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A COINCIDENCE EXPERIMENT OF TWO COHERENT BEAMS OF THERMAL NEUTRONS

M. Iannuzzi and V. Merlo

Istituto Nazionale di Fisica della Materia and Dipartimento di Fisica, Università di Roma "Tor Vergata," Roma, Italy

A. Paciaroni, C. Petrillo, F. Sacchetti

Istituto Nazionale di Fisica della Materia and Dipartimento di Fisica, Università di Perugia Perugia, Italy

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A beam of thermal neutrons is divided in two components by means of a Ge crystal and the time-coincidences of the particles of the two components are recorded. The experimental results are compared with the theoretical predictions of different interpretations of the wave function in quantum mechanics: the statistical particle interpretation, and the pure-wave and stochastic wave-particle interpretations without wave-packet reduction. Unambiguous experimental evidence is thus obtained in favour of the statistical particle prediction and against the other predictions.

Key words: quantum mechanics, wavefunction interpretation, thermal neutrons.

1. INTRODUCTION

The statistical particle (or particle ensemble) interpretation of quantum mechanics assumes that the wave function ψ is a statistical state function describing an ensemble of similarly prepared systems, in contrast with other interpretations in which the wave function provides a description of an individual system. In particular, these latter inter-

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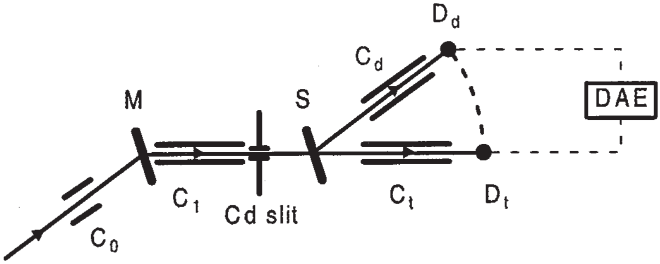

Fig. 1a. Schematic drawing of the experimental setup with the monochromator, **M**, and the beam splitter, **S**, in double-crystal non-dispersive configuration. The two ^{3}He detectors, $\mathbf{D}_t$ on the transmitted beam and $\mathbf{D}_d$ on the diffracted beam, are mounted on a circular frame (dashed line). The collimations C_0 (in pile), C_1 (monochromator-splitter), C_t and C_d (transmitted and diffracted beam) are shown. The Cd double slit is sketched. The short-dashed line is the connection of detector outputs to the Data Acquisition Electronics (DAE).

pretations may assume that either ψ is a wave field associated with the individual particle or the individual particle is identified with ψ. Since the comprehensive and influential article of Ballentine on this subject [1], the study of the interpretations of quantum theory has expanded by many theoretical contributions; by contrast, no real experiment has been performed up to-date on massive particles to distinguish rival interpretations. Actually, there are both general theoretical arguments [2] and pioneering experimental results on photons [3] which suggest that the correct interpretation of ψ is as a statistical state function. However, we believe that it is necessary to perform the experiment also on *massive* particles.

In this letter we describe a coincidence experiment of two beams of thermal neutrons, whose conceptual scheme is that proposed in Ref. [2]. The experimental setup is shown schematically in Fig. 1a. According to Ballentine, the results to be expected in each of three interpretations (the first two being the two interpretations recalled above in which the wave function describes an individual system) are, almost with his wording:

(a) The particle is identified with the wave packet. Then, each packet is divided in two components (for instance, half of the amplitude being transmitted and half deviated), and the two (ideal) detectors will be triggered simultaneously. The coincidence-counter will record a number of coincidences equal to the number of wave packets impinging on the beam splitter. Really, by taking into account the conservation rules, we shall see below that the predicted coincidences are just half such a number.

(b) The wave packet is a physical field associated to the individual particle, not directly observable but however influencing stochastically the detectors D_t and D_d. At the beam splitter, the wave packet divides between the transmitted and deviated components, and the probability of D_t recording a count during the interval τ is $r_t\tau$ (r_t is the average rate of the transmitted wave packets), while the probability for D_d is $r_d\tau$ (r_d is the average rate of the deviated wave packets). More in general, if the detectors do not interact and their separation is much greater than the extension of the two wave packets, the triggering of D_t and D_d are independent events, and the probability of recording a coincidence is $p_t p_d = (r_t\tau)(r_d\tau)$. The condition $r\tau << 1$ must apply to the experiment in order to minimize the probability of having two particles within the time interval τ in the incident beam, whose average rate is r.

(c) For the particle ensemble interpretation, a single particle incident on the beam splitter cannot be two places at once, and thus the probability of a coincidence will be zero.

We note that, while the theoretical prediction for the coincidence probability in interpretation (c) can be considered quite obvious, the conceptual framework for the theoretical predictions of interpretations (a) and (b) needs be clearly stated. We shall therefore discuss more in detail and separately the latter two interpretations, which, as it has already been reminded, are particular and possible versions of the same general assumption according to which a pure state provides a complete description of an *individual* system.

In the pure-wave interpretation (a), the theoretical prediction for the coincidence probability (i.e., coincidence rate equal to wave-packet rate at the beam splitter) derives straightforwardly from the general assumption above, if the postulate of "reduction of the state vector" at the collimators C_d and C_t is *not* invoked. Actually, this postulate is more common in the older literature on quantum mechanics, but it is rarely presented in the more recent literature. The reason is that the concept of reduction of the state vector creates serious problems in the quantum measurement theory, and it has been criticized by many authors on theoretical grounds. Let us quote very briefly from two of them. For H. Margenau [4]: "The statement is objectionable, first because of its failure to point out to the most important aspects of a measurement,...." For J.S. Bell [5]: "There are, ultimately, no mechanical arguments for this process, and the arguments that are actually used may well be called moral," ... "It remains true that, whenever is done, the wave packet reduction is not compatible with the linear Schrodinger equation." Ballentine, in Ref. [6] and in Chap. 9 of his book (Ref.[2]), gives a clarifying account of the subject, showing that the postulate is untenable in an unambiguous formulation of quantum mechanics. With the omission of wave-packet reduction (such an omission is correct, in our opinion), prediction (a) is readily obtained for ideal detectors. Yet a conceptual difficulty concerning the conservation rules remains with this interpretation: it seems to violate conservation of particle number, because when one particle impinges on the beam splitter then two separate (ideal) detectors will be triggered. In other words, since the wave function describes an *individual* particle and there is (ideally) one particle at one time in the apparatus, the occurrence of coincidences may violate the conservation rules on an event-by-event basis. However, in similar cases, particle number and energy can still be conserved *on the average*, as pointed out long ago [7]: in some events two detectors are triggered, while in others none are triggered. By adopting such point of view, for ideal detectors and splitters, the predicted coincidence rate is half the rate of the incident wave packets, and this will be taken in the following as prediction (a).

We have seen that in interpretation (b) the probability of recording a coincidence is $(r_t\tau)(r_d\tau)$. We may also mention that there exists a very particular version of this interpretation, namely the "empty" de Broglie pilot wave, which predicts different effects; however, recent experiments on photons have not supported such version [8-9]. For the discussion that will follow on the experimental results, we wish to comment that in a real experiment random accidental coincidences will always be present even for a Poissonian source of very weak intensity, because of the possible simultaneous emission (empirically, emission within the resolving time of the apparatus) of two or more particles. The coincidence rate of such events is the intrinsic background rate (noise) of the experiment. As we shall discuss in the experimental section, in our measurements the predicted rate of such coincidences was exactly 0.5 times lower than the one-particle theoretical rate of interpretation (b).

We wish also to comment that we have not discussed above experiments of neutron interferometry [10] because they concern spatial first-order correlation-effects, and cannot therefore distinguish between different interpretations of the wave function; whereas we measure temporal intensity correlations, which can yield such information.

Concluding the introduction to the present experiment, we may remark that Ballentine, in setting forth the hypothetical interpretations (a), (b), and (c), has used a neutral language which does not indicate any preference for or against each of them. In particular he has considered interpretations (a) and (b) essentially because they have been taken for granted "in the older literature on quantum mechanics, although they are often implicit and not formulated explicitly" [2]. Thus, some of the interpretations can indeed be criticized on purely theoretical grounds, but this does not obviate the need for an experimental test.

The three predictions (a), (b), and (c) are different, and coincidence measurements should be able to distinguish between them: in particular, the dependence of the coincidence rate on the incoming intensity at the beam splitter in (a) should be linear, in (b) should be quadratic, in (c) should be zero. Motivated by the above discussion, we have performed the experiment described below using thermal neutrons at the 1 MW TRIGA Reactor in Rome.

2. EXPERIMENTAL SETUP

A schematic drawing of the experimental setup is shown in Fig. 1a. The apparatus was installed on one of the central channels of the reactor. In-pile collimation (C_0) was 0.5°. A monochromatic beam of thermal neutrons, produced by Bragg diffraction from selected planes of a Ge single crystal set in symmetric transmission was collimated by means of a Soller slit (C_1), 0.5° angular divergence. An adjustable Cd double slit with 25 mm x 40 mm maximum dimension was used to define the beam size. During the measurements, the width of the slit was changed to vary the incoming beam intensity, but never exceeding 6 mm in order the beam width be smaller than the detector size. A second Ge single crystal was inserted along the path of the neutron beam, 50 cm from the exit hole, and operated at the same Bragg order as the monochromator. The two Ge crystals were configurated in parallel (or non-dispersive) arrangement. Thus, the second crystal operates as a beam splitter which either transmits without deflection or deviates according to the Bragg law all neutrons impinging on it, with probabilities α_t^o and α_d^o respectively. The deviation angle was fixed at 36°. Transmitted and deviated neutrons were collected by two identical ^{3}He detectors (1.27 cm diameter, 40 mm active length at 20 Atm. pressure) mounted on a circular frame of 57.3 cm radius, at the same distance from the crystal and with a relative separation of 36 cm on the circumference. Of course, such a separation is much greater than any coherence length or interaction distance in the experiment. ^{3}He detectors were chosen because they are thin detectors with high efficiency in the whole range of thermal energies. More precisely, since the ^{3}He absorption cross section is 5000 b at a neutron velocity of 2200 m/s and follows the simple v^{-1} law in the thermal region, the efficiency of the detectors was always in excess of 60% in the present experiment. Two Cd Soller collimators (C_t and C_d), 1 cm wide and 4 cm high, were placed in front of both detectors. By this arrangement, identical flight paths for transmitted and diffracted neutrons were obtained. Monochromatic neutrons were selected by the first Ge crystal with a relative wavelength spread $\Delta\lambda/\lambda \simeq 1.3 \times 10^{-2}$. For the following discussion on the experimental results, it is helpful to notice that the neutron beam exiting the collimator C_1 (and each of the two beams exiting the collimators C_t and C_d) had one preferred direction, with a divergence angle $\leq 0.5°$. The width of each beam was <1 cm and the detector aperture was $\simeq$1.2 cm. Then the angle subtended by the detector was comparable with or greater than the beam divergency angle. The solid-angle efficiency of the detectors, with reference to the

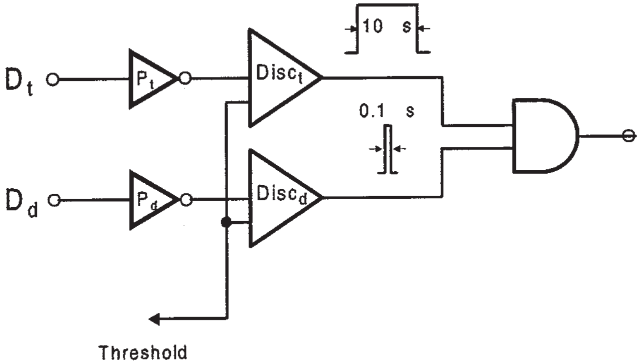

Fig. 1b. Block diagram of the DAE setup consisting of two identical preamplifiers, P_t and P_d, and discriminators, $Disc_t$ and $Disc_d$, set at the same threshold. The output from the discriminators is sent to an AND logic. The lengths of the output pulses are schematically shown.

number of neutrons exiting the collimator C_1 was thus of order unity.[1]

The measurements were carried out by using the data acquisition system shown schematically in Fig. 1b. Two identical preamplifiers and shapers were used for the two detectors. A dead-time of $\simeq 10\mu s$ was associated to the shaper and the readout electronics. The system,which allowed for collecting data with high statistics, was based on the hardware detection of coincidences within a given time window. The counting rates of the two detectors, as well as the appearance of a signal on D_d (or D_t) within a time-delay τ_t (or τ_d) with respect to a signal collected by D_t (or D_d), could be measured; τ_t and τ_d were set at 10 μs and 0.1 μs respectively. Both the Ge crystals were operated on the (311) Bragg reflection giving a negligible half-wavelength contamination and an incoming neutron wavelength $\lambda = 1.05$ Å.

3. EXPERIMENTAL RESULTS

The number of measured coincidences is the number to be compared with the theoretical predictions of interpretations (a), (b), and (c).

[1]We wish to comment that the present experiment involves a one-particle state, the state which emerges from the collimator C_1. In order to ensure the realization of such a well-collimated one-particle state, the collimator C_0 was 4m long. Both our calculations and experiment are concerned *only* with this collimated state. Differently, the experiment described in Ref. [3] involves a two-particle state, both members of which must be detected. This generally requires a 4π detector, which conversely is not necessary in our experiment.

Preliminarily, we wish to comment that the probability that the beam will contain more than one neutron within an arbitrary short time-interval is quite small, but not zero. Actually, if r is the neutron rate of the incoming beam, the *average* number of neutrons in the time interval τ is equal to $r\tau$. Then, according to the Poisson distribution, there is always a finite probability p_k of detecting k neutrons within such time interval:

$$p_k = \frac{(r\tau)^k}{k!} e^{-r\tau}. \tag{1}$$

Therefore, even in the absence of correlated coincidences of the single-particle state, the two detectors will be triggered simultaneously, i.e., within a time interval equal to τ, at the background rate (or noise):

$$r_n = \frac{r_t r_d \tau}{2} \tag{2}$$

where $r_t = \alpha_t r$ and $r_d = \alpha_d r$ are the average counting rates of the single detectors, with $\alpha_t = \alpha_t^o \eta_t$, $\alpha_d = \alpha_d^o \eta_d$; and η as the detector efficiency. Eq. (2) is obtained from Eq. (1) by assuming $r\tau \ll 1$, which is always very well satisfied in the present measurements, and by calculating $p_{k=2}$. (The probabilities of having three or more particles within the time window τ can be safely neglected). Moreover, we have taken into account that every simultaneous occurrence of two particles behind the beam splitter produces one of four possible processes beyond the crystal: 1) both particles in the transmitted beam; 2) first particle in the transmitted beam and second particle in the diffracted beam; 3) first particle in the diffracted beam and second particle in the transmitted beam; 4) both particles in the diffracted beam. The four processes have probabilities α_t^2, $\alpha_t\alpha_d$, $\alpha_d\alpha_t$ and α_d^2. Since the scheme of the experimental coincidence circuit is that shown in Fig. 1b, it is readily seen that only processes (2) and (3) can trigger the system,with time-windows τ_t and τ_d respectively, and $\tau = \tau_t + \tau_d \simeq \tau_t = 10\mu s$.

As we have previously discussed, the coincidence rates according to the prescriptions (a), (b) and (c) are, respectively: $r_a = (r_t + r_d)/2$, $r_b = (r_t r_d)\tau$; $r_c = 0$. Obviously, by taking into account the beam intrinsic noise given by Eq. (2), the more correct prediction (c) becomes: $r_c = r_n$.

The results obtained at different neutron rates r are shown in Fig. 2 by using *x-scales* appropriate to clear visualization of the comparison between the different interpretations of the wave function. Within the experimental errors, the present high-statistics measurements show that the coincidence rate is always zero independently of the beam intensity. We wish to comment explicitly that the characteristic form of Eq. (2) is the direct consequence of the presence in the beam exiting C_1 of two particles emitted simultaneously from the source. Differently, in the case of two independent beams with rates r_t and r_d, the coincidence rate within a time window τ is simply given by $(r_t r_d)\tau$. Thus,the

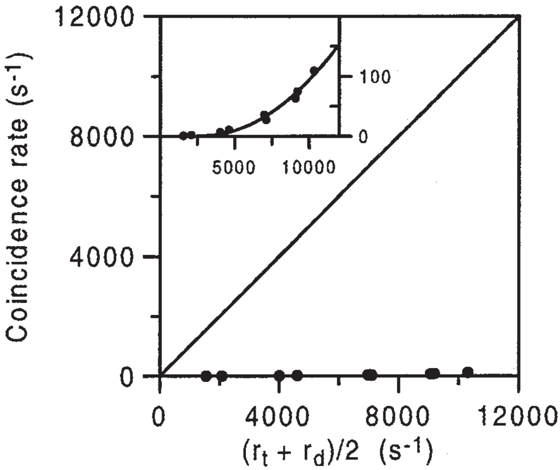

Fig. 2a. Coincidence rate as predicted by interpretation (a) (full line) in comparison with the present experimental data (dots). The data are shown on an expanded y-scale in the inset.

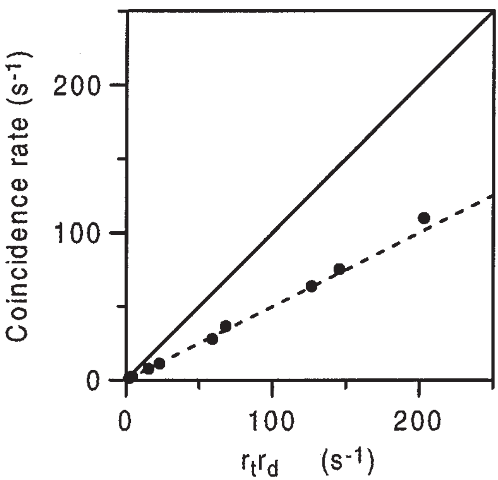

Fig. 2b. Coincidence rate as predicted by interpretation (b) (full line) in comparison with the present experimental data (dots). The dashed line is the calculated background rate (see Eq. 2), which also represents interpretation (c) (see text).

former case produces a coincidence rate which is 0.5 times smaller than the latter. The results shown in Fig. 2 exclude predictions (a) and (b) with high accuracy, and confirm prediction (c) beyond question.

We have already remarked that, in the opinion of many authors,with which we agree, the reduction postulate is untenable in an unambiguous formulation of quantum mechanics. We can now observe that the results of the present experiment,confirming the prediction given by Eq. (2), may also be explained by interpretation (a) together with the assumption of wave-packet reduction at the collimators C_t and C_d with collapse probabilities (including the detector efficiency) given by α_t and α_d respectively. However, such an approach, especially if confronted with the straightforward interpretation (c), would imply unnecessary and superfluous conceptual difficulties,as discussed in [2] and [6].

In conclusion, we believe to have shown unambiguously that, among the three rival interpretations of the wave function, only the statistical particle interpretation is consistent with the experiment.

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