NEUTRON INTERFEROMETRY AND THE NON–ERGODIC INTERPRETATION OF QUANTUM MECHANICS

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ABSTRACT. The purpose of this article is to describe a test of the non-ergodic interpretation of quantum mechanics using neutron interferometry.

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I. INTRODUCTION

Neutron interferometry has proven itself to be nothing less than a spectacular tool for the foundations of quantum mechanics. In particular, the low beam intensities and very high counter efficiency have left absolutely no doubt about the existence of interference when there is only one particle in the apparatus at a time. Reviews are given in Greenberger (1983), Rauch (1986) and Shull (1982). The purpose of this article is to describe a test of the non-ergodic interpretation using neutron interferometry. Section II reviews the non-ergodic interpretation. The experiment is described in Section III. Some comments are made in Section IV.

II - THE NON-ERGODIC INTERPRETAION

The non-ergodic interpretation is a local realistic view which assumes a certain physical viewpoint of how particles behave in the microworld that is distinct from the usual interpretations of quantum mechanics (e.g., Copenhagen, Bohm's, DeBroglie's, Nelson's, and Marshall-DelaPena's). It assumes that a sequence of particles which consecutively pass through an apparatus separated by large times is not independent in general.[1] That is, it imagines, in particular, that neutrons may indirectly interact with each other via memory effects in an hypothesized medium. Neutrons which first pass through the interference region will affect the medium which then affect the neutrons which later pass through that same region. For example, consider the double slit experiment which motivated this interpretation. The above type of indirect interaction permits one to say that a neutron passing through one slit knows if the other slit is open (closed) from this information being recorded in the medium in their common path by neutrons which previously passed (didn't pass) the other slit. Here interference can only happen after a sufficiently large number of neutrons have traveled through the apparatus and conditioned our medium. One might imagine that a sufficient number of neutrons must pass to permit an equilibrium between the medium and state preparation. Neutrons interfere with other neutrons, but only indirectly via the medium.

In other words, one might describe the non-ergodic interpretation by saying that it questions the ergodic type assumption that currently must be made in order to interpret both the existing low intensity interference experiments and the polarization correlation experiments as giving the true quantum mechanical ensemble averages. We recall, for example, that in the double slit experiment the conceptually correct quantum mechanical ensemble average for a one particle system should be

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1. By large times we mean times sufficiently great to guarantee that there is almost never more than one particle in the apparatus at a time.

made as follows. One should have many identical independent apparatus with exactly one neutron in each apparatus. All the neutrons must be prepared in the same quantum mechanical state. Then the interference pattern must be seen when the positions of all the neutrons in all the independent experiments are superimposed. Real laboratory averages are time averages out of necessity and, of course, it necessarily involves an ergodic type assumption to interpret these averages as ensemble averages. See discussions of this in Glauber (1965) and Margenau (1963).

The non-ergodic interpretation is a well defined alternative interpretation of quantum mechanics. It assumes the same Hilbert space formalism used in both the Copenhagen interpretation and any statistical interpretation in the sense of Ballentine except for the following. In these interpretations one associates the mathematical object, $\langle A \rangle = \langle \Psi | A | \Psi \rangle$, representing the average of the observable A in the state Ψ, with the laboratory procedure of taking an ensemble average. Instead, the non-ergotic interpretation identifies this same mathematical object with the laboratory procedure of taking a time average. This is the only difference. Here we are making a different association between mathematical objects of the Hilbert space formalism and laboratory procedures. The non-ergodic interpretation always makes the same numeric predictions as these interpretations but it makes them only for time averages and not for ensemble averages. It is not a concrete physical theory in the sense that it does not offer a structure to explain the hypothesized medium with memory effects. Further information about this view may be found in Buonomano (1987 or 1986, also 1980).

III - THE EXPERIMENT

The basic idea.

We will call all the usual interpretations of quantum mechanics, that we mentioned above, an ensemble interpretation. We want to compare the predictions of any ensemble interpretation with the non-ergodic interpretation in a certain experiment. The basic idea of the experiment, which is described in more detail below, is to examine (statistically) the behavior of the initial neutrons when the configuration is changed from a two-arm to a one-arm experiment and vice-versa in a Mach-Zehnder interferometer (See Figure 1). For example, assume one is seeing a good stable interference pattern at a two-arm configuration. Then quickly block one of the arms. From the viewpoint of the non-ergodic interpretation the initial neutrons that then pass the interference region, which certainly must have gone through the unblocked arm, are fooled, so to speak, into acting as if it was still a two-arm experiment. This is because the medium in the interference region is still conditioned to a two-arm experiment. It only can become reconditioned to a one-arm experiment after a sufficient number of neutons pass. The difference in the predictions between an ensemble interpretation and the non-ergodic interpretation for these initial neutrons is quite dramatic. In an ideal situation, one might have 100% of the neutrons arriving at Counter 1 and none at Counter 2 at the two-arm configuration. When it is changed to a one-arm configuration any ensemble interpretation predicts that the counting rates must abruptly change from 100% and 0% to 50% and 50% respectively at the two counters. The non-ergodic interpretation predicts that the counting rates will not change abruptly but will change slowly to 50% and 50% (See Figure 3). In particular, in the very first counting interval after the arm is closed, the counting rates must still be 100% and 0% respectively. The situation is analogous when one changes from a one-arm to a two-arm configuration. We now describes more details of the experiment. Some comments are made in the following section.

The experiment

Consider Figure 1. It is a Mach-Zehnder interferometer with a switch in one-arm, say Arm A, which permits us to quickly change the configuration alternately from a one-arm to a two-arm experiment and vice versà at specified time intervals of length P/2. So for the first P/2 seconds (the first half cycle) we have a one-arm experiment, for the second P seconds (the second half cycle) we have a two-arm experiment, etc. P must be sufficiently large so that enough neutrons are collected to see a good stable two and one-arm configuration at the counters at the two configurations respectively. We might imagine the apparatus used in Rauch and Summhammer (1984), but with a much slower chopper velocity and with a=.5 (P would be the time of a single revolution). Assume that the phase difference between the paths is such that Counter 1 is at the maximum and Counter 2 is at the minimum for a two-arm pattern. For a one-arm configuration assume both counters will register the same number of counts. Also assume that the total number of counts at the two counters is a constant at any of two configurations as the relative phases of the paths are changed. The counters are assumed to be perfect and that all the neutrons passing the interference region are detected at one or the other counter. Real experiments are a remarkably good approximation to this.

The purpose of the timing circuit shown in Figure 1 is to unambiguously know the configuration (one or two-arms) for all the counting measurements. For example, for each neutron detected we want to know if it definately passed through Arm B or whether it could have passed one or the other arm. The timing circuit is to give us this information. In the above, by quickly changing the configuration we meant that the number of neutrons that we can't unambigously classify as belonging to a one-arm or two-arm configuration is negligibly small.

Let S be the total number of cycles during an entire single experimental run. That is, S is the number of one and two-arm sub-runs of our run. So SP is the number of seconds of the run. S will be estimated for an ideal experiment in the next section as a function of the probability confidence interval that one may desire. We want to make consecutive counting measurements of length T at Counter 1 for the entire experimental run.[2] T is assumed to be small in comparison to P. Ideally we would like T and the intensity to be such that, on the average, approximately 1 neutron per T seconds arrives at both counters in a two-arm configuration (See Comment 1 below). In our experimental run of time SP seconds we will make SP/T counting measurements. That is, if we define K by K≡P/2T (assumed to be a whole number) we will then make K counting measurements at each configuration during each cycle. Figure 2 summarizes the relationship between P, S, T and K.

So the output from the apparatus to the microcomputer consists of a series of 2SK numbers which represents the 2SK consecutive counting measurments in the experimental run. Again the counting circuit permits us to know unambiguously which counts belong to a one or two-arm configuration. For convenience all these measurements may be represented in an array (N(s,k)), where s=1 to S and k=1 to 2K. N(1,1) is the number of counts at Counter 1 during the time interval [0,T] in cycle 1 (a one-arm configuration). N(2,1) is the counts in the time interval [0,T] during cycle 2. N(1,K+1) is the number of counts in the time interval [KT,(K+1)T] during cycle 1 (a two-arm configuration). Then in general, N(s,k) is the number of counts at Counter 1 in the time interval [kT,(k+1)T] during cycle s. It is a one-arm configuration for 1 <= k <= K and a two-arm configuration for K+1 <= k <= 2K. Define N(k) by averaging over all S cycles, i.e.,

$$N(k) \equiv (\Sigma_{s=1}^{S} N(s,k))/S. \qquad (1)$$

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2. We will only present the analysis for Counter 1 as it is analogous for Counter 2. Actually it will be clear that only one counter is needed. Also we are only considering one experimental run. Further independent experimental runs will increase the statistical confidence.

Now it is clear that since we unambigously know whether it was a one or two-arm configuration for all the counting measurements, any ensemble interpretation predicts the following for N(k):

$$N(k) = \begin{cases} n/4 & k = 1 \text{ to } K \\ n_{max} & k = K+1 \text{ to } 2K \end{cases} \qquad (2)$$

where n_{max} and n_{min} are the number of counts at Counters 1 and 2 respectively at a two-arm configuration in a time interval T (when the pattern is stable). $n \equiv (n_{max}+n_{min})$ is the total number of counts ariving at the both counters in a two-arm configuration.

The non-ergodic interpretation will predict that $N(1)=n_{max}/2$ and will only converge to n/4 after m measurements ($m<<K$). Also it predicts that $N(K+1)=n/2$ and will only converge to n_{max} after m measurements. Figure 3 summerizes these results. In the figure we have taken $n_{min}=0$ for simplicity (so $n=n_{max}$) and have also normalized the counts, that is the y-axis gives the percentage of the total counts at Counter 1. Observe the dramatic difference between the predictions for the first counting interval just after closing or opening the arm (See Comment 1 in the next section.). Note that the non-ergodic interpretation has no structure to predict a value for m (the rapidity of the convergence). Such information must come from experiment. It must depend on various factors which include the coherence and intensity of the beam. The lower the intensity and the less coherent the beam the greater m must be.

IV - COMMENTS

Here we make some miscellaneous comments.

1. In the above we have assumed that n was approximately one neutron per counting interval T in order to be sure that we will see the individual behavior of the neutrons. n depends on both the beam intensity and T, of course. If one detected at least 50% of the neutrons that pass the interference region, then N(k) would be giving the average behavior of every two neutrons in the worse case. These would be ideal conditions. If n were in the hundreds then the experiment could not be considered crucial since m could conceivably be this small.

2. It does not seem possible to obtain an estimate of m from published data in neutron interference experiments. For example, if one knew that there were n_{Total} neutrons collected in an entire experimental run, then this would give an upper limit on m since nm could only be a small percentage of n_{Total}. One never or rarely obtains data from the entire physical experimental run. This is because of warm-up effects and intrinsic in the manner in which an apparatus is aligned. One usually finishes aligning an apparatus by verifying that interference is obtained. This would preclude seeing the effect we are discussing. Of course, this and other important or crucial information may be known to experimentalist.

3. It is known that one sees an interference pattern with as few as 10 neutrons. This is, of course, perfectly consistent with the non-ergodic interpretation for the reason mentioned in Comment 2, unless it were known that the interference was indeed obtainable for the very first 10 neutrons of the experimental run.

4. Estimation of S and K. In an ideal experiment one may obtain an estimate of S (and K) by using the Central Limit theorem as follows. We may think of each N(s,k) as a random variable defined over our quantum mechanical ensemble. Then N(k) is a sum of S random variables. These random variables are always implicitly considered independent and identically distributed in any ensemble interpretation. Let us drop the index k to simplyfy our expressions, and let N represent any of the N(k). So we may write

$$N \equiv (\Sigma_{s=1}^{S} N(s))/S \tag{1}$$

We want to estimate an S such that

$$\Pr\{|N-n| < \delta|\} > P_o \tag{2}$$

where n≡⟨N⟩, the ensemble average of N. We might want to choose

$$P_o = .95 \quad \text{and} \quad \delta = .05, \tag{3}$$

for example. Since the N(s) are independent and identically distributed, we may use the Central Limit theorem. That is, we may use

$$\Pr(\mid (\Sigma_s N(s) - Sn)/\sigma S^{1/2} \mid < x) \cong 2\phi(x) - 1 \tag{4}$$

to estimate S. ϕ is the error function and

$$\sigma^2 \equiv \mathrm{Var}(N(s)) \tag{5}$$

for any s. The sum in Eq. (4) is from 1 to S. We may then rewrite Eq. (2) as

$$\Pr\{ \mid (\Sigma_s N(s) - Sn)/\sigma S^{1/2} \mid < \delta S^{1/2}/\sigma \} > P_o. \tag{6}$$

To satisfy this we must choose an S such that

$$2\phi(\delta S^{1/2}/\sigma) - 1 > P_o \tag{7}$$

Using the value of P_0 of Eq. (3) in a table of Φ gives

$$\lambda S^{1/2}/\sigma > 1.96 \quad (8)$$

or

$$S > (1.96\sigma/\lambda)^2 \quad (9)$$

$$= 1536\sigma^2 \quad (10)$$

where we have used the value of λ of Eq. (3). σ^2 may be obtained from experiment. If we could assume that the N(s) are Poissonian distributed then we would know that

$$\sigma^2 = n \quad (11)$$

and therefore

$$S > 1536n. \quad (12)$$

If n=1 then S must be greater than 1536 in order to guarantee a measurement of N that satisfies Eq. (1) with our various assumptions (i.e., in order to make a measurement of N within a precision of .05 of its true average with a probability greater than .95). The same estimate would apply to K. It is not necessarily valid to apply this estimate to a real laboratory experiment.

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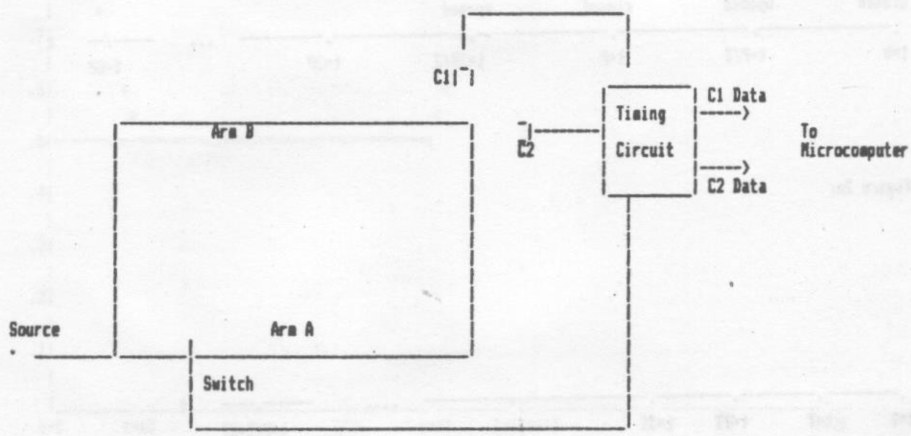

Figure 1: A Mach-Zehnder interferometer. C1 and C2 are two counters (Counters 1 and 2 respectively) which are positioned at the maximum and minimum of the interference pattern. The switch closes and opens Arm A with a cycle time of P seconds. The timing circuit permits us to unambiguously know if Arm A was open or closed for each of the detected neutrons.

```
arm is          arm is          arm is          arm is          ...
closed          opened          closed          opened
.---------------.---------------.---------------.---------------.----------  ...   -----.--   t
t=0             t=P/2           t=P             t=3P/2          t=2P                    t=SP
```

Figure 2a:

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.---------.---------.---------.------------------------   ....    ------.----    t
t=0       t=T       t=2T      t=3T                                t=P/2=KT
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Figure 2b:

Figures 2a and 2b: The figures summarizes the relationship between P, S, T and K. The single experimental run is divided into S cycles of length P seconds. Each cycle consists of Path A of Figure 1 being closed (opened) for K intervals of T seconds each. The entire experimental run is SP seconds long. Part b of the figure is just an enlarged scale to see the smaller time intervals T. KT=P/2, T << P

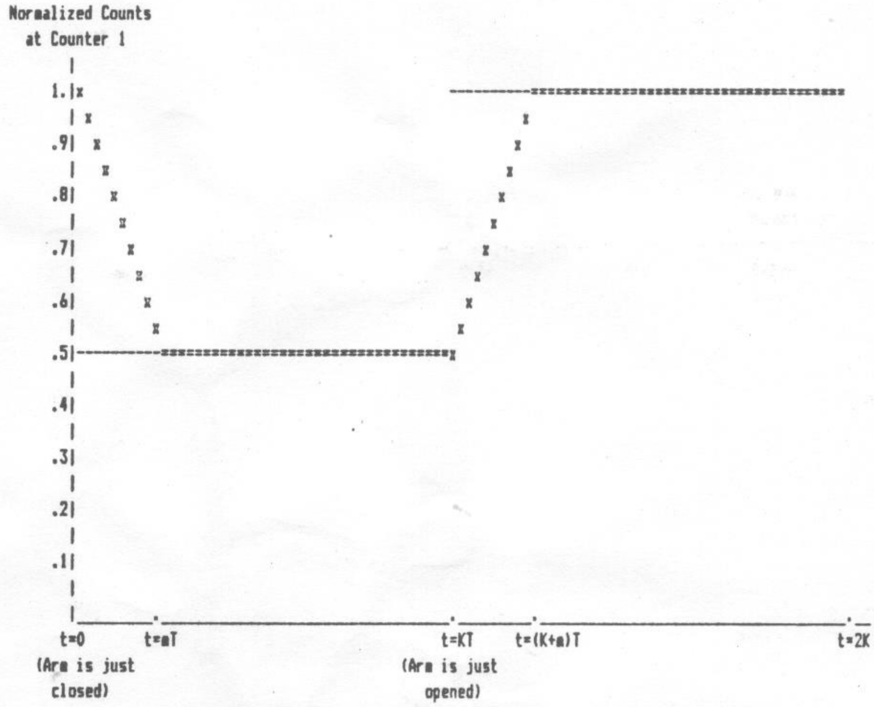

Figure 3: The average normalized number of counts at Counter 1 of Figure 1 in the time intervals [kT,(k+1)T] as predicted by the non-ergodic and the usual interpretations (i.e. any ensemble interpretation). The "===" curve is where the interpretations agree. The "---" curve gives the predictions of the usual interpretations alone, and the "xxx" curve gives the non-ergodic predictions alone. Here we have taken $n_{min}=0$ for simplicity. So all the neutrons are detected at Counter 1 at the two-arm configuration. The horizontal axis is in units of T seconds. m is the number of intervals of time T for the medium to become re-conditioned. No criteria for m is known. The "xxx" curve is shown as a straight line, but its shape is not known.