Neutrons as quantum objects

Helmut Rauch
Atominstitut, Vienna University of Technology, Vienna, Austria

Neutrons are proper tools for testing basic laws of quantum physics since they are massive and can be handled and measured with high efficiency. Suitable post-selection experiments demonstrate coherence features of sub-ensembles even when the whole ensemble seems to have lost its coherence. All experiments have the capacity to explain more details by additional pre- and post-selection methods. It will be shown that specific losses are unavoidable in any interaction. Coherence and decoherence are intrinsic quantum effects and can shed light on the measurement problem. Quantum contextuality is a consequence of the entanglement of different degrees of freedom. This makes quantum phenomena more strongly correlated than classical ones. Most experiments have been performed with perfect neutron interferometers and some others by using ultracold neutrons and spin-echo systems. An event by event based interpretation can also be brought into agreement with the experimental results. In many cases parasitic beams carry the same information as the main beam and this relates such measurements to “weak” measurements. The coupling and entanglement of various parameter spaces guide us to a more elaborate discussion of quantum effects.

1. Introduction

The ongoing discussion about the interpretation of quantum physics which oscillates between very mystic and more rational interpretations. John Bell contributed to this discussion and made very useful proposal for related test measurements (Bell 1987). In this paper it will be shown that in all experiments there are some kinds of hidden observables mainly because not all pre- and post-selection possibilities are utilised and average values are measured where more detailed investigations would be possible. In this respect we discuss neutron experiments where the particle and wave features are essential and where one can show that much more information can be extracted by using more sophisticated measurement methods. This will be demonstrated by means spatial-, momentum-, time- and polarization post-selection experiments. We will also demonstrate that unavoidable quantum losses may play an important role in the interpretation of the quantum to classic transition. These losses can be used as weak measurements to obtain basic information about the main object without interacting with it. In some sense the analysis follows the pragmatic access of Englert (2013) who showed how quantum phenomena can be explained when one follows strictly the state of knowledge one gains from an experiment starting from a few up to a high number of events and where the averaging procedure becomes more reliable. In this respect one includes the measurement time, or the number of particles used, into the analysis.
Our approach uses neutron interferometer experiments where two coherent neutron beams are produced by dynamical Bragg diffraction from a perfect silicon crystal and they are superposed at the exit crystal plate and exhibit all well-known interference phenomena (Fig. 1; e.g. Rauch and Werner 2015). Since one deals with a stationary situation one can use the time-independent Schrödinger equation and gets for the beams behind the interferometer a superposition of beam I and II which are transmitted-reflected-reflected $\psi^\text{rrr}$ and reflected-reflected-transmitted $\psi^\text{rrt}$ respectively. From symmetry follows that they are equal in intensity and phase. A phase shift $\chi$ can be applied, which is given by the index of refraction of any material and related to a spatial shift $\Delta$ ($\chi = \Delta/K$).

$$I_0 = |\psi_I + \psi_g|^2 = |\psi^\text{rrr} + \psi^\text{rrt} e^{i\chi}|^2 = |\psi_0|^2 \left(1 + |\Gamma(\Delta)| \cos \chi\right)$$

(1)

$\Gamma(\Delta)$ denotes the coherence function, which defines the coherence lengths $\Delta_c$ as its characteristic dimension and is related to the size of the wave packets involved

$$|\Gamma(\Delta)| = \left|\langle \psi(0)\psi(\Delta) \rangle \right| \propto \left|\int g(\vec{k}) e^{i\vec{K} \cdot \vec{r}} d\vec{k}\right|$$

(2)

For Gaussian beams with momentum widths $\Delta k$ one obtains

$$|\Gamma(\Delta)| = \exp\left[-(\Delta k)^2/2\right]$$

(3)

where $g(\vec{k})$ is the momentum distribution. In an experiment Eq. (1) can be approximated by

$$I_{\text{exp}} = A(1 + V \cos(\chi + \varphi))$$

(4)
Fig. 2: Wave packet (above) and partial waves (below).

$V$ denotes the visibility of the interference pattern and $\varphi$ an internal phase caused by some small deviations from the perfectness of the crystal or due to external effects like gravity or magnetic fields. In practice high visibilities (up to 95%) and high order interferences (up to 200th) have been observed.

2. Analysis of the parameters in Eqs. 1-4

All parameters of Eqs. 1-4 are average values over the beam cross section, the momentum distribution and the measurement time. In the following sections we intend to analyse the various parameters of the equations shown above. We try to show in the following sections how they can be specified by various post-selection experiments.

2.1 Wave function – momentum post-selection

The wave function follows from the solution of the time-independent Schrödinger equation and can be written for free space motion as a wave packet centred around $k_0$ with a width. For Gaussian shaped beams this can be written as

$$ -\frac{\hbar^2}{2m} \Delta \psi = E \psi $$

(5)

$$ \psi(r) \propto \int a(k)e^{ikr} dk \propto \int e^{-(k-k_0)^2/2\xi^2} e^{ikr} dk $$

(6)

which is an eigenvalue solution for the freely moving particle. $a(k)$ denotes the amplitudes of the coherently superposed partial waves and $|a(k)|^2$ the momentum distribution function as used in Eq. 2. Whereas the wave packet is localized within a region compatible with its coherence length.
Fig. 3: Sketch of a feasible momentum post-selection experiment using various monochromaters (1, … n) to observe wave features and where the intensities can be summed up to reach I₀, i.e. a situation which permits beam path (particle) information.

(Δ, Δk ≥ 1/2) the partial waves are arbitrarily widely spread as shown in Fig. 2. That means that information about the particle exists even far away from the packet. This has to be taken into account when non-locality effects are discussed (e.g. Rauch 1993). Proper momentum post-selection measurements have made these partial waves visible by applying additional monochromatization (Kaiser et al. 1992, Rauch et al. 1996). This shows how more information can be extracted by means of more sophisticated experimentation. Fig. 3 shows an arrangement where some of these far reaching components of the wave functions can be analysed and fringe visibility can be preserved although the beam I₀ without additional monochromator crystals and the artificially summed up intensity (∑ₙ Iₙ) of all measuring channels do not show interference features at all. This means that one can decide after the measurement whether one is more interested in wave features (individual channel intensities) or particle features (summed up intensity). This has to be discussed on the basis of the Greenberger-Englert duality relation which treats wave and particle properties as a duality system where the particle feature is determined by the path distinguishability (Pₚ) and the wave features by the visibility (V) of the interference pattern (Greenberger and Yasin 1988, Englert 1996). This indicates that a single particle system can exhibit far reaching features outside its wave packet range and that a two or many body system never separates when it has a common origin.

$$Pₚ^2 + V^2 ≥ 1$$  \( \tag{7} \)
2.2 Beam cross section and wave packets – position post-selection

As mentioned above the size of the wave packet is given by the Fourier transform of the momentum distribution function (Eq. 6) and can be determined from the measurement of the coherence function (Eq. 2), i.e. from the decrease of the visibility at high interference order (Rauch et al. 1996). For a neutron interferometer situation the coherence lengths are different for the various directions due to the different momentum distributions ($\Delta_{\text{longitudinal}} = 100 \text{Å}$, $\Delta_{\text{vertical}} = 50 \text{Å}$, $\Delta_{\text{transverse}} = 20 \mu\text{m}$), which are much smaller than a typical beam cross section ($\approx 1 \times 2 \text{ cm}$). When one considers the available intensity of about $10^4$ neutrons/second one notices that one deals with single particle interference and there is no interaction between successive neutrons besides the fact that they are shaped by the same monochromators, collimators and crystal reflections. Thus a situation as shown in Fig. 4 exists where the wave packets of the individual neutron do not overlap at all, but plane wave components do when more than one neutron passes at the time, which is very seldom the case.

The intensity and the coherence features vary across the beam cross section and therefore the parameters of Eq. 4 vary as well, as shown in Fig. 5. This is a position post-selection result when a position sensitive detector is used to scan the intensity, the contrast ($V$ or $\Gamma(\Delta)$) and the internal phase ($\phi$) of the interference pattern. One notices that the measured interference pattern depends on the size and position of the aperture used. One can also measure the momentum distribution at any position and will notice some differences. This means that the wave-functions are different at any position of the aperture, but they are similar to each other which permits the definition of a mean wave-function for any beam. One should keep in mind that in any experiment an average is taken over aperture area and various momentum distributions at any position within the beam cross section. This underlines that the wave packet features are determined by the apparatus only but each neutron of the beam experience a similar history which causes common features and determine the coherence properties of the beam.

![Fig. 4: Sketch of wave packets within the neutron flight path](image-url)
Fig. 5: Result of a position post-selection experiment showing the contrast (left) and the internal phase (right) across the beam cross section.

2.3 Time – post-selection

Neutron choppers can be used to measure the velocity distribution of the beam by means of time-of-flight methods. These methods are similar to the momentum post-selection methods discussed in Sec. 2.1 (Rauch et al. 1992, Jacobson et al. 1996). The energy-resolved interference pattern show a higher visibility than the full beam. A classical analysis of the data is possible as long as the resolution time of the chopper is larger than the coherence time of the beam (5 µs compared to 10 ns).

Another method measures the arrival time of each neutron. For a thermal (Poissonian) beam the probability to measure a neutron within a time interval \( t \) after another neutron has arrived is given by (Glauber 1968)

\[
W(t) = I e^{-t/\tau} \quad (8)
\]

This is shown in Fig. 6 (Zawisky et al. 1994). When measuring two neutrons arriving within short or long time intervals one can achieve a considerable higher contrast and phase sensitivity than analysing the full beam only. Since arrival time measurements can be implemented quite easily this opens a new possibility to improve experimental results. A more complete analysis has been given on the basis of a Bayes estimation by Rehacek et al. 1999. The mean time interval between two arriving neutrons is given by \( \bar{\tau} = 1/f \). One notices that for “long” pairs the contrast always reaches nearly 100% and that the interference pattern becomes shifted by \( \pi \).
Fig. 6: Arrival times of neutrons and short pair and long pair arrivals (left), measured interference pattern for the overall beam and the short and long pair arrivals (middle) and the measured and calculated contrast and sensitivity (right).

3. Unavoidable losses

In many cases losses during a quantum measurement are neglected and treated as caused by experimental imperfections only. Here we deal with unavoidable losses caused by the theory itself. Such losses may become important for the understanding of quantum decoherence and the quantum measurement process (Zeh 1970, Zurek 1981, Joos et al. 2003). It will be shown that not only dissipative interactions cause an irreversible change of the wave-function, but deterministic ones can cause such a change too. We start with the phase echo experiment where a large positive phase shift should be compensated by a large negative one. This has been verified to a high degree (Clothier et al. 1991), but a closer look shows that each phase shifter causes additional back and forth reflections as indicated in Fig. 7. When the energy of the particle $E$ is much larger than the height of the barrier ($V$) and its thickness produces phase shifts larger than the coherence length of the beam the reflectivity can be written as (e.g. Cohen-Tannoudji et al. 1977)

$$R = \frac{1}{2} \left( \frac{V}{2E} \right)^2.$$  \hspace{1cm} (9)

For thermal neutrons this is very small ($10^{-10}$) but unavoidable even when specially shaped barriers are taken into account. It should be mentioned that the same information which exists in the main
beam \((D_1)\) is available in the parasitic beams \((D_2 – D_{20})\). This relates such measurements to “weak” measurements (Aharonov et al. 1988, Dressel et al. 2014). The measurement period may be much longer but that does not enter the analysis and there is no method to retrieve all components into the original beam.

4. Discussion

These measurements and their analysis have shown that many coherence properties of a beam can be retrieved by various post-selection methods. Nevertheless a complete retrieval cannot be achieved due to unavoidable losses. These losses need not be caused by dissipative forces but can also be caused by unavoidable quantum losses. Thus irreversibility seems to start with the first interaction the system experiences and can take place at any time scale. In this respect irreversibility and the related measurement process seems to be part of the quantum formalism as stated by Englert (2013). Wave and particle features (interference and beam path) are related according to Eq.7 and they can be taken as a two level system which can be entangled in a contextual sense. This shows that quantum physics involves more entanglements and makes the world and the human being more correlated than classical physics.
References:

Aharonov Y., Albert D.Z., Vaidman L. (1988) Phys. Rev. Lett. 60, 1351

Bell J.S. (1987) „Speakable and unspeakable in quantum mechanics“, Cambridge University Press

Clothier R., Kaiser H., Werner S.A., Rauch H., Wölwitsch H. (1991) Phys. Rev. A44, 5357

Cohen-Tannoudji C., Diu B., Laloe F. (1977) “Quantum Mechanics”, Vol. 1 (John Wiley & Sons, N.Y.)

Dressel J., Malik M., Miatto F.M., Jordan A.N. (2014) Rev. Mod. Phys. 86, 307

Englert B.-G. (1996) Phys. Rev. Lett. 77, 2154

Englert B.-G. (2013) Eur. Phys. J. 67, 238

Glauber R.J. (1968) „Fundamental Problems in Statistical Mechanics“, Ed. E.G.D. Cohen (North Holland)

Greenberger D.M., Yasin A. (1988) Phys. Lett. 128, 391

Jacobson D.L., Allman B.E., Zawisky M., Werner S.A., Rauch H. (1996) J. Jap. Phys. Soc. A65, 94

Joos E., Zeh H.D., Kiefer C., Giulini D., Kupsch J., Stamatescu I.-O. (2003), „Decoherence and the Appearance of a Classical World“, 2nd Ed. Springer, Berlin

Kaiser H., Clothier R., Werner S.A., Rauch H., Wölwitsch H. (1992) Phys. Rev. A45, 31

Rauch H. (1993) Phys. Lett. A173, 240

Rauch H., S.A. Werner (2015) „Neutron Interferometry“, Clarendon Press, Oxford

Rauch H., Wölwitsch H., R. Clothier, Kaiser H., Werner S.A. (1992) Phys. Rev. A46, 49

Rauch H., Wölwitsch H., Kaiser H., Clothier R., Werner S.A. (1996) Phys.Rev. A53, 902

Rehacek J., Hradil Z., Zawiska M., Pascazio S., Rauch H., Perina J. (1999) Phys. Rev. A60, 473

Zawisky M., Rauch H., Hasegawa Y. (1994) Phys. Rev. A50, 5000

Zeh H.D. (1970) Found. Phys. 1, 69

Zurek W.H. (1981) Phys. Rev. D24, 1516