In practice in quantum mechanics, as well as in many other areas in science, it is a frequently necessary to use a time average as a substitute for the conceptually correct and ideal ensemble average. Throughout physics, real experiments must be performed using one

---

[1]E.G., Copenhagen, Statistical, Bohm, DeBroglie, Stochastic, and Fluid Interpretations.

[2]We restrict ourselves to strictly one particle systems and interference experiments in this work.

[3]This is true in general and is not particular to quantum mechanics.

[4]This does not even mention the enormous difficulties involved in giving operational meaning to words such as "independent" and "identical".

apparatus with measurements being made on a stream of particles which consecutively pass through the same apparatus.

Since all previous experiments are time averages, an ergodic type hypothesis must necessarily be made that the laboratory time average is indeed equivalent to the conceptual ensemble average. This is, of course, the reason why there has been much emphasis in the literature on low intensity interference. The thinking being that as long as the intensities are sufficiently low, then there will never or rarely be more than one particle in the apparatus at a time. Therefore the particles must be independent and the ergodic type hypothesis must be valid. Up to this point everything we have said is well known. For example explicit discussions of these points have been given by Margenau[15] and Glauber[16].

NEI has been calling attention to the fact that just because two particles are not in the apparatus at the same time by no means guarantees that are independent. One may easily imagine the existence of an indirect interaction between the particles. There are many examples of such interactions in science. First for the sake of having a very concrete example that illustrates well the type of conceptual interaction that we are discussing, we take one from experimental psychology. Consider a rat in a maze experiment. Here one performs an average over rats which consecutively pass through the same maze, but there is never more than one rat at a time in the maze. Now in this experiment one should thoroughly wash out the maze between the rats, otherwise a given rat's performance might be affected by the smell left from previous rats. Here one might say there is an indirect interaction between the rats via their scent left in the maze. An example from physics would be a very viscous fluid whose properties are affected by particles as they pass which in turn affects other particles that later pass (fluids with memory). Crystals also exhibit certain electromagnetic memory effects. Here time and ensemble averages may be quite different. One may also think of examples where the time interval between the passage of the particles is totally irrelevant. That is, even if you continue to decrease your particle beam intensity you can still have an indirect interaction.

The low intensity experiments eliminate a certain type of inter-particle interaction, a direct interaction - that is an interaction in which particle must be in the same spatial region at the same time in order to interact (interact by "touching" so to speak). None of the existing low-intensity experiments shed light on the indirect particle interaction that NEI hypothesizes. In this type of interaction one imagines that as a particle passes through the interference region it affects and is affected by the properties of this region. This permits a later particle, which definitely passes through one path only, to know the properties of the other path. The mechanism by which this may happen, i.e. what would be the analogy to the scent of a rat in the above example, NEI does not address itself to. NEI is not a physical theory but an alternate interpretation of quantum mechanics in terms of time averages[5]. One might speculate on a fluid or stochastic medium which "remembers" the particle properties as they pass the interference region. One might talk about vacuum states. Lorentz invariance would also have to be dealt with. See References (2-12) for some more details. NEI's position on Bell's Inequality is given in References (5) and (11).

---

[5]Formally it differs from the usual interpretations only in that it associates the mathematical object $\langle\psi|A|\psi\rangle$ of the Hilbert Space Formalism with the laboratory procedure of making a time average instead of an ensemble average.

SUMMHAMMER'S EXPERIMENT

It is clear that NEI is at least in principle testable since one only needs to perform a true ensemble average in any interference experiment. NEI clearly predicts no interference whatsoever for an ensemble average. Interference comes about from particles indirectly interacting with other particle via the interference region. For a true ensemble average there are no other particles to interact with either directly or indirectly. Even in practice, NEI has the virtue of being falsifiable in a large variety of experiments. Various practical tests have been discussed[2-12]. Here we only discuss the one used in JS. See JS for the complete information.

A diagram of Summhammer's experiment is shown in Figure 1. It is a Mach-Zehnder neutron interferometer. There are three ears with an aluminum phase shifter between the second and third ears which is automatically rotated through twenty angles in each experimental run. In one arm there is a shutter made of cadmium which may be randomly[6] opened or closed. When it is closed only one interferometer arm is open, and when it is open both interferometer arms are open. There are two detectors H and O which are connected to a shutter control relay via a PDP 11 computer as shown in the figure. The control of the phase plate which determines the angle is not shown in the figure.

The shutter is randomly opened and closed in the following way. The PDP computer receives a signal every time a neutron arrives at one the counters. Then under control of a random number generator in a Fortran program, a signal is sent or not sent to the shutter control unit with a probability of one-half. Therefore if the shutter was open (closed) before the neutron arrived, there is a fifty percent probability that it will remain open (closed) and a fifty percent probability it will be closed (opened) after

---

[6]The randomness of the shutter distinguishes this experiment from the so called chopper experiments[13,14] which do not test NEI[12].

the neutron is detected.

The shutter is opened and closed mechanically, it was determined independently (JS) that this takes less than .15 seconds. There is also a clock with an accuracy of 10^{-6} seconds which permits one to know the arrival time of the neutrons and when a signal was sent to the shutter to change its state. The mean wavelength of the beam was λ=1.78Å with the total spectral width, $\Delta\lambda$, being less than 1.9%. The transit time through the entire apparatus (from the reactor to the counters) was of the order of several milliseconds. The number of neutrons arriving at both counters was 3.37 and 1.17 neutrons per second with the shutter open and closed respectively. Over 80% of the neutrons that arrive in the interference region that should ideally be detected by the counters are actually detected (JS).

It is important to observe here that we know the transit time, the arrival time of the neutron at a counter, the time at which a signal was sent to the shutter control unit, and the approximate time it takes to open or close the shutter. Therefore for each detected neutron at either of the counters we can put it into one of three groups. There are those neutrons for which we can definitely say that one arm was closed before they entered the interferometer and remained closed during their passage through the interferometer. This was taken to be the case for those neutrons that arrived at least .25 seconds later that the previous signal was sent to close the shutter (.25 seconds is about twice the time it actually takes the shutter to close.). These are called the closed neutrons. There are also those neutrons for which we can definitely say that both arms of the interferometer were open before they entered and remained open during their passage through the interferometer which we call the open neutrons. This was taken to be the case if a neutron arrived at least .25 seconds later than the previous signal to open the shutter was sent. Finally there are those neutrons which don't fall into either of the previous two groups which we call the unknown neutrons. Some of these neutrons may have been in the interferometer when the arm was in the process of being opened or closed. Also many or almost all of these neutrons may actually belong to the open or closed neutron groups, this is of no importance. What is important is that each neutron of the open and closed groups can be be placed in these two groups with a very small probability error. Only the groups of open and closed neutrons are interesting to analyze to test NEI and the unknown group is ignored.

Each experimental run consists of the following. The phase plate is initially at some fixed angle. The initial state of the shutter is closed. Neutrons begin passing through the apparatus and at one or the other of the counters. As each neutron is detected the various relevant times are recorded. When the data is analyzed the neutron is then classified into one of our three groups. After a total of about 500-700 neutrons are detected, the phase plate is changed to next angle. Another 500-700 neutrons are collected at this angle, and this is repeated for each of the 20 angles. These angles give about two and half interference cycles. There were 19 of these experimental runs used for the data analysis in JS[7].

---

[7] We observe that the experiment may also be considered one in which the shutter is consecutively opened and closed but for random lengths of time. As such it is related to the experiment discussed by Mandel[17].

QUANTUM MECHANICAL PREDICTIONS

The quantum mechanical predictions in this experiment are completely clear. For each neutron in the closed group the interferometer arm was strictly closed before and during it's passage. Therefore there can be no interference whatsoever for this group. The usually interference plot made in a neutron interferometer experiment of the number (or probability) of neutrons arriving at either counter versus the phase angle must give a straight line ignoring the statistical fluctuations. For an ideal interferometer 50% of the neutrons must go into each of the counter independent of the angle. If one wants to imagine the neutron to be some sort of localized classical wave train these predictions are also completely clear. Analogously, for each neutron in the open group both arms of the interferometer were strictly open before and during the passage of neutron through the apparatus. Therefore one must see a full normal interference pattern for the neutrons in the open group. Plotting the number of neutrons arriving at either counter versus angle must give the usual full interference curve. In this case the curve must ideally be identical to curve obtained with this same apparatus but with the shutter always open for the whole stream of particles.

NEI'S PREDICTION

Let us first consider the experiment without the shutter, i.e. it is then just a Mach-Zehnder Interferometer experiment. Again NEI explains interference here by postulating that as each neutron passes through the interference region it affects, in an unexplained way, the state of that region so that the behavior of neutrons that later pass are affected. It imagines that if a stream of neutrons all enter the interference region from one arm instead of both arms then the average state of the interference region would be different in the two cases. In other words a given neutron knows whether it is a one or two arm experiment indirectly from other neutrons that previously passed the same region. Here there can be no interference whatsoever for the very initial neutrons. A certain minimum number of neutrons, N, must first pass to condition or program the interference region. There is no basis for predicting N.

Now we may consider the effects of the shutter. Imagine a given neutron arriving at the interference region where it must receive information from the interference region to decide whether it goes to counter H or O. Whether it saw the apparatus as a one or two arm interferometer was randomly decided and is not of direct importance in NEI. It is the state of the interference region that is of importance. Here the state of the interference region must, so to speak, give it the wrong information in general about how to behavior at least part of time. In any non-ergodic interpretation the neutrons behavior at the interference region depends on the state of neutrons, which in turn depends on its state before it entered the apparatus and on which arm it did or didn't travel through. A certain non-negligible portion of the closed neutrons cannot behave as they would have if one arm were closed for the whole stream of neutrons. Similarly a certain portion of the open group must behave differently than they would if both arms were open for the whole stream of neutrons. For example, consider the case of an ideal experiment with the visibility equal to one. In this case fifty percent of the closed group should go into each counter according to quantum mechanics (independent of the phase angle, of course). In the open group one will find certain phase angles at which all the neutrons must go into one counter and none in the other. There is a conflict between the probability distribution that one must impose on the set of incoming neutrons for the open and closed groups of neutrons. We have not succeeded in quantifying this conflict in terms of an inequality, but nonetheless consider this clear. NEI must predict unknown, but significantly different results than the usual interpretations of quantum mechanics.

EXPERIMENTAL RESULTS AND CONCLUSION

The experimental data of Summhammer's experiment may be analyzed in several different ways. First we consider the results shown in Figure 3 of JS. This compares the open group with a run made when the arm was continuously open. Any of the usual interpretations (which may also be called ensemble or ergodic type interpretations) predict that the curves must be identical in an ideal experiment. The open group curve (Figure 3c[8]) shows a little less (about 5-10%) interference than the that of Figure 3e, but this may be expected since there are no doubt vibrations from opening the shutter mechanically which would tend to weaken the interference. Also the continuously open run was made under somewhat different experimental conditions then the open group runs. Again, since NEI consists of many possible physical theories it makes no specific prediction. But it clearly says that there must be significant differences with quantum mechanics. One may imagine non-ergodic theories which predict very little difference in the above case. But such theories would also predict that one should see interference in the closed group. No such interference was seen (the permanently closed curve is not shown in JS). Therefore these results are consistent with any of

---

[8] This curve and the other curves in JS were made in the following way. Each run gave 20 experimental points of counts versus phase angle for each counter. These counts were normalized to compensate for the fact that the neutron intensity from the reactor was not constant during a given run. Then a curve fit was made separately for each run and the counts were calculated at 339 phase angles. These counts were then added at their respective phase angles producing a composite of all the runs. These counts were further normalized to one to produce the various probability curves shown in JS. In our own informal analysis for convenience we used only 14 of the 19 runs which permitted us to add directly (after first normalize for intensity variations) at their respective phase angle avoiding the necessity of performing the intermediate curve fits. In the various cases we compared this with the more accurate procedure of JS, no significant differences were seen.

the usual interpretations. However these results in and of themselves should only be considered to give a qualitative comparison since the two sets of data were not taken under identical experimental conditions and therefore no concrete conclusions can be drawn here.

We now consider Figure 4 of JS. This figure isolates out subgroups of the open and closed groups of neutrons. Curve 4b (i.e., the curve shown in Figure 4b) shows the behavior of the very first neutrons that are detected after the shutter is opened. More accurately it includes only those neutrons that were both the first neutrons that arrived after a signal was sent to open the shutter and also arrived at least .25 seconds later than that signal was sent. Figure 4e shows the behavior of the first neutrons that were detected after the shutter was closed. And Figures 4a and 4d show the behavior of the very last neutrons that were detected just before a signal was sent to open and close the shutter respectively. Any of the usual interpretations predicts that the open Curves 4b and 4d and the closed Curves 4a and 4d must be the same respectively. Superimposing curve fits on this data in the two cases shows this to be the case. Although we don't have the structure to say that these results are absolutely inconsistent with NEI, it is very difficult to imagine any non-ergodic theory which is consistent with these results. A non-ergodic theory presupposes that the neutrons is conditioned by the passing neutrons. The subset of first neutrons should not behavior the same as the subset of last neutrons in both the open and closed cases in NEI.

Figure 5 of JS presents a detailed chi-square analysis of the subgroups of the first, second and third neutrons that are detected at least .25 seconds after the arm was opened and closed respectively. This analysis shows with extremely high probability that the data of the first, second and third neutrons behave in the same way statistically in the both the opened and closed cases. We superimposed minimum squared curve fits of the first, second and third neutron when the arm was open (closed). The curves are practically indistinguishable. This is conclusive evidence against NEI, since the initial consecutive neutrons should exhibit different statistical behavior.

Finally we consider the following analysis related to the type of non-ergodic theory considered in Reference (12) which must be imagined to be consistent with the chopper experiments (see a previous footnote). In a chopper experiment at low intensity one must imagine a more complicated memory. It cannot be stationary, it must change in time in an appropriate manner related to the chopper frequency. Any such memory conditioning must involve more neutrons to accomplish. In JS the times at which the neutrons arrive at the counter determine when a random decision is made to change the shutter state. This arrival time is in turn related to the statistics of the neutron beam (and the shutter state) which is again in turn related to the coherence properties of the beam since the spectral density of the beam is the Fourier transform of the second order correlation function. Although the change of the state of the shutter is random the times at which this is done are not independent of the beam properties. One might speculate (perhaps exaggeratedly so) that this might affect the result. In any case, any such effect would require more neutrons to develop. In particular, it would imply that the initial neutrons at a fixed phase angle in the open (closed) state should behave differently than the final neutrons at that same phase angle. So we divided the counts at each phase angle into an initial group and a final group of neutrons. That is, we separated the first N neutrons and last N neutrons at each phase angle, where we used several different values of N. Then they were separated into the open and closed cases as before and compared with each other an the cases of Figures 3 and 4 discussed above. In all the respective superimposed curve fits no significant differences were seen.

In conclusion, the data was analyzed in various ways. All of them gave results consistent with the usual interpretations of quantum mechanics and inconsistent with any expected prediction of NEI. Therefore the hypothesis that the experimental time averages are equivalent to the conceptual quantum mechanical ensemble average now has solid experimental support. That is, the physical assumption that particles which consecutively pass through an interference apparatus must be independent as long as they pass through the apparatus alone now has experimental confirmation.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the help of J. Summhammer of the Atominstitut der Österreichishen Universitäten for various helpful conversations and his and his institutes hospitality during a visit. I also thank him for making all the raw data of his experiment available for this author to do his own analysis, and for providing detailed information about the data organization.

REFERENCES

1. Summhammer, J. - "Neutron Interferometric Test of the Non Ergodic Interpretation of Quantum Mechanics", preprint.

2. Buonomano, V. - "The Non-Ergodic Interpretation of Quantum Mechanics and Neutron Interferometry", *Physica* B 151, 349-350 (1988).

3. Buonomano, V. and Prado, A.F. - "Stochastic Processes for Indirectly Interacting Particle and Stochastic Quantum Mechanics", *Foundations of Physics* 18(4), 401 (1988),

4. Buonomano, V. - "The Non-Ergodic Interpretation of Quantum Mechanics", in *Proceedings of the International Conference on Microphysical Reality and Quantum Formalism*, Urbino, Italy, 1985. Eds: G. Tarozzi and A. Van der Merwe, Reidel Publishing Company, 1988.

5. Buonomano, V. - "The E.P.R. Paradox and the Non-Ergodic Interpretation of Quantum Mechanics", in *Quantum Mechanics versus Local Realism: The Einstein, Podolsky and Rosen Paradox*, Editor: F. Selleri, Plenum Press, 1988. Pages 327-343.

6. Buonomano, V. - "The Double Slit Experiment and the Non-Ergodic Interpretation of Quantum Mechanics", in *Quantum Uncertainties: Recent and Future Experiments and Interpretations*, Editors: W. Honig, E. Panarella and D.W. Kraft, Plenum Press, 1987. Pages 427-434.

7. Buonomano, V. and Bartmann, F. - "Testing the Ergodic Assumption in the Low Intensity Interference Experiments", *Il Nuovo Cimento*, 95B(2), 99-105 (1986).

8. Buonomano, V. - "The Number of Photon Counting Measurements, the Visibility and the Intensity", *Lettere al Nuovo Cimento*, 43(2), 69-75 (1985).

9. Buonomano, V. - "Quantum Mechanics as a Non-Ergodic Classical Statistical Theory", *Il Nuovo Cimento*, 57B, 146-170 (1980)..

10. Buonomano, V. - "Low Intensity Interference Effects and Hidden Variable Theories", *Il Nuovo Cimento*, 45B, 77-89, (1978).

11. Buonomano, V. - "A Limitation on Bell's Inequality", *Annales de L'Institut Henri Poincare*, 29A, 379-394, (1978).

12. Buonomano, V. - "Neutron Interferometry and the Non-Ergodic Interpretation of Quantum Mechanics", Unpublished.

13. Rauch, H. and Summhammer, J. - "Static Versus Time Dependent Absorption in Neutron Interferometry", *Physics Letters*, 104(1),

44-46, (1984).

14. Summhammer, J., Rauch, J. and Tuppinger, D. - "Stochastic and Deterministic Absorption in Neutron Interference Experiments", Physical Review A, April 1987.

15. Margenau, H. - "Measurements and Quantum States: Part I", Philosopy of Science 30, 1, (1963).

16. Glauber, R.J. - "Optical Coherence and Photon Statistics", in *Quantum Optics and Electronis* , Editors: C. de Witt, A. Blandin, and C. Cohen-Tannoudji, Gorden and Breach 1965. Page 63.

17. Mandel, L. "On the Possibility of Observing Interference Effects with Light Beams Divided by a Shutter", JOSA 49, 931, (1959).

Figure 1. Summhammer's experiment. A Mach-Zehnder neutron interferometer with a shutter in the right arm which may be random opened and closed. This turns the apparatus randomly to a one or two arm experiment. Figure reproduced from JS.

RELATÓRIOS TÉCNICOS — 1989

01/89 — **Uniform Approximation of Continuous Functions with Values in [0,1]** — *João B. Prolla*

02/89 — **On Some Nonlinear Iterative Relaxation Methods in Remote Sensing** — *A. R. De Pierro.*

03/89 — **A Parallel Iterative Projection Method for Convex Programming with Quadratic Objective** — *Alfredo N. Iusem* and *Alvaro R. De Pierro*

04/89 — **Fifth Force, Sixth Force, and All That: A Theoretical (Classical) Comment** — *Erasmo Recami* and *Vilson Tonin-Zanchin*

05/89 — **An Application of Singer's Theorem to Homogeneous Polynomials** — *Raymundo Alencar*