The wave function collapse as symmetry breakdown and effect of field quantization

K Lewin

Herderstr. 9, 12623 Berlin, Germany

klauslewin@hotmail.com

Abstract: It is pointed out that ordinary quantum mechanics as a phenomenological theory cannot account for the wave function collapse if it is not seen within the framework of free field quantization which is needed to understand the particle structure of matter during wave packet evolution and to explain the collapse as symmetry breakdown by detection. Deuteron photo decay and the decay of a two-fermion spin singlet state (Bohm’s version of EPR) with subsequent detection of one fermion serve as examples. A projection postulate and superluminal signals are not necessary to understand what entangled states predict.

1. General remarks

Since the violation of Bell’s inequalities [1] by the results of EPR-Bell coincidence experiments during the seventies (see [2]) local realism in the sense of the historical EPR paper [3] classifying QM as incomplete theory had to be abandoned. Completeness of QM in the sense of the Copenhagen interpretation seemed the only alternative. However, long-standing problems like the EPR paradox, the interpretation of the wave function collapse and the discussion of a projection postulate remained. Moreover, Bohm’s version of the EPR arrangement [4] couldn’t be understood without a superluminal correlation (violation of Einstein locality). That contradiction to special relativity induced a discussion about the correctness of the formalism of QM. 1972 P.A.M. Dirac noted: “Nonlocality is against the spirit of special relativity... Certainly, one is not satisfied by such a theory. It seems to me that the problem of compatibility of quantum theory with special relativity is not yet solved”[5].

An essential point of the current discussion is the question of pre-existing quantum numbers before a particle detection, mostly provoked by the thinking of experimentalists. Regarding neutron interferometry H. Rauch remarked 1994: “The question of how the well-defined particle properties of the
neutron are transferred through the interferometer is not a meaningful one in the Copenhagen inter-
pretation, but from the physical point of view it should be an allowed one” [6]. That requires a critical
view on the application of the so called conception of truth as ingredient of the Copenhagen inter-
pretation according to which particle properties that are not directly measurable cannot be a point of physical
discussion (see, e.g. Omnès 1994 [7]). A conceptual view on QM in the sense of a theory describ-
ing an objective reality was discussed, e.g. by Mermin 1998 noting: “QM represents a theory de-
scribing an objective reality independent of observers and their knowledge. Such a theory has to deal
with individual systems because the world contains them. In a nondeterministic world, probability has
nothing to do with incomplete knowledge and ought not to require an ensemble of systems for its
interpretation. The fact that physics cannot make deterministic predictions about individual systems,
does not excuse us from pursuing the goal of being able to describe them as they currently are” [8].
Having in mind this viewpoint in the following, we first consider shortly the
fundamental role of symmetries in QM
and then indicate that particle presence during wave packet evolution is not unders-
tandable if QM is not seen within the frame work of free field quantization [9]. That enables explana-
tion of the wave function collapse as local interaction and symmetry breakdown by detection. The
formalism of QM as complete theory is not questioned and a way to pre-existing quantum numbers is
opened. Concluding we consider two examples favoring the described approach to the conceptual
problems.

2. Symmetries and the group theoretical approach to QM
Sketch of the general group theoretical approach to QM:

\[
\hat{U}(\xi) = \exp[-\frac{i}{\hbar} \hat{p} \xi] \quad (\xi \text{ – translation parameter})
\]

\[
\hat{U}(\alpha) = \exp[-\frac{i}{\hbar} \hat{l}_3 \alpha] \quad (\alpha \text{ – rotation angle })
\]

\[
\hat{U}(t) = \exp[-\frac{i}{\hbar} \hat{H} t] \quad (t \text{ – time parameter})
\]

where \( \hat{p}, \hat{l}_3, \) and \( \hat{H} \) are the group generators with momentum, angular momentum and energy di-
mension, respectively. But a priori these operators do not represent the corresponding dynamical vari-
ables which only appear after taking into account the symmetries of translation, rotation and time in-
variance of the Hamiltonian, in which – via their eigenvalue equations – they introduce definite values
of momentum \( \hat{p} \), angular momentum \( \hat{l}_3 \) and energy \( \hat{E} \). By comparison of coefficients, the infinites-
imal transformations

\[
\hat{U}(d\xi), \hat{U}(d\alpha) \text{ and } \hat{U}(dt)
\]

lead to the fundamental commutation relations (after generalization to three dimensions via some
intermediate steps described in text books) and to the time dependent Schroedinger equation

\[
[\hat{x}_i, \hat{p}_j] = i\hbar \delta_{ij} \quad (i,j = 1,2,3)
\]

\[
[\hat{l}_i, \hat{l}_j] = i\hbar \hat{l}_k \quad (i,k,l \text{ cyclic})
\]

\[
\hat{H}\psi(t) = i\hbar \frac{d}{dt}\psi(t)
\]
Because of the absence of classical initial conditions, the Hamiltonian alone rules the dynamical evolution. Unitary state evolution

\[ U(t,t_0) \psi(t_0) = \psi(t) \]  

(7)

reflects the symmetries

\[ \hat{H}' = \hat{U}^+ \hat{H} \hat{U} = \hat{H} \]  

(8)

of the Hamiltonian in each moment of the dynamical evolution.

The (immaterial) wave function represents the quantum mechanical counterpart to classical trajectories (Einstein’s “ghost waves”, see [10]). Fundamental indeterminacies of dynamical variables replace classical determinism.

3. Particle presence during wave packet evolution

To remove contradictions from QM, particle detections as symmetry breakdown must not be seen as instantaneous events (with future effects [11]) but retroactively concern the whole evolution between preparation and detection (selection of a component of the wave packet). That retroactivity is understandable only by particle presence during wave packet evolution disagreeing with the so called conception of truth of the Copenhagen interpretation. But how to get particle presence in a wave packet theoretically? Obviously field quantization is necessary. A simplified investigation was done in nonrelativistic quantum statistics using box normalization (see appendix of Ref. [9]). The obtained formula

\[ \Delta(\hat{\Psi}^+ \hat{\Psi}) \geq F(n) \xrightarrow{n \to \infty} 0 \]  

(9)

(\hat{\Psi} - field operator, \(n\) - particle number of the quantum statistical ensemble, \(F(n)\) only depends on \(n\)) can be interpreted beyond the conception of truth independently of any detection as growing accuracy of the field intensity if the number of particles having indeterminate dynamical parameters is growing.

Here we only indicate a plausibility consideration: Ordinary QM as a phenomenological theory may be seen parallel to classical electrodynamics being unable to take into account the photon structure of the electromagnetic field (photo effect, Compton effect, …).

Can field quantization open a way to take into account particle presence? In a wave packet

\[ |\psi\rangle = \int d^3 \vec{p} |a(\vec{p})\rangle \exp\left[ i \frac{\hbar}{\mathcal{E}} (\vec{p} \cdot \vec{r} - Et) \right] \]  

(10)

particle presence becomes plausible beyond phenomenological QM if the one-particle state

\[ |a(\vec{p})\rangle = a^\dagger(\vec{p}) |0\rangle \]  

(11)

is seen as the action of a corresponding creation operator on the vacuum state so that the action of the integral operator (wave packet operator) on the vacuum state

\[ \int d^3 \vec{p} a^\dagger(\vec{p}) \exp\left[ i \frac{\hbar}{\mathcal{E}} (\vec{p} \cdot \vec{r} - Et) \right]|0\rangle \]  

(12)
may be reinterpreted as presence of a particle with indeterminate dynamical parameters during wave packet evolution. Consequently, a wave function collapse by detection appears as symmetry breakdown of the former state and as local interaction between the incoming \((a \text{ posteriori} \text{ pre-existing})\) particle and a few detector particles around the detection point. A projection postulate is no point of discussion.

4. **Deuteron decay and retroactive breaking of charge symmetry by proton detection**

We study the decay of a two-fermion bound state into its constituents with detection of one decay fragment. Special example: **deuteron photodisintegration** \(\gamma + d \rightarrow n + p\) with subsequent proton detection. The detection occurs on the inner surface of a detection hemisphere around the decay center whose radius \(R\) is large compared with the radius \(r_c\) of the decay center \(C\): \(R \gg r_c\) (Figure 1). Only electrically charged particles can be detected. To guarantee the disintegration, the photon energy must exceed the deuteron binding energy of about 2.2 MeV but it should be lower than \(\approx 10\) MeV in order to guarantee approximately opposite directions of the nucleon momenta after the decay so that the two-nucleon system may be described by a one-particle system with reduced mass. Figure 1(a) illustrates the evolution of the two-nucleon system after the decay that can be described by the outgoing spherical wave packet (13).

![Figure 1](image_url)

Figure 1: The left part (a) indicates the outgoing spherical wave packet SWP in plane projection describing particle motion between the decay center \(C\) and the detection hemisphere DH with indeterminate space angle, position and momentum. The right part (b) shows the situation after proton detection at the point Q. Now the two nucleon momenta \(\vec{p}_p = -\vec{p}_n\) \(a \text{ posteriori}\) are determined by the detection.
\[ \psi(r, \vartheta, \varphi; t) = \frac{4\pi}{r} \int_0^\infty dp p^2 a(p) \exp \left[ \frac{i}{\hbar} \left( pr - E t \right) \right] \hat{Y}(\vartheta, \varphi) \quad (r = |\vec{r}_p - \vec{r}_n|) \]  

(13)

which is modulated by an angular dependent function \( Y(\vartheta, \varphi) \) of spherical harmonics because of the photon spin and the tensor force in the deuteron ground state.

Before detection no possibility exists to differ between neutron and proton because the deuteron Hamiltonian is ruled by the charge independent strong nuclear force. The complete state of the two-nucleon system between decay and proton detection \( |N_1, N_2\rangle \) factorizes into a space-time state

\[ \psi(\vec{r}_p, \vec{r}_n; t) \equiv \psi(r, \vartheta, \varphi; t) = \langle \vec{r}_p, \vec{r}_n | \psi(t) \rangle \]  

(14)

a spin triplet state \( |\vec{s}_p, \vec{s}_n\rangle = |^3S_1\rangle \) and an isospin singlet state

\[ |^1I_0\rangle = \gamma_2 \left( |J^2_{(L)}\rangle - |J^2_{(R)}\rangle \right) = \gamma_2 \left( |n^\dagger_{(L)} I_{(L)} \rangle |p^\dagger_{(R)} I_{(R)} \rangle - |n^\dagger_{(R)} I_{(R)} \rangle |p^\dagger_{(L)} I_{(L)} \rangle \right) \]  

(15)

with \( |p^\dagger_{(L,R)}\rangle \) and \( |n^\dagger_{(L,R)}\rangle \) as proton and neutron charge eigenstates of a nucleon emitted into the left (L) or right (R) semi-space, respectively (Figure 1b):

\[ |N_1, N_2\rangle = |\psi(t)\rangle \otimes |^3S_1\rangle \otimes |^1I_0\rangle \]  

(16)

As long as no detection occurs, the nucleon charges are not defined because of the entangled state (15). Only a detection (17) records a proton. Figure 1(b) shows an essential deviation from the Copenhagen interpretation: The proton detection in a point Q retroactively breaks charge symmetry

\[ |^1I_0\rangle \xrightarrow{\text{det}} |p^\dagger_{(L)} n^\dagger_{(R)}\rangle \]  

(17)

and the (modified) spherical symmetry of the wave packet by selection of a component of the state (13) determining a proton path (on a macroscopic scale) between the decay center and the detection point and thus indicating a pre-existing proton that explains the quantum mechanical prediction (17) of the entangled isospin state (15) identifying the second nucleon as neutron.

On the other hand, if the detection (in the traditional way) is understood as event without retroactivity, the undetected second nucleon wouldn’t “know” what the entangled state predicts after proton detection – it could not be identified as neutron without a superluminal signal.

In a theory describing an objective reality independent of human observers, the detection (17) appears as breaking of charge symmetry by a local electromagnetic interaction between the incoming proton and a particle/a few particles of the detector around the detection point. That natural view disagrees with earlier measurement theories in which the wave packet would interact with the detector as a whole and then would need a projection postulate.
5. Bohm’s description of the EPR problem and retroactive breaking of spin up – spin down symmetry.

As second example we study Bohm’s version of the EPR arrangement:

After the spontaneous decay of a two-fermion bound \( ^1S_0 \) state, all three components of the spin vectors \( \vec{S}_i \) \( (i = 1, 2) \) of the constituents are indeterminate under the condition (“hidden” spin conservation at the emitter)

\[
\sum_{k=1}^{3} S_{k1}^2 = \sum_{k=1}^{3} S_{k2}^2 = \frac{\gamma}{4} \quad (18)
\]

Now replacing isospin in the preceding example by spin we again assume that the entangled spin singlet state by detection of fermion 1 retroactively goes over into a state with definite \( z \) component \(-1/2\) as result of the SG measurement

\[
\gamma (\uparrow)_{j_1} \downarrow_{j_2} - (\uparrow)_{j_2} \downarrow_{j_1} \psi(t) \rightarrow (a) (\uparrow)_{j_1} \downarrow_{j_2} |\psi_1(t)\rangle + (\uparrow)_{j_2} \downarrow_{j_1} |\psi_2(t)\rangle \quad (19)
\]

where the transition (a) describes the unitary evolution under influence of the inhomogeneous magnetic field leading to spin-orbit coupling and (b) describes the detection at a time \( t_1 \).

A pre-existing fermion 1 in the Stern-Gerlach device \textit{a posteriori} restricts its position indeterminacy to one of the two channels (branch waves before detection) and thus carries a corresponding definite spin quantum number. The detection has broken the spin up – spin down symmetry of the two-branch wave function and consequently the spherical symmetry of the \( ^1S_0 \) state. That explains via spin conservation at the emitter what the entangled spin state predicts for the spin component in the same direction of the possibly far apart fermion 2: \( s_{2z} = -s_{1z} \) (Figure 2).

Again, particle presence during wave function evolution being inevitable in a theory describing an objective reality independent of human observers, makes a projection postulate superfluous and needs no violation of Einstein locality to remove Bohm’s version of the EPR paradox. The above investigation supports the assumption that the long-standing conceptual problems of QM including the wave function collapse and the discussion of a projection postulate are a matter of inappropriate interpretation and not a matter of the quantum mechanical formalism as complete theory. Concerning particle presence during wave function evolution more general work in quantum field theory should be a future task.
Figure 2: The situation before and after the SG detection of one fermion in plane projection with \( s_{2z} \) obeying the conservation law \( s_{1z}+s_{2z}=0 \). The spherically symmetric \( ^1S_0 \) state is broken and goes over into the more special symmetry of the lateral cone surfaces with definite spin eigenvalues \( s_{iz} \) (i=1,2).

Conclusion:
- To understand particle presence during wave packet evolution, ordinary QM as a phenomenological theory should be seen within the frame-work of field quantization.
- A particle detection appears as symmetry breakdown of the wave packet and retroactively leads to pre-existing quantum numbers. Completeness of QM is not questioned.
- Pre-existing quantum numbers appear as key to solve the EPR-paradox and to make a projection postulate superfluous.

References
[1] Bell J S 1965 Physics 1 195
[2] Freedman S J and Clauser J F 1972 Phys. Rev. Lett. 28 938
[3] Einstein A, Podolski B and Rosen N 1935 Phys. Rev. 47 777
[4] Bohm D 1951 Quantum Theory (Prentice Hall, Englewood Cliffs 1951) p 614
[5] Hiley B J 1977 Contemp. Phys. 18 411
[6] Rauch H 1994 More quantum information due to postselection in neutron interferometryFundamental Problems of Quantum Theory (Annals of the New York Academy of Sciences) 755 p 284
[7] Omnès R 1994 The Interpretation of Quantum Mechanics (Princeton University Press Princeton) pp 85, 353
[8] Mermin N D 1998 Pramana 51 549; Griffiths R B 2003 Found. Phys. 33 1423
[9] Lewin K 2009 Found. Phys. 39 1145
[10] Jammer M 1966 The Conceptual Development of Quantum Mechanics (McGraw-Hill, New York) p 285
[11] Bloch I 1967 Phys. Rev. 156 1377