Chapter XII

(to be revised and corrected)

From EPR to Bell's inequality based experiments and a rational explanation of Stern-Gerlach-type experimental results.

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Abstract
In this paper, which is dealing with correlations of quantum variables, I will propose a theoretical experiment where subatomic systems, such as pairs of electron-positron in the spin singlet state, are described in conformity with peculiar topological properties. The experiment, which can be submitted to a lab test (so far still difficult to execute), aims at confuting, in section 13, the *Simple version of EPR and Bell's Theorem* elaborated in 1985 by David Mermin and also at revaluing Einstein's philosophical position against the ideas that quantum mechanics is a complete theory and that probabilities are non-epistemic. Furthermore, the introduction of radically new physical concepts, which can be clearly visualized, will provide, in section 14, an explicit alternative to the counter-intuitive notion of *quantum states superposition*, particularly in cases of incompatible measurements of spin 1/2, and then, in section 15, a rational explanation of results obtainable in all Stern-Gerlach-type experiments.

PART 1

1. *The EPR experiment*

Einstein, one of the founding fathers of quantum mechanics (QM), was a strong believer in observer-independent reality and ridiculed the view generally accepted by scientists that the only existing reality is that which is created, again and again, by acts of conscious observation. Determined to sustain that any physical system has its own reality even when not measured, Einstein, jointly with Boris Podolsky and Nathan Rosen, elaborated a conceptual experiment, published in 1935 and entitled "Can Quantum Mechanics of Physical Reality Be Considered Complete?"[1] , which became famous (by the authors initials) as the EPR paradox.

EPR is based on three fundamental assumptions, which together are known as the notion of *local realism*:

1)-*reality*: physical systems exist independently of acts of observation;

2)-*locality*: each physical system, *S*, has objective properties, none of which can be influenced by operations executed on physical systems that are widely separated from *S*.[2]

3)-*separability*: systems which are spatially separated have real physical states.

Through the EPR experiment, the three authors intended to contrast quantum mechanics, assuming that

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[1] A. Einstein, B. Podolsky and N. Rosen, "Can Quantum Mechanical Description of Physical Reality Be Considered Complete?", Phys. Rev. 47, pp. 777-780 (1935).

[2] Two physical systems macroscopically distant from each other cannot exchange any instantaneous information, according to the principle of special relativity that forbids the transmission of signals at a superluminal velocity.

If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.

The experiment can be summarized as follows: imagine two photons, γ_1 and γ_2, which from a common origin, at time t_0, speed away from each other in opposite directions at the same velocity and at a sufficient distance in order to maintain the validity of the locality principle. At a given instant t_1 one can measure the position of particle γ_1 with a certain accuracy and deduce that γ_2 must be positioned with equal accuracy at the same distance from the origin. So, according to EPR, the measurement effectuated on the first particle will have certainly modified and made uncertain its momentum, but couldn't in any way have modified the position of the other particle. Furthermore, once the position of γ_1 has been measured, the momentum of γ_2 could also be considered to have been measured (in accordance with the principle of conservation of such a quantity in total).

This strategy would then allow us to know simultaneously both the position and the momentum of particle γ_2, so that such quantities would constitute elements of physical reality. The EPR argument against the Copenhagen interpretation of QM, particularly against Bohr's *complementary principle* and Heisenberg's *uncertainty principle*, paved the way to a long philosophical debate that, after more than eighty years, has yet to reach a definite conclusion.

Bohr didn't seem perturbed at all by the EPR publication and, after a period of reflection, he expressed his counterarguments, declaring that all physical quantities of a system are by their own nature undetermined and without any meaning before being measured, and that their measurements cannot be inferred with the complicity of other systems.

At this point, there were two different interpretations, both unsatisfactory. Indeed, neither of them seemed to be empirically tenable. For a long time, Bohr and Einstein remained stuck in their respective positions, since there were no criteria to establish which one was wrong.

In the early fifties, the American physicist David Bohm of Princeton University became interested in the philosophical implications of QM and conceived a simplified version of EPR (from here onwards denoted "EPRB")[3], in which the measurements of position and momentum of two photons could be substituted by measurements of the spin-one-half ($\hbar/2$)[4] of two correlated particles (for example a pair of electrons or a pair electron-positron) emitted from a common source.

Of course, in the EPRB experiment the measurement of two conjugate observables are subject to the uncertainty principle too, but in this case such a principle is radical, since the spin is a dichotomous quantity, i.e. it can assume only one of two possible values, $+½\,\hbar$ or $-½\,\hbar$, which will be also denoted with "+" and "−" respectively.

In order to understand the EPRB experimental version, imagine a source capable of emitting pairs of spin one-half particles, labeled "**a**" and "**b**", which exist in a so called "spin singlet state". The two particles speed immediately away from the source in opposite directions (fig. 12.1);

[3] D. Bohm. "The Paradox of Einstein, Rosen, and Podolsky." *Quantum Th.*, 611-623, 1951.

[4] The spin, or intrinsic angular momentum, is a property of all wave-particles to rotate around an axis in a way that doesn't have a counterpart in classical physics.

imagine also that the experimental setup includes two Stern-Gerlach apparatuses, labeled "*a*" and "*b*", vertically (V) positioned, facing parallel to each other along the direction of the *y*-axis and perpendicular to the direction along which the particles move. A Stern-Gerlach apparatus, briefly S-G, can measure the *spin* component of the particle that passes through its inhomogeneous magnetic field, as described in chapter I, section 5, figure 1.7 (here reproduced at p. 58) and will emerge out of it deflected in one of two ways denoted "*up*" or "*down*". As you can see in figure 12.1, *a* is positioned in the left sector behind which is observer A, while *b* is positioned in the right sector behind which is observer B.

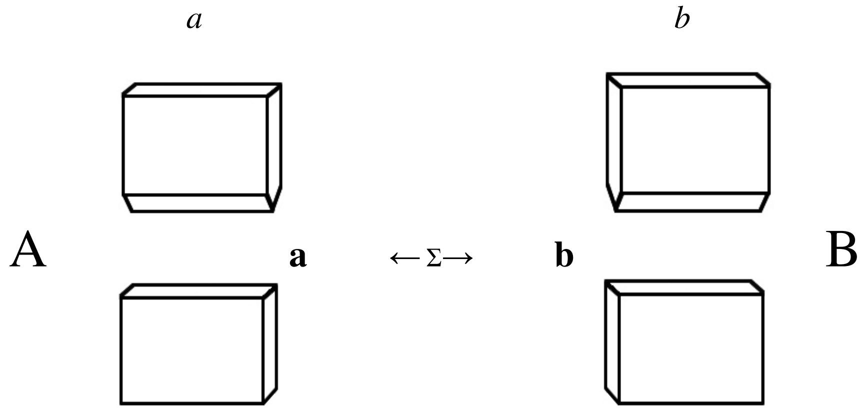
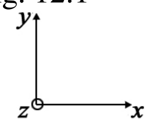


Fig. 12.1



Both the S-G *a* and *b* can be oriented at pleasure along one same direction, vertical (V), horizontal (H) or any other intermediate direction, so that a vertical S-G will measure a spin *up* or *down*, a horizontal one will measure a spin right or left, while a S-G oriented at 45° will measure an intermediate spin that we may call "up-right", "up-left", "down-right" or "down-left", with this meaning that the choice of the S-G direction defines the axis to which the particle spin component is referred.

To simplify, both the S-G have been oriented vertically and not necessarily located at the same distance from the source. As soon as **a** and **b** move away from each other towards their respective detectors *a* and *b*, observer A knows only that **a**'s spin has probability ½ to be measured *up* and probability ½ to be measured *down*. Observer B has the same expectation relatively to **b**'s spin.

The quantum wave function of the theory describes this situation as a superposition of two states: in one of them **a**'s spin **is** parallel to the *y*-axis ($|\mathbf{a}, up\rangle$) and **b**'s spin is antiparallel to the same axis ($|\mathbf{b}, down\rangle$), while in the other state **a**'s spin **is** antiparallel ($|\mathbf{a}, down\rangle$) and **b**'s spin is parallel ($|\mathbf{b}, up\rangle$), so that the wave function $|\psi\rangle$ may be written in the following form

$$|\psi\rangle = (|\mathbf{a}, up\rangle\, |\mathbf{b}, down\rangle - |\mathbf{a}, down\rangle\, |\mathbf{b}, up\rangle)\, /\sqrt{2}$$

or

$$|\psi\rangle = (|\mathbf{a}, \uparrow\rangle\, |\mathbf{b}, \downarrow\rangle - |\mathbf{a}, \downarrow\rangle\, |\mathbf{b}, \uparrow\rangle)\, /\sqrt{2} \qquad (1)$$

The above function does not allow us to assert that the spin of the two particles is in a well-defined state. It simply tells us that, before being measured, the set of combinations is in a (rather incomprehensible) state called "entanglement", a word invented by Schrödinger.

Now, supposing that observer A effectuates a measurement of the spin component of particle **a** along a given direction, for example along the *y*-axis, and measures it swerved *up*, then the spin component of particle **b** will be in the state |**b**, *down*⟩ and its outcome would be *down* along the same direction with 100% certainty, with no need to be measured. In this case the two particles are denoted as "perfectly anti-correlated". In other words, the spin-measurement effectuated on one of the two particles determines with absolute certainty the spin of the other, according to the principle of conservation of angular momentum, as predicted by quantum theory.

In synthesis, in an entangled state, the spin one-half of a particle has probability ½ to be found either *up* or *down* (+ or −) along any direction of the S-G apparatus. If the two particles are measured along parallel directions, the results will always be perfectly anti-correlated (+, − or −, +) and this means that, in the instant in which a spin measurement is taken on one of the two particles, the other collapses into the opposite spin state.

On one hand the Copenhagen interpretation of QM affirms that, in EPRB experiments, the two particles are in a fundamentally undetermined state, in which their respective spins don't have any numerical value until a measurement occurs, while on the other hand we still may not believe in an intrinsic indeterminism and agree with Einstein's philosophical view. In fact, in such an experimental situation, it seems logically correct to believe that the two measurements on **a** and **b** are pre-determined since the instant of their separation, presumably because of their well-defined dynamic properties.

2 *Completely unrelated measurements of spin*

But what happens if the experiment were executed with the directions of the two S-G apparatuses, *a* and *b*, oriented at right angles? In this case, the spin measurements of the two particles will have independent outcomes. For example, having positioned *a* vertically (V) and *b* horizontally (H) as in figure 12.1 bis, if A effectuates a measurement of **a** spin and finds it *up*, although he knows that **b** spin is in the state |**b**, *down*⟩, this, when emerges from *b*,. will have probability ½ to be measured *right* and probability ½ to be measured *left*. Since the spin measurement of one of the two particles renders completely uncertain the spin of the other, on the basis of QM two measurements of spin executed in this way are said "mutually incompatible". In conclusion, they are connected by the *uncertainty principle*, exactly as measurements of position and momentum of two photons which fly in opposite directions from a common source.

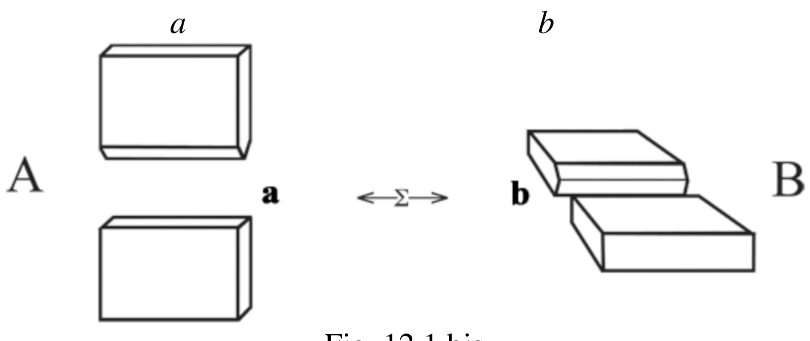


Fig. 12.1 bis
(the two detectors M1 and M2 are not necessarily situated at the same distance from the source)

It's useful to remember that, according to the superposition principle of the theory, the particle **a** directed towards *a* will be in the superposition of states |V, *up*⟩ + |V, *down*⟩. At this point, if observer A measures **a**'s spin and finds it *up*, then particle **b** will be in the state |V, *down*⟩. On the other hand, if observer B measures **b** spin emerging from *b* (horizontally positioned) and, for example, he finds it *right*, then **a** spin will be in the state |H, *left*⟩, and vice versa. In this case, before a measurement is effectuated, the vector state |ψ⟩ of the entangled system can be explicitly described as follows:

$$|\psi\rangle = [|\mathbf{a}, \mathrm{V}\rangle\, |\mathbf{b}, \mathrm{V}\rangle + |\mathbf{a}, \mathrm{H}\rangle\, |\mathbf{b}, \mathrm{H}\rangle] /\sqrt{2}, \tag{2}$$

or

$$|\psi\rangle = [|\mathbf{a}, \updownarrow\rangle\, |\mathbf{b}, \updownarrow\rangle + |\mathbf{a}, \leftrightarrow\rangle\, |\mathbf{b}, \leftrightarrow\rangle] /\sqrt{2},$$

i.e. as a quantum *superposition* of two states, in which it appears that each state contains something of the other.

As soon as a measurement occurs on **a** or **b**, the system collapses with probability ½ in one of the two states, i.e. |**a**, V⟩ |**b**, V⟩ or |**a**, H⟩ |**b**, H⟩. This means that, independently of the distance between the two particles, if observer A effectuates a measurement on **a** spin projection and, for example, finds it *up*, the particle **b** will be in the state |V, *down*⟩. On the other hand, if observer B measures **b** spin projection and finds it *left*, the particle **a** will be in the state |H, right⟩. Once an observer has measured the spin component of his particle along one direction, its value along the orthogonal direction is insignificant. In this case, the two observables are mutually incompatible and their associated operators do not commute, in the same way of the position and the momentum of a pair of correlated photons ($xp \neq px$), as proposed in the original EPR. What about Einstein's belief in the existence of *elements of physical reality*? At this level of knowledge, it remains an open philosophical question.

3. *Bell's inequality*

During the sixties, the Irish physicist John Stewart Bell (1928–1990) took into consideration an EPRB experiment and evaluated the idea of positioning the two Stern-Gerlach magnets with their field's directions oriented neither parallel nor differing by 90° from each other, but differing by an intermediate angular value, for example 45°.[5] Bell's simple but ingenious intuition seemed to be the theoretical presupposition to solve the debate between Einstein and Bohr, thanks to the formulation of a theorem known as *Bell's inequality*.[6] The theorem incorporates three assumptions, the *existence of a reality independent of the observer, the locality, the correctness of logic,* and it is itself a demonstration of impossibility, from the point of view of any theory based on these three classical assumptions, to empirically verify numerical values which violate the above mentioned inequality. Expressed in this way, the theorem doesn't concern only quantum physics, but a general conception of reality.

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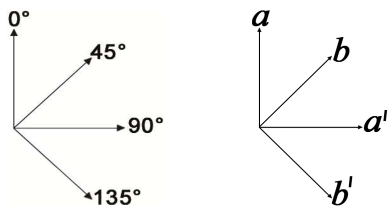
[5] Supposing that the spin component of **a** in exit from a S-G apparatus, say vertically positioned, is measured *down* by observer A, then the spin component of **b** should be in the state |**b**, *up*⟩, and the probability of being found *up* by observer B through a S-G apparatus at 45° will certainly be more than ½; precisely, according to QM formalism, the probability will be ½(1+cos 45°)=0, 853.

[6] J. S. Bell, 1964, "On the Einstein-Podolsky-Rosen Paradox", *Physics*, 1: 195–200, reprinted in Bell 1987.

Referring to figure 12.2, we will imagine a source capable of emitting two particles in the spin singlet state, **a** and **b**, which propagate along opposite directions towards the randomizing switches C1 and C2, from which each particle is sent towards one or the other of two S-G magnets, here indicated with *a*, *a*' in the left sector and with *b*, *b*' in the right sector. In this particular case, *a*, *a*', *b* and *b*' are oriented, in order, at angles of 0°, 45°, 90° and 135° (see graphs below), i.e. one along a vertical direction, another along a horizontal direction and the remaining two along intermediate directions (the first of which can be called "south west-north east" and the second "north west-south east").

In each test, **a** and **b** will have the spin component associated to the numerical values of *a* or *a*' and *b* or *b*', respectively, depending on the magnet they pass through. As you can see in the figure, there is also a coincidence analyser connected to a screen that will show the two results obtained for each pair of particles measured. The two results can be opposite (+ −, − +) or same (+ +. − −). Therefore, *a*, *a*', *b* and *b*' represent also four numbers, each having a value that can be +1 or −1, agreeing for example that +1 stands for the spin measured *up*, *right* or intermediate-*up-right*, while −1 stands for the spin measured *down*, *left* or intermediate *down-left*.



	0°		45°	
	a		*b*	
		Σ		
A	►C1	**a** ←●→ **b**	C2◄	B
	a'		*b*'	
	90°		135°	

Coincidence analyzer

Fig. 12. 2

4. *Correlation function*

The correlation function, denoted with "*E*(*x*, *y*)", is defined as the average of the product of the results emerging from the four possible couples of S-G magnets (*a* and *b*, *a* and *b*', *a*' and *b*, *a*' and *b*') after repeating the measurements a large number of times. Thus, in the experimental setup sketched in fig. 12.2, we will have a combination of four correlation functions, and Bell's inequality, will take the following form:

$$-2 \leq E(a, b) - E(a, b') + E(a', b) + E(a', b') \leq +2 \tag{3}$$

If we assign to *a*, *a*', *b* and *b*' of (3) any combination of +1 and −1 and define the number *Q* as

$$Q = (a \cdot b) - (a \cdot b') + (a' \cdot b) + (a' \cdot b'), \tag{4}$$

where *Q* represents the numerical result of the algebraic sum of the four correlation functions, we will obtain $Q = \pm 2$ independently of the values +1 and −1 introduced in (3).

Even though we have to run one only experiment at a time, it's clear that after a very large number of runs we will obtain the results of all possible combinations of *a* with *b*, *a* with *b*', *a*' with *b* and *a*' with *b*'.

Assuming that in each run the coincidence analyzer registers both results of **a** spin and **b** spin with 100% efficiency, each run will allow us to take note of one of the four different combinations +1 −1, −1 +1, +1 +1, −1 −1. Calculating the statistical average of *n* runs (with *n* as large as we like), we will obtain a number that will not be able to escape from the interval ε [−2, +2], and Bell's inequality will have the form

$$-2 \leq \Delta \leq +2, \tag{5}$$

which is the expectation of scientists who have a classical view of the physical world. So, Einstein and his followers did not take into consideration the idea that a theory based on local realism could predict a violation of Bell's inequality.

On the other hand, in experimental setups conceived for measuring the spin component of two electrons (or a pair of electron-positron) emitted by a common source and directed in opposite directions, each towards one of two S-G magnets with their field directions differing of an angle ϑ, QM predicts a Bell's inequality violation when $\vartheta < \pi/2$, and a maximum violation ($\Delta=2\sqrt{2}$) when the four magnets *a*, *a*', *b*, *b*' are oriented as in figure 12.2. But the experiments are generally devised for measuring *pairs of photons* in the singlet state. In this case, the theory predicts a Bell's inequality violation when $\vartheta < \pi/4$, and the same above maximum violation when the optic axes of the four analyzers (polarizer filters) *a*, *a*', *b*, *b*' are oriented at 0°, 45°, 22,5°, 67,5°, respectively.

Avoiding formal details and for the only purpose of showing how QM comes to predict Bell's inequality maximum violation, we will rewrite (3) as follows:

$$Q = E(a\hat{}b) - E(a\hat{}b') + E(a'\hat{}b) + E(a'\hat{}b'), \tag{6}$$

where *a^b* represents the angle between the directions of *a* and *b* (45° in the experimental setup of figure 12.2). By choosing this angle we will obtain, for the spin components associated to *a* and *b*, two numerical values which can be opposite (+1 −1, −1 +1) or same (+1 +1, −1 −1).

The correlation function *E*(*a*, *b*), in this case, is defined by Bell as *the sum of probabilities of obtaining opposite* (*favourable*) *results minus the sum of probabilities of obtaining same* (*unfavourable*) *results*. Calculating the probabilities based on QM formalism, we have

$$E(a\hat{}b) = \tfrac{1}{2}[1 + \cos(a\hat{}b)] - \tfrac{1}{2}[1 - \cos(a\hat{}b)] = \cos^2[\tfrac{1}{2}(a\hat{}b)] - \sin^2[\tfrac{1}{2}(a\hat{}b)] = \cos(a\hat{}b), \tag{7}$$

so that, from (6) we'll have

$$Q = \cos(a\hat{}b) - \cos(a\hat{}b') + \cos(a'\hat{}b) + \cos(a'\hat{}b') = \cos(45°) - \cos(135°) + \cos(45°) + \cos(45°) = 2\sqrt{2} \tag{8}$$

5. ***The experiments carried out by Aspect (and others) which proclaimed Einstein's philosophy untenable.***

After the formulation of Bell's inequality, it was to be hoped that someone could devise a laboratory experiment capable of verifying whether or not its violation were a correct prediction of QM. This happened in 1981 in Paris[7] when the newly graduated physicist Alan Aspect was able to

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[7] A. Aspect. P. Grangier and G. Roger, *A new violation of Bell's inequalities*, published on 12th July 1982 in Physical Review Letters **49**, 91

create a series of important experiments, during which the polarizations of pairs of correlated photons (emitted by excited atoms of calcium) were measured. The two photons, initially in a state of zero polarization, were moving away along opposite directions, each one towards a polarizer filter oriented at a certain angle. The first experiments were executed using a polarizer with one only channel and, later on, with two channels, with a view to obtaining more accurate results.

To verify whether Bell's inequality were violated, Aspect created an ingenious apparatus in which each photon passed through a switch (a periodically oscillating glass) capable of directing it, at random, to one of two polarisation detectors oriented at different angles. For the purpose of closing the so called "communication loophole"[8] (in other words, avoiding any sort of hypothetical transmission of signals from one photon to the other), he did it in such a way that the choice of direction operated by the switches happened in an interval of time far inferior of 43 nanoseconds (the time corresponding to the distance of 13 meters between the two switches divided by the velocity of light), in other words, while the pair of photons were still in flight. However there was no demonstration that the adjustment of the switches were purely random as Aspect hoped. In any case it seemed unbelievable that between the photons and the measurement apparatus there could be some sort of conspiracy, able to fool the observer!

$Q_{sperim} = 2{,}697 \pm 0{,}015$ is the datum measured in the above experiment, conducted in 1986 by Aspect et al. Some years later, Gregor Weihs[9] and his colleagues were able to achieve a better result, ($2{,}73 \pm 0{,}02$). These measurements concord with QM predictions and are in disagreement with any local theory of hidden variables. Two particles, which have interacted with each other, seem to behave in an interdependent manner (also at a distance that would allow reciprocal exchange of information at superluminal speed) and, together, should constitute what physicists call a "unitary quantum of action".

Einstein's conception of reality was then declared defeated, while a new phenomenon, called *non-local effects*, came to be part of the many mysteries of quantum world.

With regard to Aspect's and other physicists' works, the results observed in their experiments are laid open to two different types of criticism.

1. The data which violate Bell's inequality might not be valid because obtained through additional hypotheses introduced with the aim of avoiding the very low efficiency of photo-detectors.

2. The above data, assuming that they are valid, imply that nature includes, among all its unexplained physical phenomena, a further one considered the most mysterious: *non-locality*, which however doesn't exclude the possibility of elaborating a quantum theory based on realism and determinism.

The first point is based on the conviction of a few physicists, such as Franco Selleri, who affirms that

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[8] In executing experiments for verifying, on the basis of Bell's inequality, whether or not nature complies with local realism, there are three types of loopholes to be be taken into account: the *communication* or *locality loophole* (occurring when the two measurement apparatus are separated from each other by a distance insufficient to maintain the validity of locality principle); the *fair sampling loophole*, persisting when it is not possible to execute measurements of the whole sampling of pairs emitted from the source; the *freedom of choice loophole*, occurring when the choices of the quantities to be measured on the two components of the system in the singlet state cannot be considered casual. No experiment can be free of all the above loopholes.

[9] G. Weihs, 1998, Physical Review Letters **81**, 5039.

It's useful to discuss the experimental situation concerning Bell's inequality, since there is circulating insistently the idea that the problem has been empirically solved in favour of Bohr, demonstrating that Bell's inequality is not valid in nature, and that Einstein's local realism has been definitely refuted (translation from Italian into English is mine).
(E' utile discutere la situazione sperimentale relativa alla diseguaglianza di Bell, dato che circola insistentemente l'idea che il problema sia stato empiricamente risolto a favore di Bohr, dimostrando che la diseguaglianza di Bell non vale in natura, e che sia quindi stato definitivamente liquidato il realismo locale di Einstein).[10]

With regard to the second point, I am personally inclined to believe that subatomic systems might possess dynamical and topological properties, and although accepting the reasonable idea that pairs of particles emitted from a same source will constantly maintain their perfect correlation at any distance until none of them interacts with any other physical system, I would question the existence of what Einstein called "spooky action at a distance", i.e. the idea that an interaction of one particle at one place can instantaneously influence the other particle at the other place.

6. ***Preliminary considerations on Bell's inequality violation***.

The results obtained in some of the experiments up to now executed (using pairs of correlated photons under certain circumstances) violate Bell's inequality and, consequently, *non-local effect* is considered a really existent phenomenon, which has lead the majority of scientists to the conviction that nature is *fundamentally* non-local and that all local models of hidden variables are no longer tenable.

Nonetheless, those scientists assume the exclusive validity of experiments based on the so called "strong inequalities", i.e. the experiments whose results are obtained with the introduction of additional hypothesis that are neither verifiable nor falsifiable, while they ignore completely the experiments based on "weak inequalities", which are a consequence of local realism.[11]

Despite the general conviction that, after all the experimental results that represent a violation of Bell's inequality, it is no longer possible to return to an intuitive conception of physics, there are still grounds, as I believe, for thinking that the debate between Einstein and Bohr may not yet be definitely concluded. If one poses the question "which of the two is right?", my answer could be: "neither of them and nobody else has so far proposed any very convincing argument or lab experiment for proving whether or not QM is a well-founded theory.[12]

Whatsoever, QM is resisting practically uncontested and, when the phenomenon of non-locality came to be part of the many mysteries of quantum world, the scientists who intended to contrast the positivistic paradigm were left with the only possibility of relying on a *deterministic*-non-local theory or on a semi-classical one.

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[10] Franco Selleri, *Fondamenti della fisica moderna*, Ed. Jaca Book, Milano, 1992, p. 51

[11] Alexander Afriat and Franco Selleri, *The Einstein, Podolsky, and Rosen Paradox in Atomic, Nuclear, and Particle Physics*, Plenum Press, New York, 1999, pp. 99-121.

[12] While I am writing, a loophole-free Bell test, has been executed by a team of physicists led by Ronald Hanson at the Delft University of Technology in the Netherlands, and the results have been published September 03 2015 in the journal *Nature.* On the one hand, according to the opinions of several antirealists such as physicist Anton Zeilinger, the experiment seems to have achieved a response good enough to prove the real existence of spooky action at a distance, but they agree on the need of its replication in different laboratories and also of detection of a larger number of correlated pairs , On the other hand, there are physicists, e.g. Bradley Christensen, who claim that this experiment does not have to do with confirmation or refusal of local quantum theories.

Going back about three decades, David Bohm, who was involved in researching a completeness of QM, had been the first physicist to provide a *deterministic* explanation of phenomena pertaining to quantum world. In his theory,[13] formulated in 1952 and based on hidden variables, he introduced, in a rather arbitrary way, the concept of *quantum potential*. This new concept was supposed to be capable of establishing an instantaneous connection between two particles in an EPRB experiment, for example, between two electrons originating from a common source and speeding away in opposite directions, each towards a S-G magnet oriented at a given angle. Assuming that the two electrons emitted from the source carry well-defined sets of instructions, quantum potential acts in such a way that the measurement of the spin component effectuated on one electron changes "instantaneously" the spin of the other. Thus, Bohm's theory is non-local and, although being based on hidden variables, is nonetheless in conflict with Einstein's special relativity (and is in keeping with Newtonian ideas of space and time). David Lindley highlights the above conflict with the following words:

In Bohm's theory the instantaneous transmission of influence from one electron to the other is supposed to be a real physical phenomenon, with real physical consequences: when one electron is measured, it literally creates an interaction with the quantum potential that affects the other electron. But how then are we to reconcile this idea with the fact that some observers will decide the influence is passing from electron A to electron B, while others will decide it is going the other way? Bohm's theory insists on an objectively real description of events that's the same for everyone, but relativity doesn't allow such a definition of instantaneity.[14]

In his theory, Bohm assumes the validity of the reality principle and determinism: quantum particles have well-defined properties, but since some of them are hidden, they are empirically unknowable as well as difficult to imagine. However, he had to admit to the existence of non-local effects, due to the (hidden) quantum potential. In the final analysis, all this didn't help him to contrast the fundamentally probabilistic nature of QM.

In short, the EPR argument is neither adequate for demonstrating the incompleteness of quantum mechanics, nor for justifying bohmian mechanics, this being essentially a pseudo-deterministic remake of the standard theory. Nonetheless, Bohm must be praised for his new formulation of EPR, through which he had succeeded in stimulating the scientific community to work towards a possible solution of the historical debate between Einstein and Bohr.

On the one hand there are physicists who do not give up the idea that QM could be proved incomplete or founded on wrong principles. On the other hand, some *variables* of local theories and non-local deterministic theories will always remain *hidden*, unless a satisfactory and logically agreeable description of them may be found.

The many mysteries of QM and the latest, non-locality, have convinced the majority of scientists that the physical world is basically non-intelligible. In fact, most of them believe that there is no hope to explain unambiguously the logic which micro-systems obey to, or to imagine their behavior without making use of the incomprehensible notion of *quantum states superposition*. But what could it mean that the spin of the electron, before being measured, let's say along the direction of the *y*-axis, is in the superposition of the two states $|y, up\rangle + |y, down\rangle$, i.e. in a potential state whereby both possible results coexist? As well known, the classical language is inadequate to

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[13] D. Bohm, "A suggested interpretation of the quantum theory in terms of hidden variables, I and II,"Physical Review, vol. 85, pp. 166–193, 1952.

[14] D. Lindley, *Where does the weirdness go?*- Publ. Basic Books, 1996, p. 119.

describe such a situation. Which physicist wouldn't feel uncomfortable at not being allowed to make any sort of assertion about the spin of the electron between one measurement and the other? Obviously, Bohr would answer that the QM formalism synthesizes in a very rigorous way all the information that the observer can possess on a given physical system. But what could he say about the "paradox" implicit in the act of measurement that has been discussed in the second chapter (*The Dead-Alive Physicist* experiment)?[15] What about the passage from the *quantum superposition* of the two spin states $|y, up\rangle + |y, down\rangle$ to one only classic and well-defined state, spin *up* or spin *down*? According to the current scientific knowledge, it is likely that most physicists would be in agreement with the following Lindley's rather fatalistic conclusion:

Since we don't have much of an idea about what an electron looks like in the first place, it's perhaps a little easier to accept without protest that it can inhabit a weird and indescribable state.[16]

Slightly different and less pessimistic appears the philosophical position of Penrose, who discriminates between *x-mysteries* and *z-mysteries*. The first may be considered as brainteasers that sooner or later will find an answer; the second group of mysteries, such as non-locality, are considered aspects of nature that should be accepted as permanently beyond human comprehension.

Penrose's arguments are very interesting, but they do not seem to lead to any radical conceptual change. Even though seriously involved in the search for answers to some of the x-mysteries, at present it appears that he is mainly interested in elaborating conjectures and hypotheses, for example thinking that

one must strongly consider the possibility that quantum mechanics is simply *wrong* when applied to macroscopic bodies – or rather the laws **U** and **R** supply excellent approximations, only, to some more complete, but as yet undiscovered, theory.[17]

Then, again on the theme of x-mysteries, he declares his conviction that

The resolution of the puzzles of quantum theory must lie in our finding an improved theory […]. But even if one believes that the theory is somehow to be modified, the constraints on *how* one might do this are enormous. Perhaps some kind of "hidden variable" viewpoint will eventually turn out to be acceptable. But the non-locality that is exhibited by the EPR-type experiments severely challenges any "realistic" description of the world that can comfortably occur within an ordinary space-time – a space – time of the particular type that has been given to us to accord with the principles of relativity – so I believe that a much more radical change is needed.[18]

Studying in depth the questions arising from EPR-Bohm experiment, Bell's inequality, all tests providing results in violation of this latter, and taking account of the above quotations (particularly the pessimistic words of Lindley), I've tried to develop and propose my own point of view. Starting from some intuitions concerning the fundamental constituents of the physical world, I have wracked my brain for quite a long time before achieving a plausible and rational description of their properties (based on radically new physical concepts which can be clearly visualized). Finally, relying on these concepts, I've devised some experiments capable of providing an intelligible explanation of some specific aspects of QM until now considered inexplicable.

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[15] The Dead-Alive Physicist experiment-

[16] D. Lindley, *Where does the weirdness go?*- Publ. Basic Books, 1996, p. 169.

[17] R. Penrose, *the Emperor's New Mind* – Oxford University Press, 1999, p. 384. In it, the term "**U**" stands for "unitary evolution of the wave function", while "**R**" stands for "reduction of the wave function".

[18] Ivi, p. 385)

7. ***A thought experiment based on additional properties of subatomic systems***

According to the philosophical view of EPR-Bohm (EPRB), quanta correlations are pre-determined at the source, i.e. each of the two particles in the spin singlet state "knows", since its origin, how to react with the measurement device towards which it is directed. But it should be stressed that the EPRB argument does not include a model capable of explaining *how* quantum correlations are predetermined at the source and therefore, it is not strong enough to contrast Bohr's philosophical position. We should definitely need something different!

In the experiment I'm going to propose (in three different versions), I will describe quantum systems and their dynamics with specific topological properties.

The experiment is based on three physical concepts:

(a) – The atomic systems are spherical loops:[19] particularly, their intrinsic angular momentum is correspondent to a rotation about a number n of axes with $n \geq 3$, among which only one plays an effective role in the measuring process; more precisely, it is the axis which forms the minor angle with the direction of the S-G magnetic field and which will here be called "**DSA**" (Dominant Spin Axis).

(b) – Two loops in the spin one-half singlet state, after being emitted from the source, move away in opposite directions maintaining the initial orientation[20] until they interact with the magnetic field of the S-G apparatuses towards which they are directed.

(c) – The **DSA** of a loop which is crossing a S-G apparatus is subject to a precession[21] around the direction of its field.

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In the following sections we will assume that the intensity of the S-G magnetic field increases from its north pole, the lower component labelled "–", to its south pole, the upper cuneiform component labelled "+" (Figure 12,3).

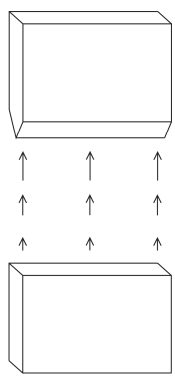

Fig. 12.3

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[19] Each of these loops is thought as a stationary wave enclosed inside a spherical pluripolar horizon, i.e. as energy forced to circulate restlessly along a close path and, therefore, behaving like an electrical field that generates a magnetic field..

[20] This condition referred to a pair of loops in the singlet state can be defined "principle of conservation of spatial orientation".

[21] It is called "Larmor precession" from the name of physicist Joseph Larmor. In the new context of the loops, the precession means that, while a loop is crossing the inhomogeneous magnetic field of a S-G apparatus, its spin axes which do not interact with the field will rotate around the **DSA** (an adequate description of this process is available in section 14).

As well-known, in all the experiments up till now executed, the spin of electrons (more precisely, silver atoms vaporized in an oven) emerging from a S-G apparatus, e.g. vertically positioned, has been always observed in one of two possible deflections, *up* or *down*, and never in any other intermediate deflection. These results have not yet found a logical explanation and, as I presume, the reason should be due to the fact that the electron is to simply imagined as a tiny magnetic bar. But now, having conceived an innovative model of the electron (and more generally of atomic systems), it will be possible to provide a logical explanation to those results. In fact, the idea that atomic systems, such as electrons, may rotate around more than one axis, instead of one only, sounds much more reasonable, even though difficult to depict. At this point, I think useful to mention the Scottish mathematician Ian Stewart who, in dealing with the argument of quanta correlations, considers plausible that, in some way beyond our comprehension,

> The electron, however, really does seem to behave as though it is rotating about both axes simultaneously. It is almost as if there are two ghost electrons, one spinning about the north axis and one about the east, and the real electron is a combination of the ghosts […]. Indeed you really need three ghosts, because we haven't yet added the spin about the up axis. In many different types of experiment, this ghostly picture of an electron has been shown to give a natural picture of reality.[22]

Before starting, in order to have a much clearer understanding of the three versions of the experiment, I suggest you to prepare *a pair of tetrahedrons* of the same size, *a pair of hexahedrons* and *a pair of octahedrons*, using card, scissors and glue. Then, you will draw on their faces the loops and the appropriate symbols, such as arrows and signs +, −.

8. ***The Experiment, version n. 1***.

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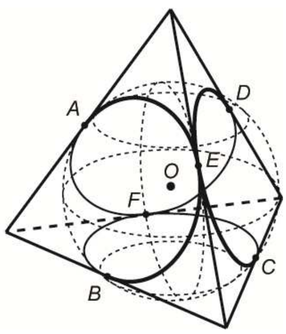
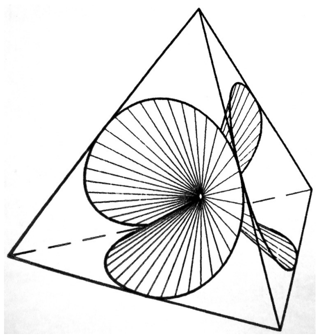
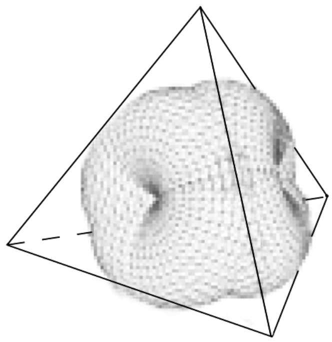
In chapters IX and X I've described samples of spherical loops belonging to the family of the five platonic polyhedrons, and in this first version of the conceptual experiment, we will deal with loops of the tetrahedron. A spherical curve $LC_{2/3}$, a spherical cone $LS_{2/3}$ and a spherical torus of the tetrahedron (already proposed in chapter IX and there illustrated in Tables 9.4, 9.5 and 9,6) are here shown in figures 12.4*a*, *b*, *c*. The second and the third figures, which may be considered more appropriate, will be avoided because they would seriously complicate the description.



$LC_{2/3}$
Fig. 12.4*a*



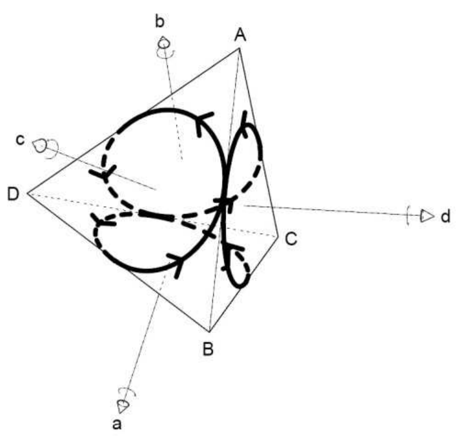
$LS_{2/3}$
Fig. 12.4*b*



$LV_{2/3}$
Fig. 12.4*c*

The following two figures illustrate two loops, each spinning about 4 axes, which form one another an angle of 141, 507° = 2*arc cosine*(1/3).

[22] Ian Stewart, *Does God play dice?* Penguin Books, second ed. 1997, p. 334.



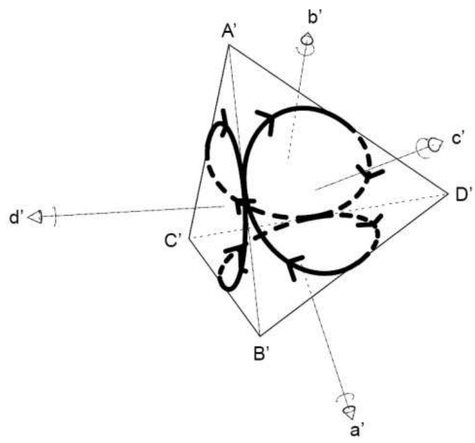


Fig. 12.5*a* Fig. 12.5*b*

(two $LC_{2/3}$ of the tetrahedron with their respective spin axes)

Joining A with A', B with B' and C with C', we will obtain a structure that can be imagined as a pair of atomic particles in the spin singlet state (figure 12.5*c*).

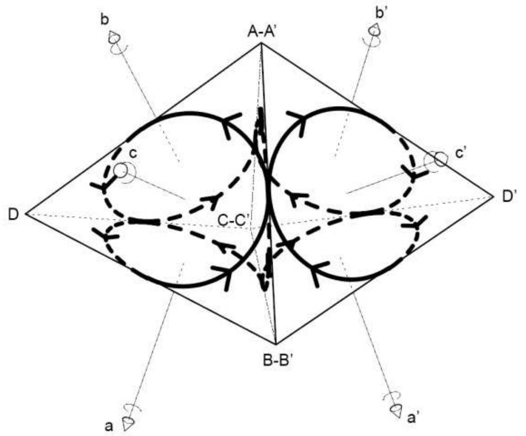
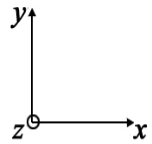


Fig. 12.5*c*

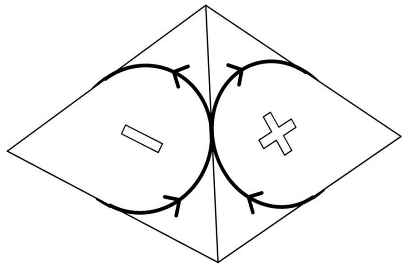
(pair of loops $LC_{2/3}$ of the tetrahedron in the spin singlet state).

Each loop is here shown inscribed in the tetrahedron for two reasons: first, to have a proper vision of its depth and of its four spin axes orientation and, secondly, to make possible the application of symbols (such as +, − and arrows) on the four faces on which each loop is inscribed.

To simplify, from now on the spin axes will be eliminated and substituted by the symbol "−" where the spinning of the loop is clockwise, and by the symbol "+" where it is counterclockwise,[23] as you can see in the following figures.



[23] In a loop, the direction (clockwise or counterclockwise) of each curve which lies on a plane is here defined around the straight line passing trough the centre of the loop and the centre of the curve (choosing the centre of the loop as point of view). Note that the choice of the symbols "−" and "+", respectively referred to clockwise and counterclockwise spinning of the loop, is not based on any particular criterion, such as that of *the right hand*. In other words, if those symbols were inverted, the results and the comprehension of the experiment would be the same. In our description the north pole of each spin axis is labelled "−" and the south pole "+".

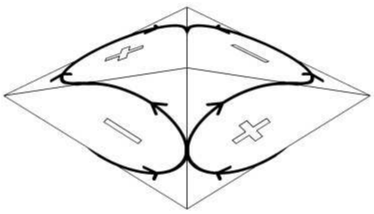


a **b**

Fig. 12.6

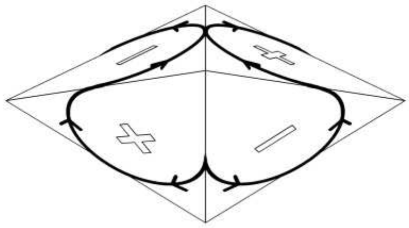
(front view of figure 12.5)

The above pair of loops in the spin singlet state, indicated with "**a**" and "**b**", will be rotated clockwise around the positive direction of the *x*-axis (along which they will propagate), a first time by 30° (figure 12.7), a second time by 150°(figure 12.8) and a third time by 270° (figure 12.9,).[24]



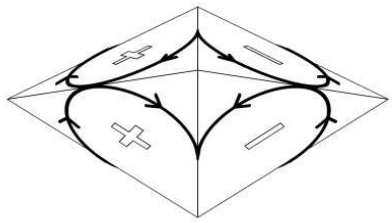
a **b**

Fig. 12.7



a **b**

Fig. 12.8



a **b**

Fig. 12.9

Choosing one of these structures, for example that one of figure 12.8, we can show how it behaves after its separation into two loops, **a** and **b**, respectively directed towards the S-G magnets (from now onwards labelled) M1 and M2, here both vertically oriented.(figures 12.10 – 12.11).

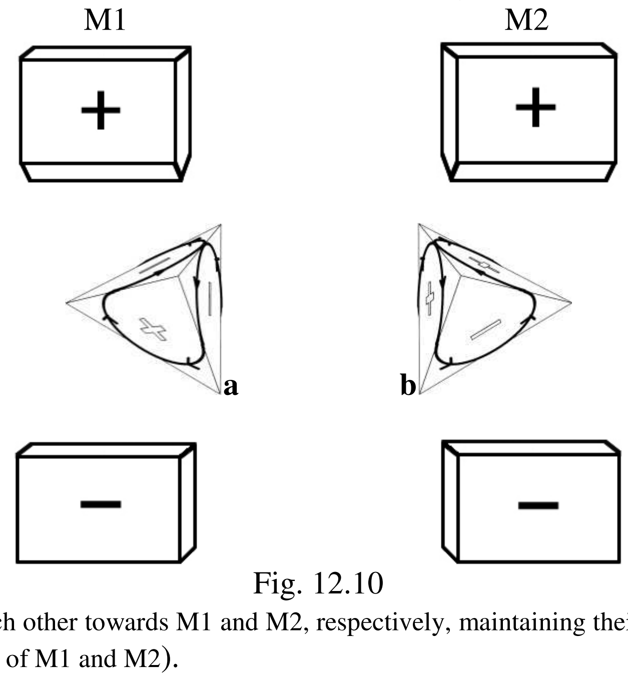


Fig. 12.10

(**a** and **b** move away from each other towards M1 and M2, respectively, maintaining their original orientation and cross their respective magnetic field of M1 and M2).

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[24] If each of above pairs of loops were rotated by 180° about the *y*-axis, we would obtain three other configurations, thus having a sampling of six pairs of loops in the spin singlet state, all positioned in the same way and each different from the others. But only *the first three* will be used for describing the experiment, since the others are not essential; in fact they would produce exactly the same global results.

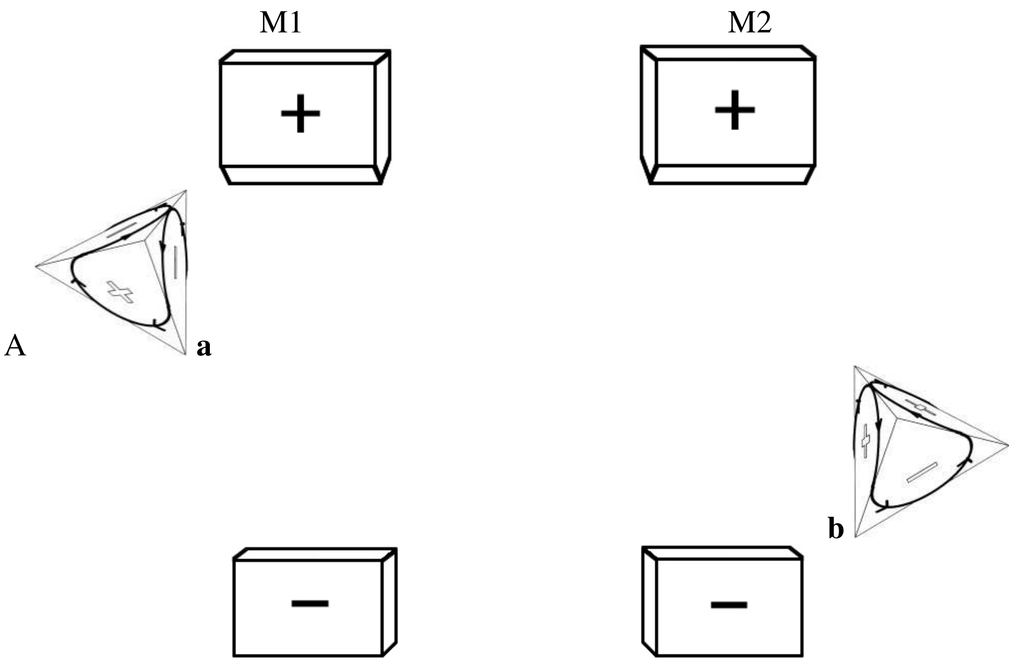
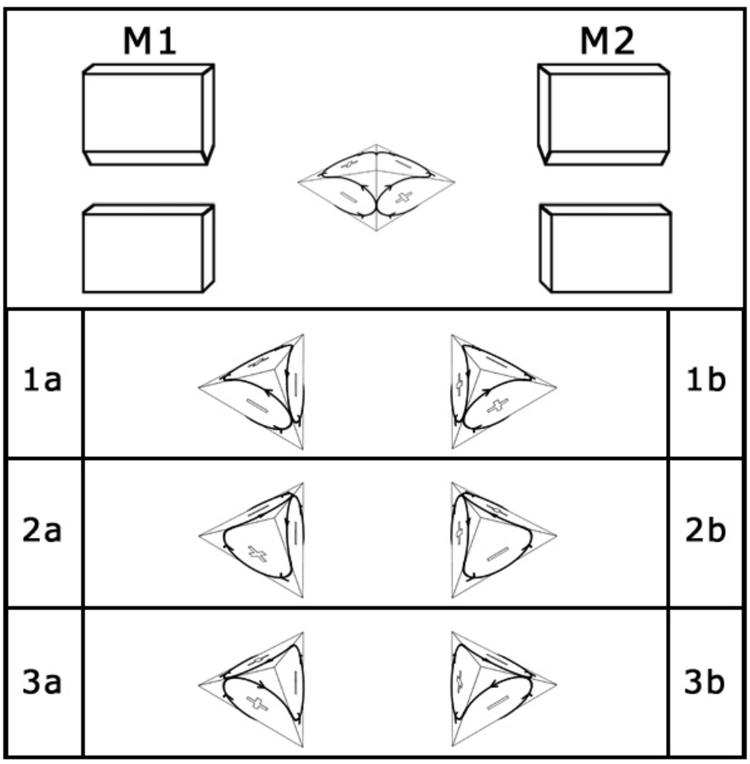


Fig. 12.11

(**a**, which has the negative pole of its **DSA** facing the positive component of M1, will be deflected up, while **b**, which has the positive pole of its **DSA** facing the positive component of M2, will be deflected down).

Table 12.1



(the three different configurations of the pairs of loops in the spin singlet state of figures 12.7, 12-8 and 12.9)

This table illustrates the two detectors M1 and M2 vertically positioned and, in numerical order, the three pairs of loops of figures 12.7-12.9, each separated in two correlated loops, **a** and **b**. In this case, two observers A and B, respectively situated on the left and on the right sector, in each run of the experiment will obtain spin measurements perfectly anti-correlated. More generally, in all the cases where M1 and M2 are oriented in the same way, the results obtained from joint measurements of spin on **a** and **b** will be opposite (+, − or −, +). In fact, since the spins of each pair of loops are here predetermined at the source, if **a** emerges from M1 with its spin deflected *up* (*down*), then the corresponding **b** will emerge from M2 with the spin deflected *down* (*up*) with probability 1.

The next step is crucial (for all three versions of the experiment) and consists in taking the 3 pairs of loops shown in Table 12.1 and in executing on them the following operations:[25] 1) - the positions of M1, M2 and the position of each **a** will be maintained unchanged; 2) - each **b** will be rotated clockwise by120° about the positive direction of the *x*-axis along which it moves; 3) - each **b** will be rotated clockwise by 240°.[26]

The above operations will appear much clearer in the following example: from Table 12.1 we take the first pair of loops (figure 12.12); we leave **a** unchanged and, after having rotated **b** by120° clockwise about the positive direction of the *x*-axis, we will obtain figure 12.13; then, repeating the same operation, but this time rotating **b** by 240°, we will obtain figure 12.14.

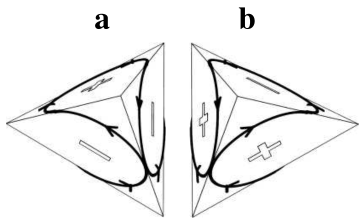


Fig. 12.12

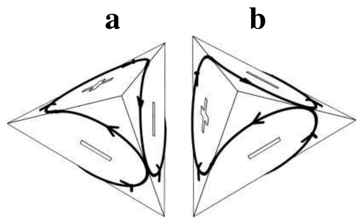
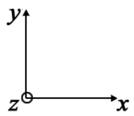


Fig. 12.13



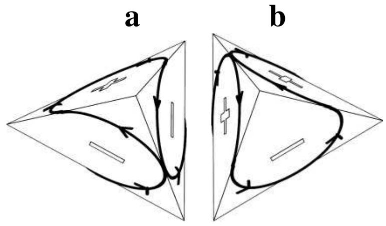


Fig. 12.14

Operating in the same way on the two other pairs of loops, the results will be those shown in Tables 12.2 and 12.3.[27]

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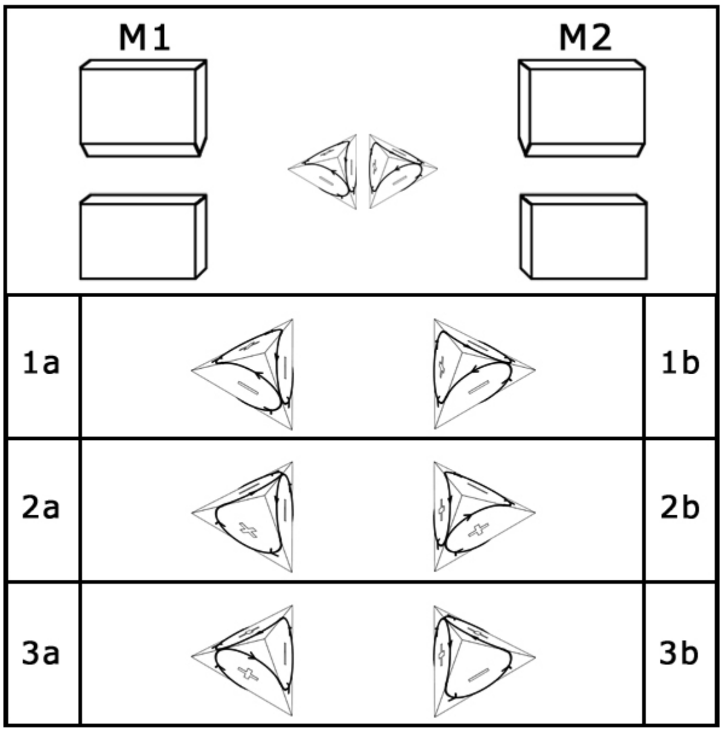
[25] The operations are three, since among them is included the rotation identity of each **b** by 360° with respect to the correspondent **a**, as illustrated in Table 12.1, where we can also say that neither **a** nor **b** are subject to any change.

[26] These operations are equivalent to maintaining unchanged the loops **a** and **b** and rotating M2 by the same angular values counterclockwise about the positive direction of *x*-axis, or rotating M1 clockwise about the negative direction of the *x*-axis, or rotating both M1 and M2, provided that their directions are set at an angle of 120°. But the way here adopted will much simplify the whole description of the experiment..

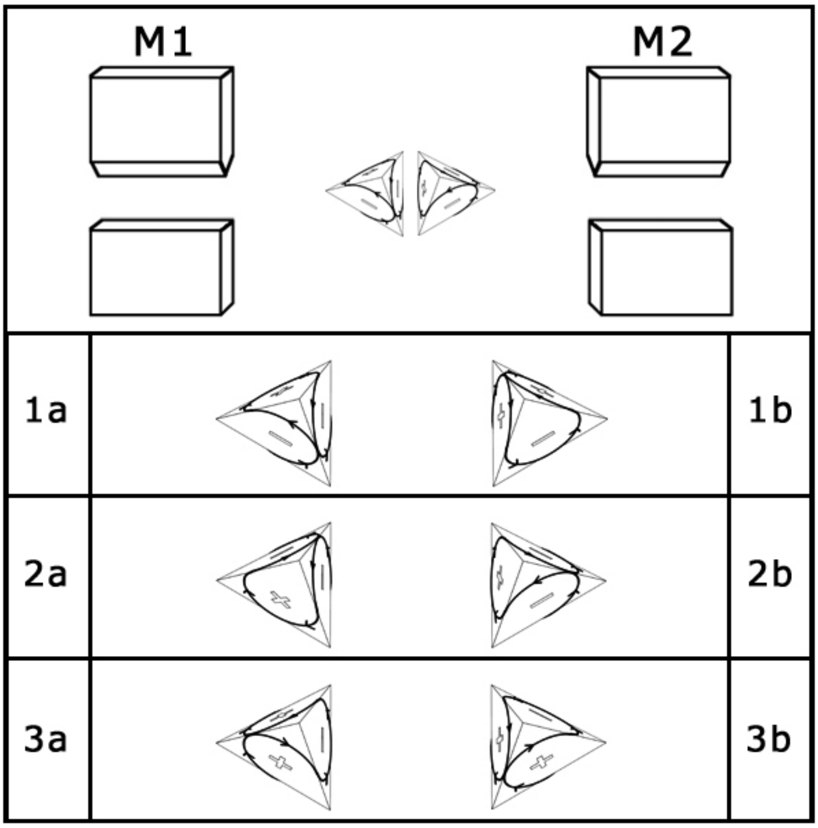
[27] The operations could be also executed in the opposite way, maintaining unchanged all the **b** and rotating each **a**. They could otherwise be executed by rotating both the loops **a** and their corresponding **b**, provided that their respective orientations are at an angle of 120°. In both these cases the results would be the same as in Table 12.4, but the pairs of loops would be seen in different positions.

Table 12.2



(each **b** is rotated by 120° with respect to the corresponding **a**)

Table 12.3

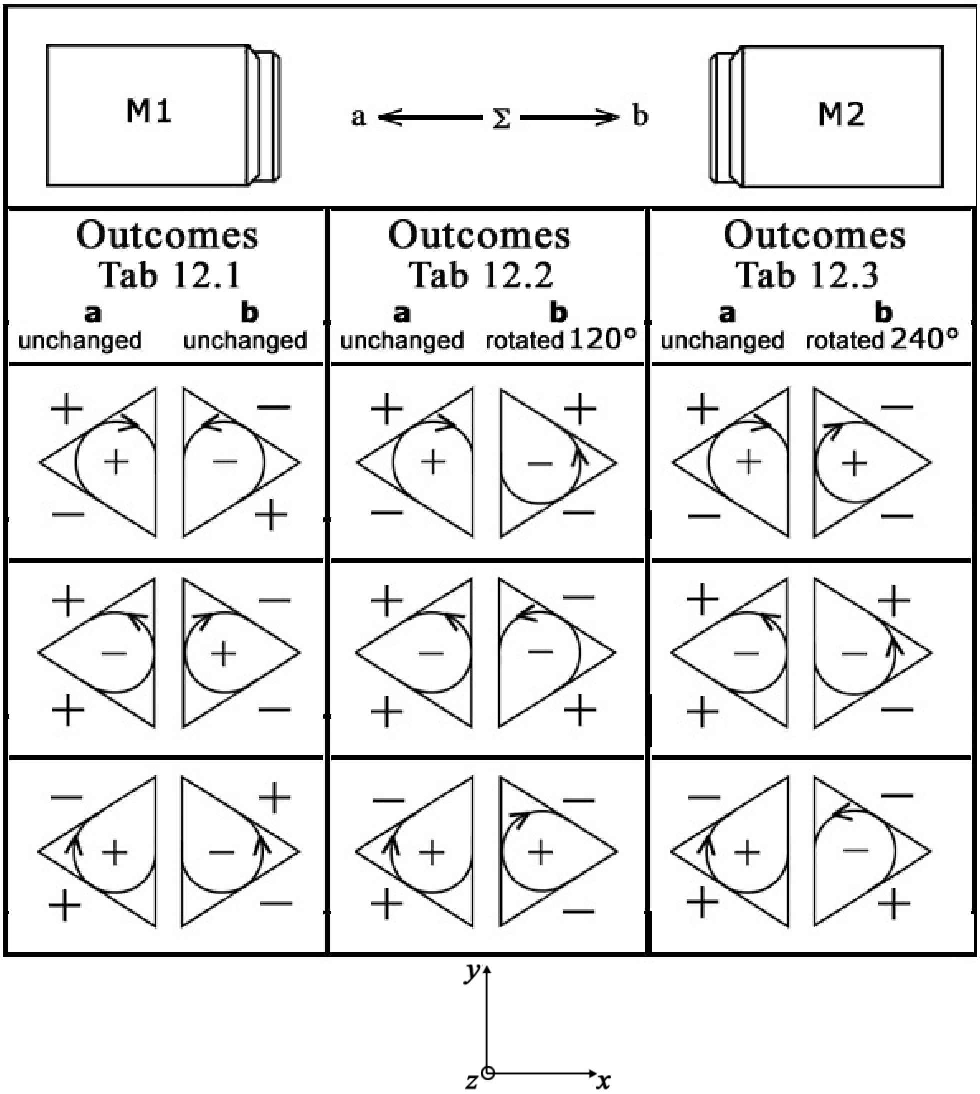


(each **b** rotated by 240° with respect to the corresponding **a**)

Tables 12.1, 12.2 and 12.3 enable us to visualize the 9 different configurations that the pairs of loops can assume after having executed on them the above operations in sequence.

In Table 12.4,which summarizes Tables 12.1, 2 and 3, the 9 pairs of loops and the two detectors M1 and M2 are seen from a point of view perpendicular to the page. Here, in the first column and inside each pair of loops, you can read opposite spin symbols (+, − and − , +) alternating from top to bottom; you can also read two other symbols, one above and one below each of the 18 loops: they indicate the spin of the two portions of loop that here are not visible. The symbol of the fourth spin is not shown, because it coincides with the direction along which the loops move and therefore, it doesn't play any role.

Table 12.4



In order to simplify the description, in the above four Tables, as you can note, the direction of the two **DSA** belonging to each pair of loops and the direction of the magnetic field of both detectors lay on the plane of *xy*. Clearly, such an orientation of the **DSA** here represents an extreme case, but the results of measurements would not change if the **DSA** of each pair of loops tilted over either side of the *xy* plane at an angle included in the interval ε[π/3, − π/3].

Table 12.5 shows the probabilities of obtaining opposite and same results deriving from joint measurements of spin which can be executed, in the course of a very large number of runs, on the 9 different pairs of loops as illustrated in the previous Tables 12.1-12.3. From now on, *opposite results* (+, − or −, +) will be indicated with "**O**" and *same results* (+, + or −, −) with "**S**".

Table 12.5

Probabilities for obtaining O and S Results					
Tab.12.1		Tab.12.2		Tab.12.3	
+ −	**O**	+ −	**O**	+ +	**S**
− +	**O**	− −	**S**	− −	**S**
+ −	**O**	+ +	**S**	+ −	**O**
3 **O**		1 **O** and 2 **S**		1 **O** and 2 **S**	
Totally 5 **O** and 4 **S**					

Executing the experiment with a large number of runs, observers A and B will expect to measure *opposite* outcomes with probability

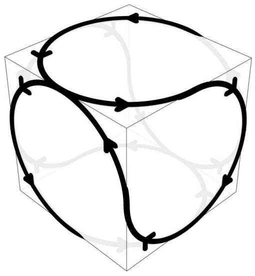
$$P_{\mathbf{O}} \geq \mathbf{5/9}$$

and the larger is the number of runs, more accurately the probability of obtaining **O** outcomes will approach this value. We shall have more to say about above relation, but not before having described the other two versions of the experiment.

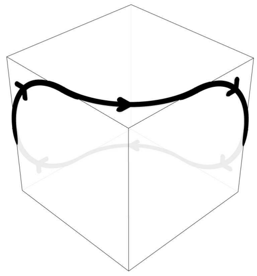
For calculation of probabilities $P_{\mathbf{O}}$ and $P_{\mathbf{S}}$ see Appendix 2, pp.59-63

PART 2

10. ***The Experiment, version n. 2***



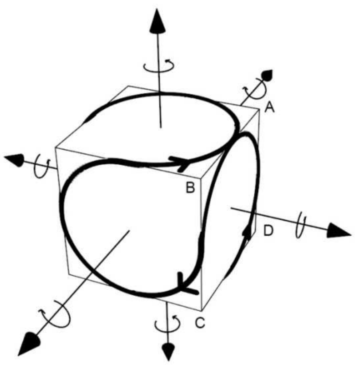
$LC_{3/4}$
Fig.12.15



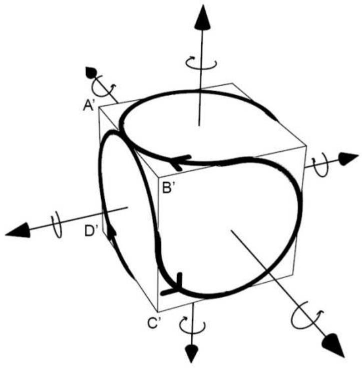
$LC_{1/4}$
Fig.12.16

The above two figures represent the spherical curve $LC_{3/4}$ of the hexahedron on the left and the spherical curve $LC_{1/4}$ on the right , each spinning about three axes perpendicular to one another.

We will hereafter consider the loop $LC_{3/4}$ of the hexahedron positioned on the left side (figure 12.17) and, on the right side, its image reflected in a mirror (figure 12.18).



a
Loop $LC_{3/4}$
Fig. 12.17



b
Mirror image
Fig. 12.18

The two loops of the above figures are related by a symmetry operation which is called "parity symmetry" (*P*). The clockwise rotations become counterclockwise and vice versa when seen in a mirror. *In the real world*, a particle which is equivalent to its mirror image is interpreted as its antiparticle. Supposing that the left loop simulates an *electron*, then its right loop will simulate a *positron*. Their respective spin axes, in this case, are two by two parallel, i.e. they are pointing in the same direction. Figures 12.19 and 12.20 represent a pair electron-positron in the spin-singlet-state, where their respective spin axes are, two by two, antiparallel.[28]

Joining A, B, C, D respectively with A', B', C', D', we obtain a pair of loops, **a** and **b,** in the spin singlet state (figure 12.19). In all the following figures, according to our usual procedure, in

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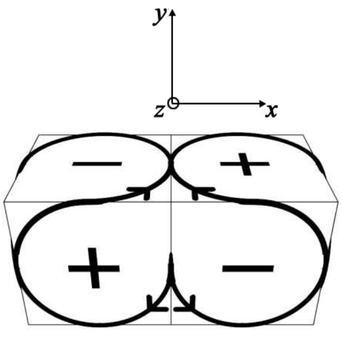
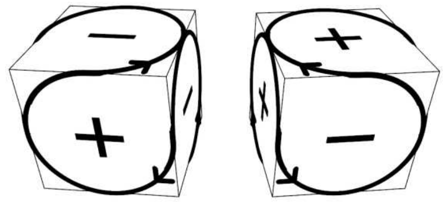
[28] They might be interpreted as ortopositronium and parapositronium, which have different life-time: their annihilation occurs, respectively, in 1,386 x 10^{-7}s and in 1,244x10^{-10}s.

the loops **a** and **b**, (which are supposed to simulate a pair of electron-positron)[29] the axes concerning clockwise and counterclockwise spinning (see section 8, footnote 23) will be respectively substituted by the symbols "–" and "+" (figure 12.24).



a b

Fig. 12.19

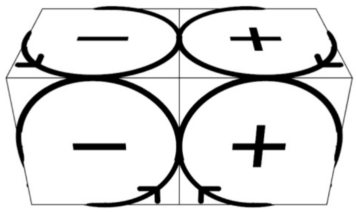


a b

Fig. 12.19 bis

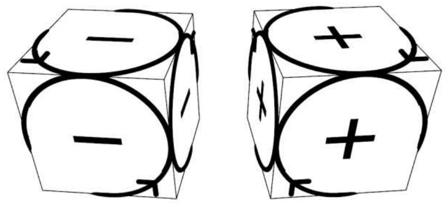
a pair of loops $LC_{3/4}$ of the hexahedron, **a** and **b**, simulating a pair electron-positron in the spin singlet state

The above figure 12.19 will now be rotated clockwise about the positive direction of the x-axis, a first time by 90°, a second time by 180° and a third time by 270° (figures 12.20–21–22). Thus we can clearly visualize four different configurations.



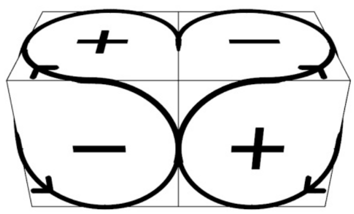
a b

Fig. 12.20



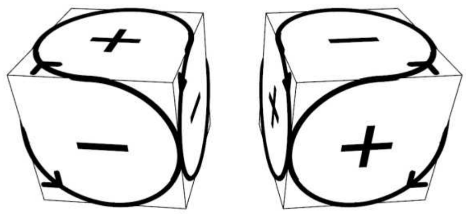
a b

Fig. 12.20 bis



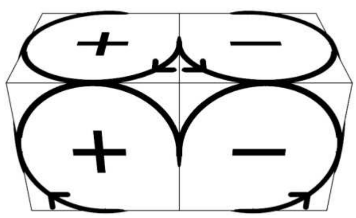
a b

Fig. 12.21



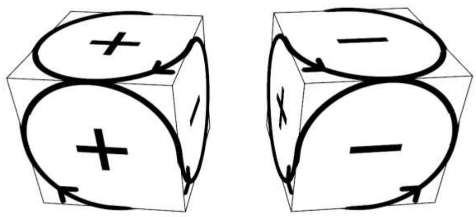
a b

Fig. 12.21 bis



a b

Fig. 12.22



a b

Fig. 12.22 bis

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[29] In this case, each pair electron-positron is supposed to be generated by a spin-zero meson (π°, called "neutral meson") in its second most important decay (1,198%), after its main one (98,798%); in this second type of decay, called "Dalitz decay", one photon is also generated).

Since the two particles **a** and **b** differ from each other for having *opposite charge*, there is an important question to answer: *which property could represent the physical difference between the charge of the electron and the opposite charge of the positron?* Well, a reasonable answer can be provided, for example, changing the loop *LC* (Loop Curve) into *LV* (Loop Volume), i.e. into a spherical torus (figure 12.22).

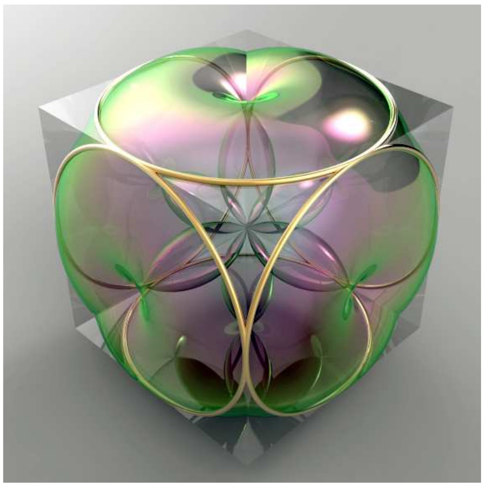
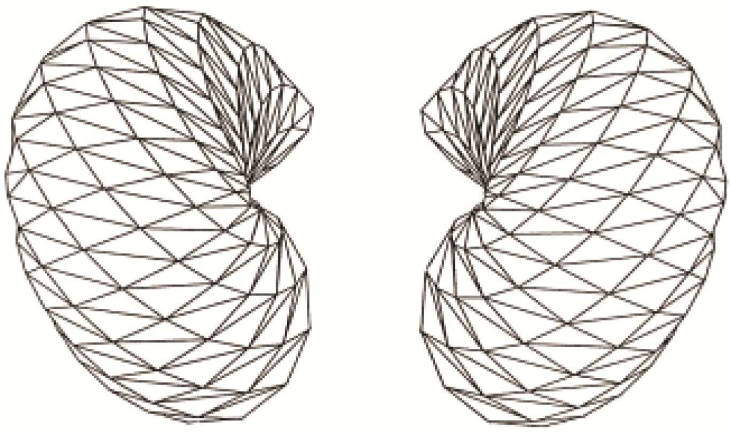


Fig. 12.22

Spherical torus, Loop $LV_{3/4}$, of the hexahedron

Furthermore, we can depict the pair of spherical tori **a** and **b**, respectively, as a left-chiral and as a right-chiral particles (figure 12.23 is showing a *partial* representation of chirality of the above $LV_{3/4}$). In this case, we could say that the two particles are related by a symmetry called "charge conjugation symmetry". This concept will be much better illustrated later on (in section 12, figures 12.36-37-37 bis, and in section 13, figures 12.44-44 bis).



a **b**

Fig. 12.23

(in this configuration, **a** and **b** have opposite chirality and are not superposable on each other)

According to our usual procedure, in the loop **a** (which simulates an electron) the axes concerning clockwise and counterclockwise spinning will be respectively substituted by the symbols "–" and "+", while in **b** (which simulates a positron) the symbols will be inverted (figure 12.24).

Referring to figure 12.24, we are going to show, in a sequence of images, the behavior of **a** and **b** from their separation up to their respective spin measurement through a S-G apparatus (figures 12.28 - 29) .

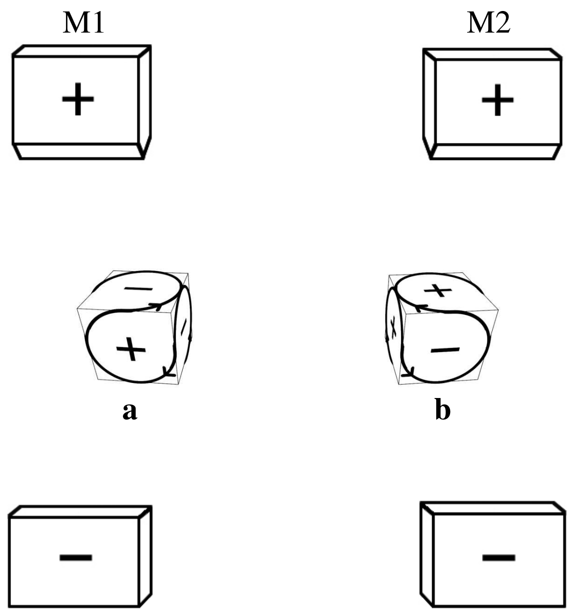


Fig. 12.28
(**a** and **b** move away from each other, both maintaining unvaried the original spatial orientation and then crossing the respective magnetic field of M1 and M2)

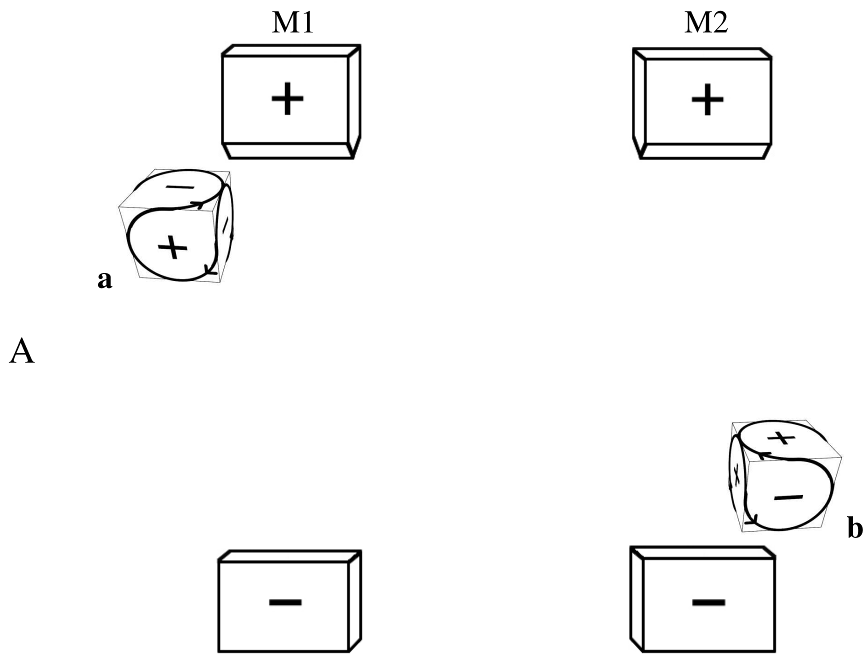
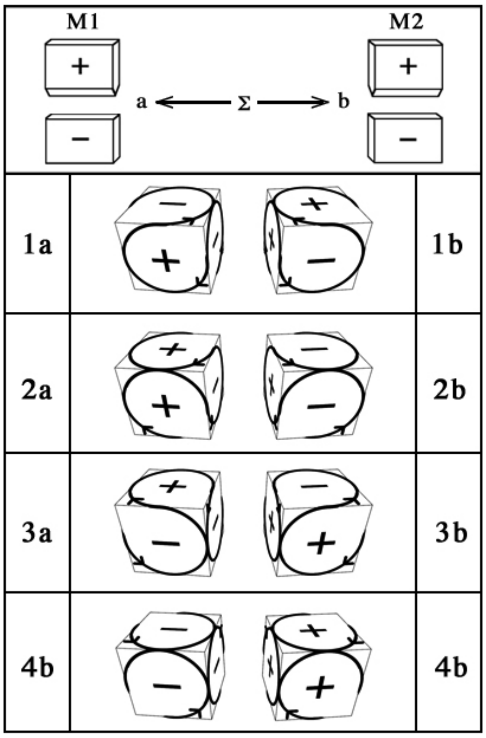


Fig. 12.29
(the spin of **a** is measured *up* and the spin of **b** *down*)

If we execute the same experiment with the pair of loops of figure 12.27, the result will be the same as above, but if we execute it with the pair of either figure 12.25 or figure 12.26, the results will be inverted, i.e. **a**'s spin will be measured *down* and **b**'s spin *up*.

We will now take the four pairs of loops shown in figures 12.24 - 12.27 (as listed in Table 12.6) and apply on each of them the rules analogous to those described in section 8 (just above figures 12.13 – 12.15). The positions of M1, M2 and each **a** will remain unchanged, while each **b** will be rotated clockwise about the direction of the x-axis, a first time by 90° (Table 12.7), a second time by 180° (Table 12.8) and a third time by 270° (Table 12.9).

Table 12.6



(the four different configurations of the pairs of loops in the spin singlet state illustrated in figures 12.24-12.27)

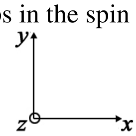
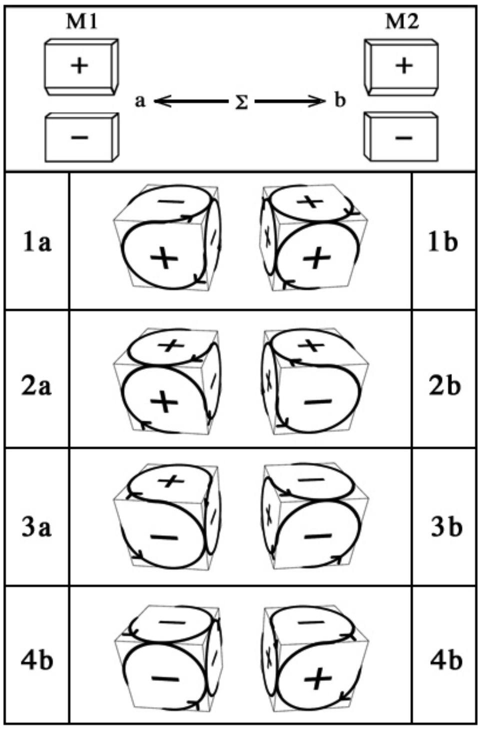
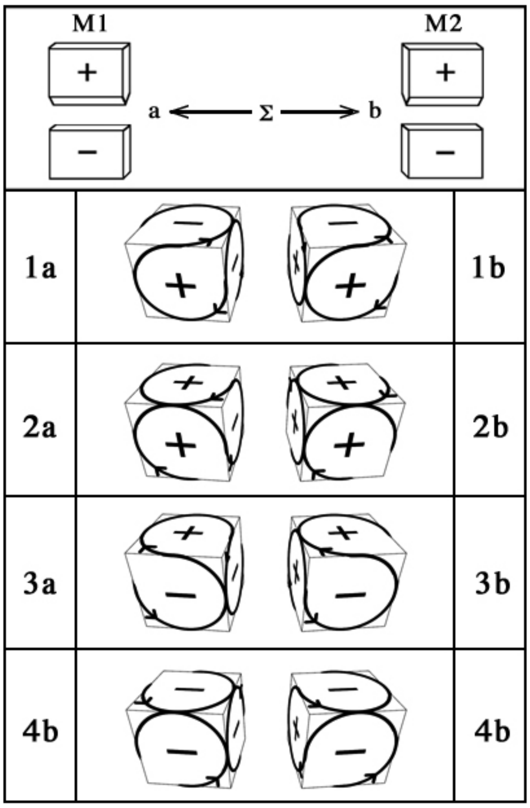


Table 12.7



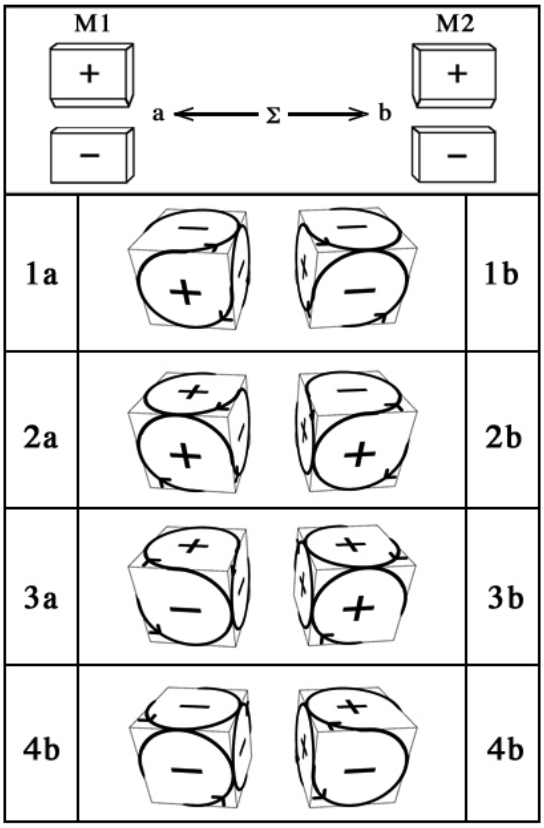
(each **b** is rotated by 90°clockwise about the positive direction of the x-axis).

Table 12.8



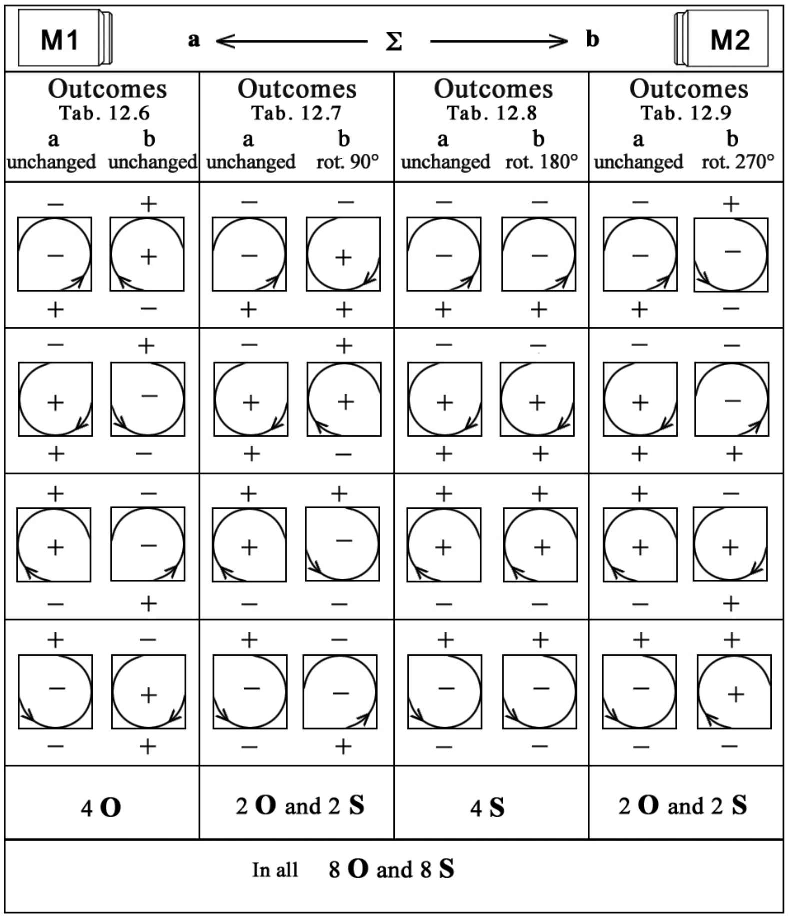
(each **b** is rotated by 180°)

Table 12.9



(each **b** is rotated by 270°).

Table 12.10



This Table summarizes all the pairs of loops which are displayed in the above four Tables and which are seen from a point perpendicular to the page. Here we can observe that the number of **O** and **S** outcomes is equally 8 for the 16 different configurations. This is an important detail which we will return to later on.

As already mentioned in the first version, in order to simplify the description, we reiterate that in all the above figures and Tables the direction of the two **DSA** belonging to each pair of loops and the direction of the magnetic field of both M1 and M2 lay on the same plane of *xy*. As in the first version, this represents clearly a particular case, about which we have to remark that the results of measurements wouldn't change at all if the **DSA** of each pair tilted over either side of the *xy* plane at an angle included in the interval ε[π/4, − π/4]. With this we also mean to say that the probabilities of obtaining opposite or same results by joint measurements of spin need not involve trigonometric calculation (nevertheless, trigonometry will play a role in experimental setups where a beam of particles is emitted from a source and propagates along a line perpendicular to a pair of detectors in sequence, each oriented along a direction that forms a given angle ϑ with the direction of the other, as explained in chapter I).

11. ***Calculation of probabilities P_O and P_S obtainable by joint measurements of spin, depending on the choice of the orientation for the four S-G apparatuses (two situated in the left sector and two in the right sector).***

Referring again to the experimental setup of figure 12.2, where the directions of the four S-G apparatuses, *a*, *a*', *b*, *b*', are respectively oriented at 0°, 90°, 45°, 135°, we are going to calculate and list in Table 12.11 the probabilities *P***o** and *P***s** for each of the four different configurations of the pair of loops.

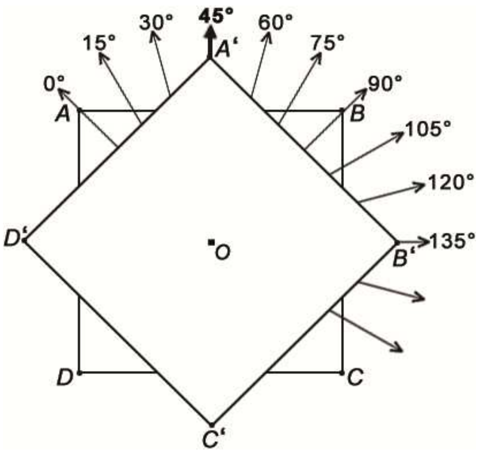


Fig. 12.30

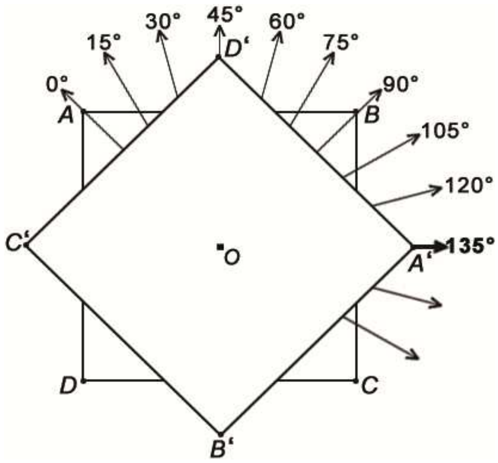


Fig. 12.31

In each of these figures the two hexahedrons are seen perpendicularly to the page and to the direction of propagation of their respective loops, **a** (behind) and **b** (in front), which here are not shown for avoiding confusion. In figure 12.30 the loop **b** is rotated by 45° with respect to **a**, while in figure 12.31 it is rotated by135°).

In the following calculations we are supposing that the experiment is repeated a great number of times, so that the four different configurations, as well as the four random combinations of spin detection (a b, a b', a' b, a' b'), will all recur with equal probability.

Table 12.11

Calculation of probabilities *P***o** and *P***s** for each of the 4 configurations (c1, c2, c3, c4) with $\vartheta = (a\wedge b) = (a'\wedge b) = (a'\wedge b') = 45°$		
configurations	*P***o**	*P***s**
C1	*P***o** = 1	-
C2	*P***o** = ½	*P***s** = ½
C3	*P***o** = 1	-
C4	*P***o** = ½	*P***s** = ½

Sum of all *P*o = 3.
Sum of all *P*s = 1.

Subtracting from the sum of all *P*o the sum of all *P*s and dividing by 4 (since we are considering 4 experiments corresponding to the 4 different configurations that each pair of loops can assume [as explained in the above paragraph, Table 12.6)], we will obtain:

$$E(a, b) = E(a', b) = E(a', b') = \tfrac{1}{4}\,(3 - 1) = \tfrac{1}{2}. \qquad (9)$$

Table 12.12

Calculation of probabilities *Po* and *Ps* for each of the 4 configurations (c1, c2, c3, c4) with $\vartheta = (a\wedge b') = 135°$		
configurations	*Po*	*Ps*
C1	*Po* = ½	*Ps* = ½
C2	-	*Ps* = 1
C3	*Po* = ½	*Ps* = ½
C4	-	*Ps* = 1

Sum of P_O = 1.
Sum of P_S = 3.
For the 4 different configurations we have

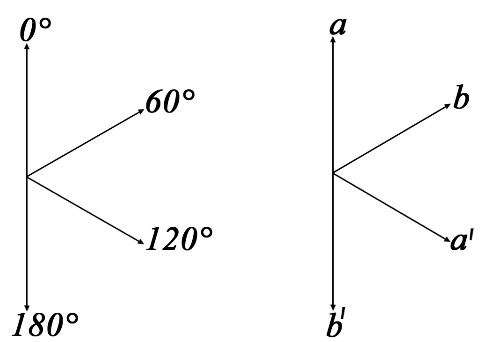
$$E(\mathrm{a}, \mathrm{b}') = ¼ (1 - 3) = -½ \tag{10}$$

According to (6), we can calculate the value of Q from (9) and (10), obtaining

$$Q = ½ - (-½) + ½ + ½ = \mathbf{2} \tag{11}$$

which represents the positive limit of Bell's inequality (5).

We will now examine the same situation choosing (a^b) = (a'^b) = (a'^b') = 60° and (a^b') = 180° (see graphs and figures 12.32 – 12.33), again with the aim of calculating the probabilities P_O and P_S for each of the four different configurations.



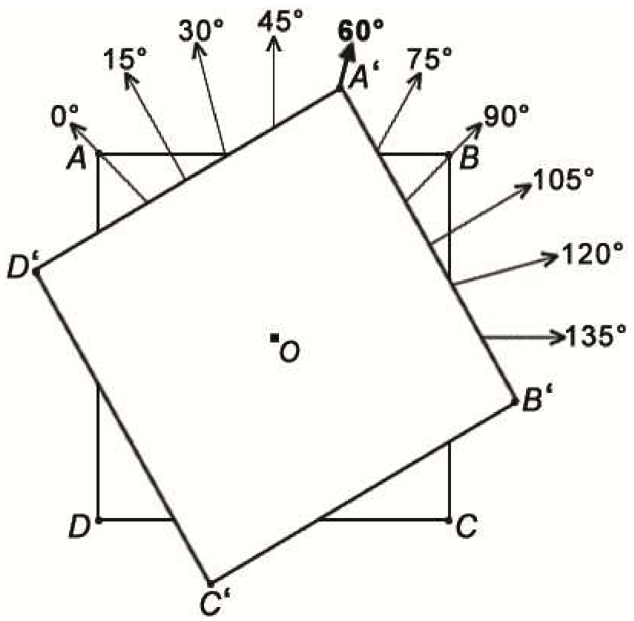


Fig. 12.32

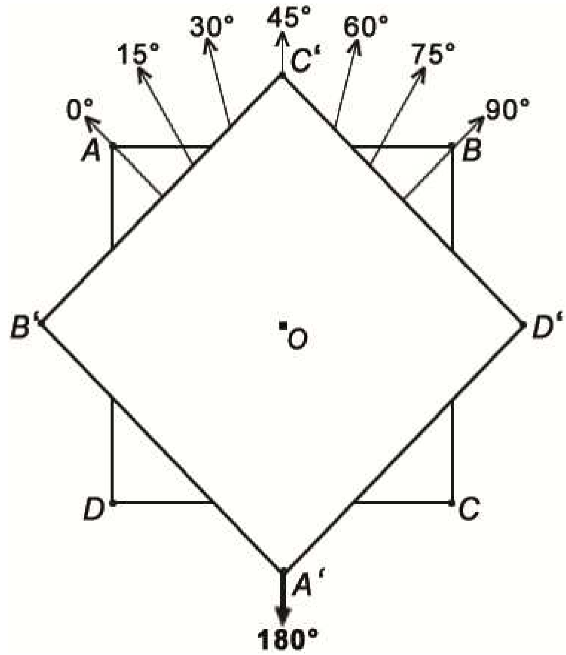


Fig. 12.33

(in figure 12.32 **b** is rotated by 60° with respect to **a**, while in figure 12.33 it is rotated by 180°).

Table 12.13

Calculation of probabilities Po and Ps for each of the 4 configurations (c1, c2, c3, c4) with $\vartheta = (a \wedge b) = (a' \wedge b) = (a' \wedge b') = 60°$		
configurations	Po	Ps
C1	Po = 1	-
C2	Po = 1/3	Ps = 2/3
C3	Po = 1	-
C4	Po = 1/3	Ps = 2/3

Sum of Po = 8/3
Sum of Ps = 4/3
so, for the 4 different configurations, we'll have

$$E(a, b) = E(a', b) = E(a', b') = \tfrac{1}{4}\,(4/3) = \mathbf{1/3} \qquad (12)$$

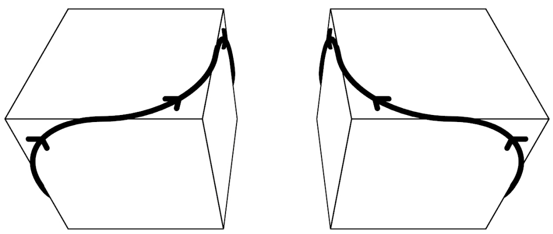
Table 12.14

Calculation of probabilities Po and Ps for each of the 4 configurations (c1, c2, c3, c4) with $\vartheta = (a\wedge b') = 180°$		
configurations	Po	Ps
C1	-	$Ps = 1$
C2	-	$Ps = 1$
C3	-	$Ps = 1$
C4	-	$Ps = 1$

Sum of all $P_O = 0$
Sum of all Ps = 4
and $E(a, b') = ¼ (0 − 4) = \mathbf{-1}$ (13)
thus, from (12) and (13) we will have:
$Q = 1/3 − (− 1) + 1/3 + 1/3 = \mathbf{2}.$ (14)

12. ***A pair of loops $LC_{1/4}$ of the hexahedron simulating a pair electron-positron.***

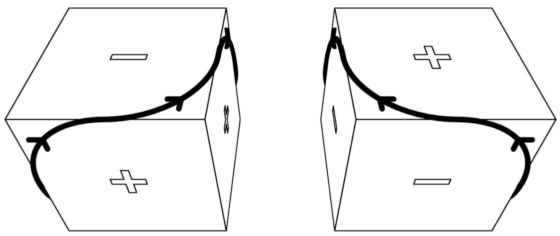
In order to propose a plausible idea of how to conceive a pair of electron-positron we can now consider, instead of the Loop $LC_{3/4}$, the simpler Loop $LC_{1/4}$ and its mirror image, as shown in figure 12.34.



Loop $LC_{1/4}$ Mirror image

Fig. 12.34

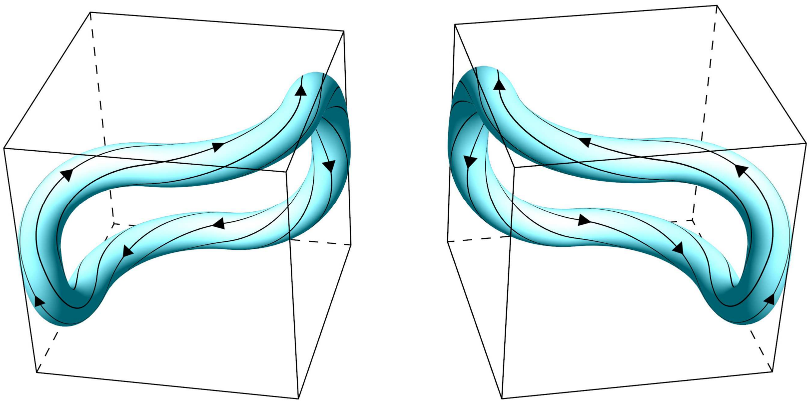
(pair of loops simulating a pair electron-positron in the spin singlet state just after being separated)



a **b**

Fig. 12.35

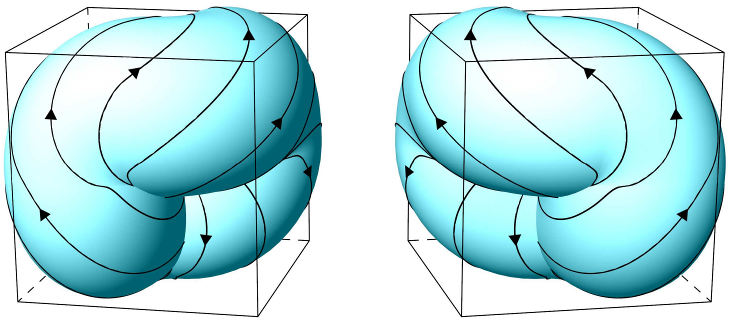
The description which is supposed to follow will be avoided for a simple reason: all the Tables and the calculation of probabilities of obtaining same or opposite outcomes from joint measurements of spin through the four S-G apparatuses *a*, *a*’, *b*, *b*’, whose directions are maintained respectively oriented at 0°, 90°, 45°, 135°, as in figure 12.2, (or at 0°, 120°, 60°, 180°), would be substantially the same that we have obtained in the previous section, on condition that a very large number of experiments are executed. The only difference, as we can see in figures 12.36-37, consists in the effects deriving from the charge, which is described as a left-handed chirality for the loop **a** and as a right-handed chirality for the loop **b**; more precisely, the loop **a** is a flux with two units of left chrality, while **b** is a flux with two units of right chirality, in both cases corresponding to 720° of twist.



a **b**

Fig.12.36

(**a** and **b** are here shown as spherical tori which have left-handed and right-handed chirality, respectively; note that these two *LV* (Loops of volume), since they have been derived from the above pair of *LC* (loops of curve) , will be spinning as shown in figure12.35)



a **b**

Fig. 12.37

(in this case, the section of each loop is extended up to its center)

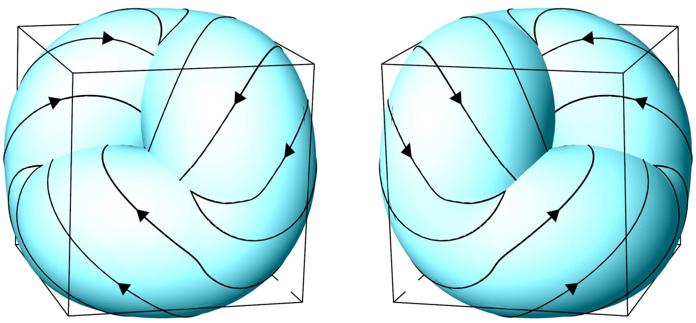


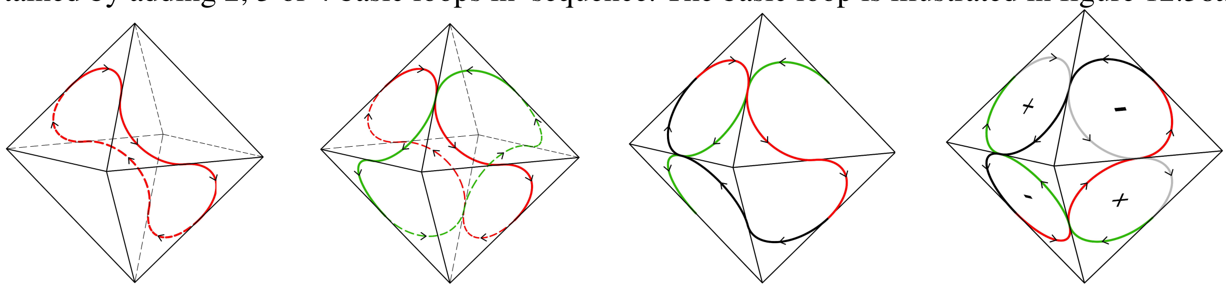
Fig. 12.37bis

(same figure 12.37 from a different point of view)

PART 3

13. *The Experiment, version n. 3*

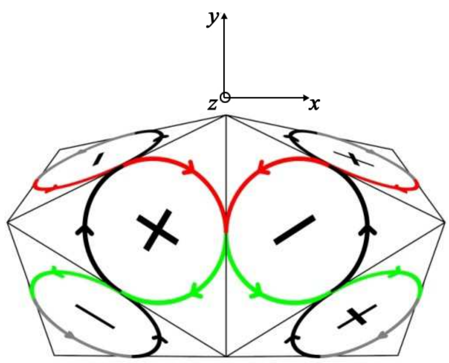
In this last version, referring to the loops of the octahedron group, we will use a pair of 4-$LC_{1/3}$ in the spin singlet state, as shown in chapter XI figure 11.35 *a*, and here repeated in figures 12.38*a*, *b*, *c*, *d*. We can observe that each of these particular loops (see figure 12.38*d*) is characterized by four alternative paths, each of 720° and distinguished by colour. Furthermore, we note that the two loops of figures 12.38*b* and *c*, respectively characterized by two and three alternative paths, would equally fit the description of the experiment. The above three loops are obtained by adding 2, 3 or 4 basic loops in sequence. The basic loop is illustrated in figure 12.38*a*.



$LC_{1/3}$ *a* — 2-$LC_{1/3}$ *b* — 3-$LC_{1/3}$ *c* — 4-$LC_{1/3}$ *d*

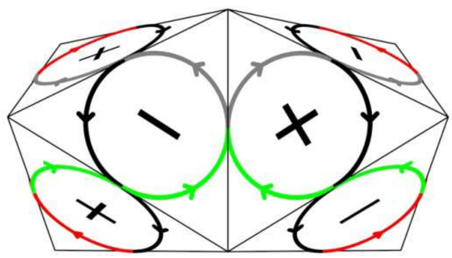
Figg. 12.38 *a*, *b*, *c*, *d*.

(figure *a* represents the basic loop of 720°, while *b*, *c* and *d* are, respectively, the combination of 2, 3 and 4 *a*-loops)



a **b**

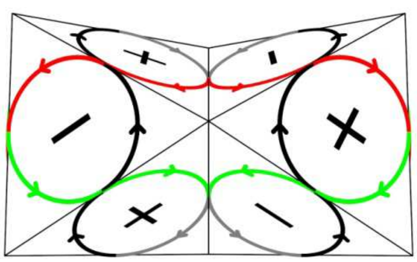
Fig. 12.39



b **a**

Fig.12.40

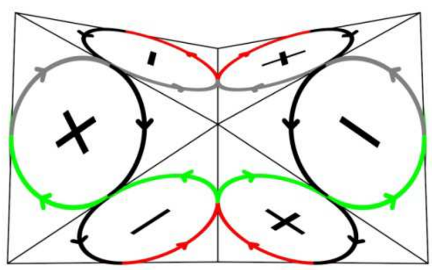
figure 12.9 rotated by 180° about the y-axis



a **b**

Fig.12.41

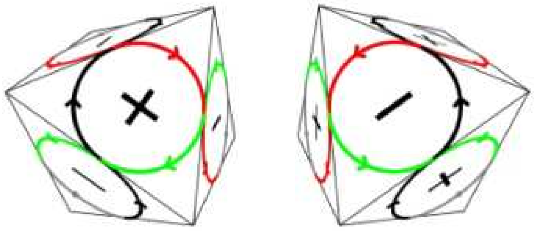
(figure 12.39 rotated by 180° about the x-axis)



b **a**

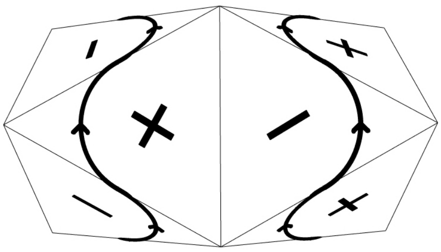
Fig. 12.42

(figure 12.41 rotated by 180° about the y-axis)



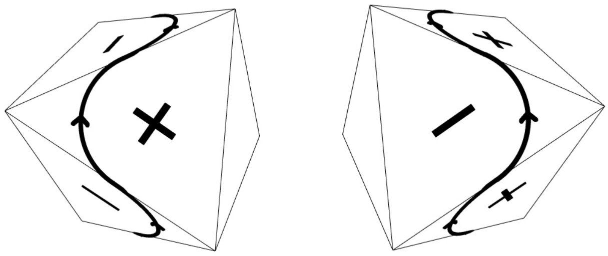
a **b**

Fig. 12.43
(the two components of figure 12.39)



a **b**

Fig. 12.44

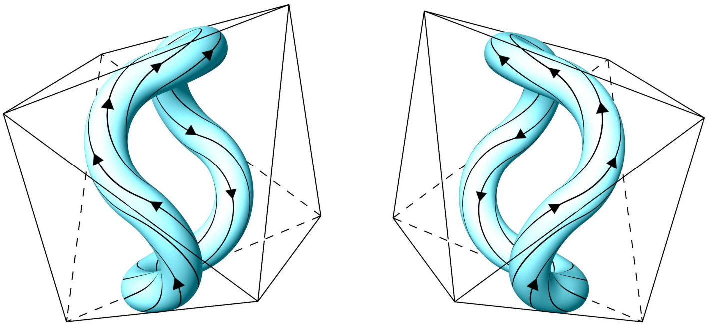


a **b**

Fig. 12.44 bis

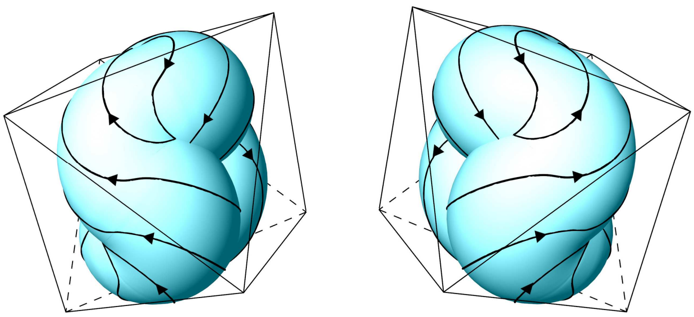
(pair of 1-$LC_{1/3}$ simulating a pair electron-positron in the spin singlet state; this pair has been obtained considering the pair of black loops of figure 12.39 and 12.43)

Adding two extra dimensions to the above pair of loops, we obtain two spherical tori, which in this case are also characterized by chirality (figure 12.45).



a **b**

Fig. 12.45
(pair of spherical tori, **a** and **b**, respectively with left-handed and right-handed chirality)



a **b**

Fig. 12.45*bis*
(this is a limit case of the spherical torus, since the 2 extra dimensions added to each loop are extended up to its center)

We have shown four different configurations of the pair of loops 4-$LC_{1/3}$, **a** and **b**, in the spin singlet state,[30] but in the following description we will consider a pair of basic loops, for example the pair of figure 12.43. This pair, in the following description, will be shown with **a** and **b** separated and then with their progressive distancing from each other in opposite directions of the *x*-axis along which they propagate. The detectors M1 and M2 (both vertically oriented) towards which the pair of loops **a** and **b** are respectively directed are here positioned at the same distance from the source. However, as already explained in section 1, the result would be the same even if they were placed at different distances, no matter how great.

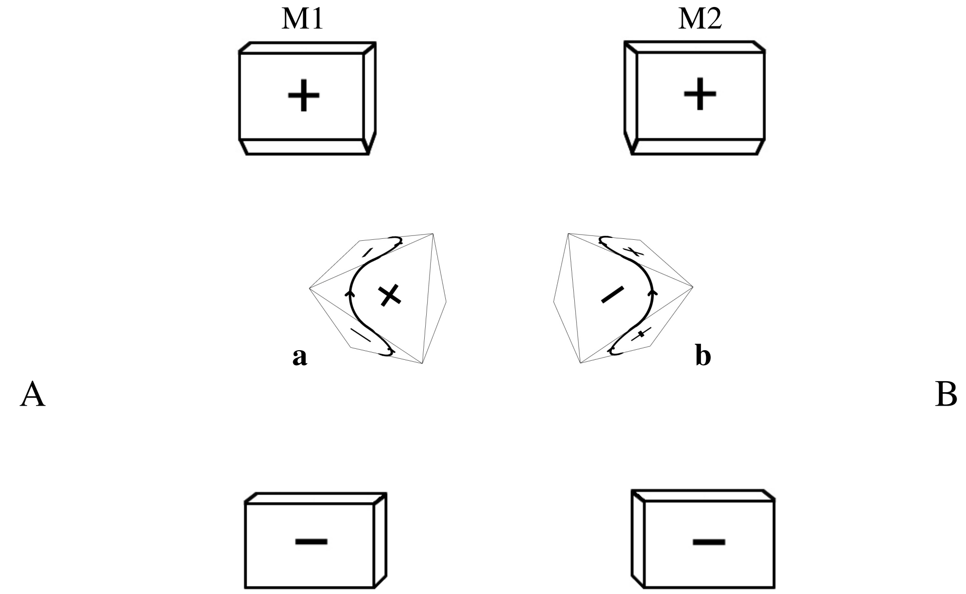


Fig. 12.46
(**a** and **b** are crossing their respective S-G magnetic fields of)

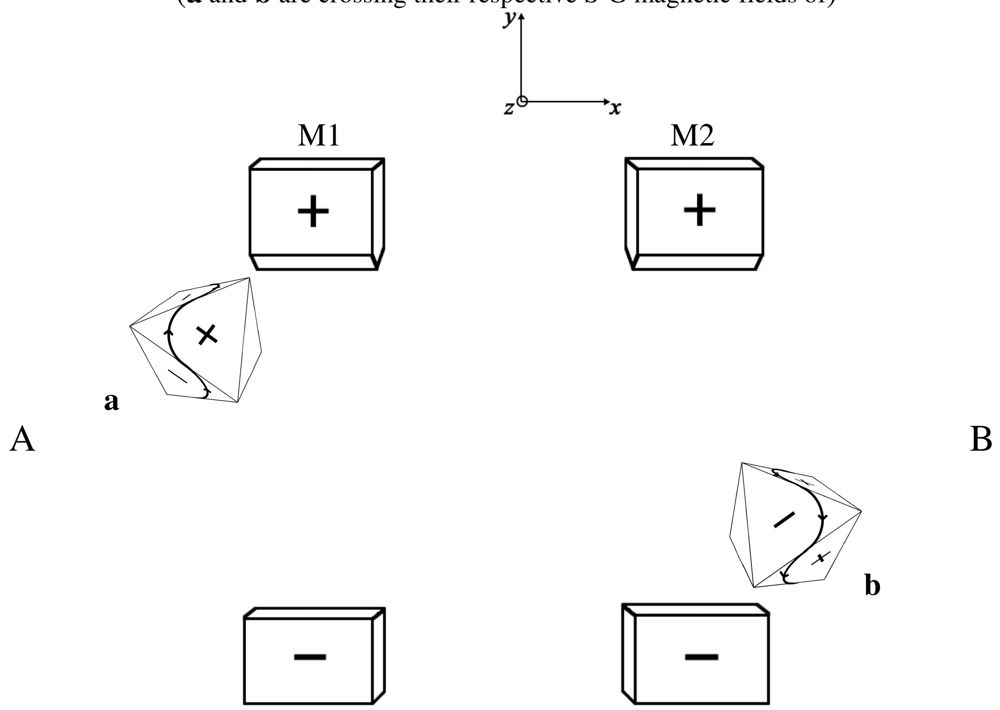


Fig. 12.47
(A will measure **a**'s spin s=y−, while B will measure **b**'s spin s=y+)

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[30] In this case, their spin axes, two by two, are not antiparallel, but converge forming an angle of 38,94244°.

We note, like in the other versions, that in the above figures 12.46-47 the direction of the two **DSA** of the pair of loops and the direction of the magnetic field of both M1 and M2 lay on the same plane of *xy*. So, this is again an extreme case, but the results of measurements wouldn't change if the **DSA** of each pair tilted over either side of the *xy* plane at an angle included in the interval ε[π/6, − π/6].[31]

If the experiment is executed a large number of times, we can calculate the probabilities *P***o** and *P***s** of obtaining opposite and same outcomes, according to the directions along which we decide to orientate the detectors *a*, *b*, *a*', *b*' (see figure 12.2). Then, we can consider three different choices for the respective directions of the four detectors: at 0°, 20°, 40°, 60° - at 0°, 45°, 90°, 135° - at 0°, 60°, 120°, 180°. With no need to go into details, it can be demonstrated that through the first choice we will obtain $Q = 2$, while either through the second and the third choice we will have $Q = -2$.

[31] The **DSA** can vary its direction on the plane of *yz* of an angular value included in this interval, since the loop of the octahedron can be rotated 60° for six times about the *x*-axis along which it propagates (see Chapter XI, figures 11.35 *a*, *b*, *c*, *d*).

PART 4

13. ***Objections to the "neutral version of EPR and Bell's Theorem" proposed by David Mermin.***

Avoiding to describe the detailed procedure adopted by David Mermin in his conceptual experiment (ref. quoted in section 6, note 11), we will just mention his main issues.

Referring to figure 12.48, Mermin imagines that the two Stern-Gerlach apparatuses, M1 and M2, can be rotated independently of each other and regulated randomly along one of *three coplanar directions* separated by 120° and perpendicular to the line along which the pairs of particles **a** and **b** (in the spin one-half singlet state) move.

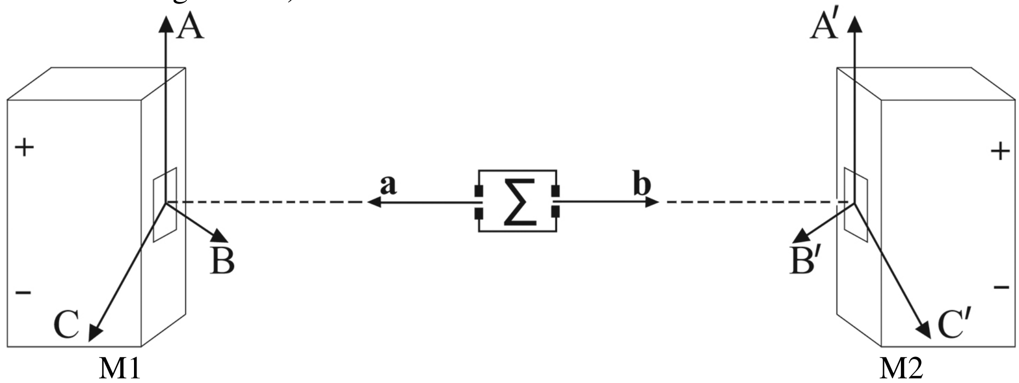


Fig. 12.48

Then, after having examined the data accumulated in a large number of runs, he highlights the two following relevant features:

(i) In those runs in which the two detectors happen to have been given the same settings, the outcomes of spin measurements are always opposite (+ − or − +).

(ii) If all runs are examined without any regard to the settings of the detectors, then the pattern of outcomes is completely random. In particular, the probability of obtaining opposite or same outcomes is equally ½.

These features are a consequence of QM formalism. Therefore, Mermin affirms that, if the hidden variables of local theories were correct for explaining feature (i), then the probability of obtaining opposite outcomes, without regard to the settings of the two detectors, will be

$$P\mathbf{o} \geq \mathbf{5}/9,$$

contradicting feature (ii). Thus Mermin, from his conceptual experiment based on rigorous logic, draws the conclusion that the above relation represents the *simple version of Bell's inequality* (also called "Bell's baby inequality") and that, consequently, all local realistic models must be rejected.[32]

Well, we have come to the same conclusion in our first version of the experiment (section 8, Table 12.5 and following Table 12.15), based on

pairs of loops $LC_{1/3}$ of the tetrahedron

in the spin singlet state, according to which we have to admit an *incompatibility* with QM.

---

[32] These kinds of experiments have never been executed and in the next future they may become possible. In that case, they could allow us to discriminate between the results predicted by QM and those predicted by version n. 2 or n. 3 of our experiment).

This is not at all surprising, because the experimental setup of our first version is equivalent to Mermin's conceptual experiment, the only relevant difference being in additional properties explicitly described for our pairs of loops. Therefore, should we say that Mermin's demonstration is correct? We will provide an answer to this question in a while, just after a few careful considerations.

Table 12.15

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	120°	1/3	2/3
0°	240°	1/3	2/3
120°	120°	1	—
120°	240°	1/3	2/3
120°	0°	1/3	2/3
240°	240°	1	—
240°	0°	1/3	2/3
240°	120°	1/3	2/3

This Table, where the number of all different settings of M1 and M2 is $3^2 = 9$, can be divided into three equivalent basic Tables, each composed of three consecutive settings and we can observe that one of them, for example the basic Table composed of the first three settings (0° and 0°, 0° and 120°, 0° and 240°), is sufficient to calculate the correct probabilities of **O** and **S** outcomes. This is a simplified procedure that we will take into account for all following relations and Tables.

We have seen in the description of our first experimental version that, supposing to execute a large number of runs, in each of which M1 and M2 are rotated independently from each other and regulated randomly along any of the three directions separated by 120°, the probabilities (P**o** and P**s**) of obtaining, from joint measurements of spin, **O** and **S** outcomes, applying the above procedure, will be:

$$P\mathbf{o} = \frac{1}{3}\left(1 + \frac{1}{3} + \frac{1}{3}\right) = \mathbf{5/9}$$

$$P\mathbf{s} = \frac{1}{3}\left(0 + \frac{2}{3} + \frac{2}{3}\right) = \mathbf{4/9},$$

while quantum mechanics predicts **O** and **S** results with equal probability ½. We will now see why by examining the three different cases which can occur:

1st case) – when the detectors M1 and M2 (or when the loops **a** and **b**, according to the equivalent procedure adopted in Table 4) are both oriented in the same way, the probability of obtaining **O** outcomes is $P\mathbf{o} = \mathbf{1}$.
2nd case) - when the directions of M1 and M2 are each other oriented at an angle of 120° , $P\mathbf{o} = \frac{1}{2}(1+\cos 120°) = \mathbf{1/4}$.
3rd case) - when the directions of M1 and M2 are each other oriented at an angle of 240°, $P\mathbf{o} = \frac{1}{2}(1+\cos 240°) = 1/4$.

Each of above three cases has probability 1/3 to be realized. Hence, the global probability of obtaining **O** results predicted by QM is:

$$P\mathbf{o}_{\mathrm{qm}} = P\mathbf{s}_{\mathrm{qm}} = \frac{1}{3}\left(1 + \frac{1}{4} + \frac{1}{4}\right) = \frac{1}{2}$$

.

Before raising objections to Mermin's conceptual experiment, we want to be very scrupulous. We are going to assign to each detector an arbitrary even number of directions separated by a same angular value, for example 24 directions separated by 15°. If we consider all the possible combinations of how the directions of M1 and M2 can be set with respect to each other, their number is $24^2 = 596$; but a Table with such a long list, as we have remarked in the paragraph under Table 12.15, can be subdivided into 24 equivalent Tables. Therefore, the following basic Table 12.16 will be representative of the complete list of 596 settings (note that here all the fractions, in order to simplify their sum, have the same denominator).[33]

Table 12.16

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	12/12	—
0°	15°	11/12	1/12
0°	30°	10/12	2/12
0°	45°	9/12	3/12
0°	60°	8/12	4/12
0°	75°	7/12	5/12
0°	90°	6/12	6/12
0°	105°	5/12	7/12
0°	120°	4/12	8/12
0°	135°	4/12	8/12
0°	150°	4/12	8/12
0°	165°	4/12	8/12
0°	180°	4/12	8/12
0°	195°	4/12	8/12
0°	210°	4/12	8/12
0°	225°	4/12	8/12
0°	240°	4/12	8/12
0°	255°	5/12	7/12
0°	270°	6/12	6/12
0°	285°	7/12	5/12
0°	300°	8/12	4/12
0°	315°	9/12	3/12
0°	330°	10/12	2/12
0°	345°	11/12	1/12

Total **O**s = 40/3, total **S**s = 32/3.

Since here the two detectors have 24 different settings, if we execute a large number of runs, the probabilities of obtaining **O** and **S** outcomes by joint measurements of spin will be the same as before:

$$P\mathbf{o} = 1/24 \times 40/3 = \mathbf{5/9}$$
$$P\mathbf{s} = 1/24 \times 32/3 = \mathbf{4/9}$$

From Table 12.16 it's quite easy to deduce that, even if M1 and M2 were independently and randomly set at any orientation from 0° to 360°, the result would be again the same. Consequently,

[33] The correctness concerning the calculation of probabilities to obtain the opposite and same outcomes listed in each of the twelve Tables from 12.15 up to 12.26 can be demonstrated foffowing a procedure analogous to that adopted in figures 12.30 - 12.33.

we have definitively ascertained that *the first version of our theoretical experiment is in conflict with QM*.

It is now important to ask a question: *does the technical Bell's inequality*, P**o** $\geq$ **5/9**, *proposed by Mermin imply a universal validity?* Well, I think the answer is negative. In fact it can be demonstrated that, in the case of models based on the loop's properties introduced in the second and third versions, the three directions (separated by 120°) proposed in Mermin's argument are not representative of *the whole continuum of all possible directions*. Let's see then which conclusions can be drawn by dealing with these loops. For this purpose, we will consider the second version of the experiment, where the source emits

pairs of loops $LC_{3/4}$ of the hexahedron

in the spin singlet state, and calculate the probabilities ($P_{\mathbf{O}}$ and $P_{\mathbf{S}}$) of obtaining *opposite* and *same* outcomes from joint measurements effectuated in a large number of runs in which the detectors M1 and M2 are not limited to only three positions.

If we follow the reasoning adopted by Mermin (assigning to M1 and M2 three only directions separated by 120°), the probability of obtaining **O** results will be P**o = 5/9**. You can check the truth of this conclusion simply consulting Tables 12.18, 12.19, 12.20 and considering only the settings of the detectors M1 and M2 respectively at 0° and 0°, 0° and 120°, 0° and 240° (which are the same already shown in Tale 12.15). But here is the point where we can highlight the weakness of Mermin's argument! In fact, if we choose five directions separated by 72°, we will have 25 pairs of different settings for M1 and M2, and the basic Table 12.17 will be representative of the complete list.

Table 12.17

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	72°	3/5	2/5
0°	144°	1/5	4/5
0°	216°	1/5	4/5
0°	288°	3/5	2/5

P**o** = 1/5x13/5 = 13/25 = **0,52** < 5/9

Therefore, *the technical version of Bell's inequality* stated by Mermin in clearly ***violated.***[34]

Now we will choose nine directions separated by 40°, then fifteen directions separated by 24°, as displayed in the respective Tables 12.18 and 12.19.

[34] The correctness of calculation of probabilities referred to **O** and **S** outcome listed in each Table can be demonstrated. .

Table 12.18

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	40°	7/9	2/9
0°	80°	5/9	4/9
0°	120°	1/3	2/3
0°	160°	1/9	8/9
0°	200°	1/9	8/9
0°	240°	1/3	2/3
0°	280°	5/9	4/9
0°	320°	7/9	2/9

***P*o** =1/9x41/9 = 41/81 = **0,506** < 5/9

Table 12.19

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	24°	13/15	2/15
0°	48°	11/15	4/15
0°	72°	3/5	2/5
0°	96°	7/15	8/15
0°	120°	1/3	2/3
0°	144°	1/5	4/5
0°	168°	1/15	14/15
0°	192°	1/15	14/15
0°	216°	1/5	4/5
0°	240°	1/3	2/3
0°	264°	7/15	8/15
0°	288°	3/5	2/5
0°	312°	11/15	4/15
0°	336°	13/15	2/15

***P*o** = 1/15x113/15 = 113/225 = **0,502** < 5/9

Abandoning the odd numbers of directions which clearly violate the Bell's simple version enunciated by Mermin, we are now going to deal with even numbers, starting from six directions separated by 60°, i.e. at 0°, 60°, 120°, 180°, 240° 300°. If we execute a large number of runs operating on detectors M1 and M2 in the usual way, we will obtain a result in total agreement with features (i) and (ii) stated by Mermin. Indeed, following this criterion, we find that the probability of obtaining **O** and **S** outcomes is equally ½, as clearly shown in Table 12.20.[35] We have to underline that such a result is connected with a plausible new physical concept concerning the dynamical properties of the electron.

Table 12,20

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	60°	2/3	1/3
0°	120°	1/3	2/3
0°	180°	—	1
0°	240°	1/3	2/3
0°	300°	2/3	1/3

Total **O** = 3, total **S** = 3
and therefore, if we execute a large number of runs, the probabilities of obtaining opposite results and same results from these 6 different settings of the two detectors will be equally ½:

$$P\mathbf{o} = P\mathbf{s} = 1/6 \text{x} 3 = \mathbf{1/2}$$

Note that this result, if we suppose to execute the experiment with a very large number of trials, is the same derived from Table 12.10, because each of its 16 configurations would recur with the same probability of the others, and the final result would be $P\mathbf{o} = P\mathbf{s} = 1/16 \cdot 8 = \mathbf{1/2}$ (observe that in Table 12.10 the four rotations of the loop **b** with respect to **a**, are equivalent to assigning to M1 and M2 four directions separated by 90°).

Since, as usual, we like to be very careful, we will assign to each detector 24 directions separated by 15° (Table 12.21).

[35] In this case there are 36 possible combinations, but it is not necessary to list all of them, since, as stressed before, just the six combinations listed in Table 12.22 are sufficient to represent the whole set of 36.

Table 12.21

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	12/12	—
0°	15°	11/12	1/12
0°	30°	10/12	2/12
0°	45°	9/12	3/12
0°	60°	8/12	4/12
0°	75°	7/12	5/12
0°	90°	6/12	6/12
0°	105°	5/12	7/12
0°	120°	4/12	8/12
0°	135°	3/12	9/12
0°	150°	2/12	10/12
0°	165°	1/12	11/12
0°	180°	—	12/12
0°	195°	1/12	11/12
0°	210°	2/12	10/12
0°	225°	3/12	9/12
0°	240°	4/12	8/12
0°	255°	5/12	7/12
0°	270°	6/12	6/12
0°	285°	7/12	5/12
0°	300°	8/12	4/12
0°	315°	9/12	3/12
0°	330°	10/12	2/12
0°	345°	11/12	1/12

*P***o** = *P***s =**1/24x12 = **1/2**

(compare this Table with Table 12.16 and see the difference)

If we assume the validity of the 3 exclusive directions for M1 and M2 (at 0°, 120°, 240°), as stated in Mermin's argument, the result (*P***o = 5/9**) would be misleading, since there are evident cases (described in the five Tables 12.17 – 12.21) in which those 3 directions do not represent the statistical average of all possible directions (from 0° to 360°) for the settings of the two detectors, if these are rotated independently and regulated at random in each of a large number of runs.

Furthermore, we can insist in disproving the line of Mermin's reasoning, this time taking into account

pairs of loops 4-$LC_{1/3}$ of the octahedron

in the spin singlet state. The implications are surprising, as shown in Table 12.22.

Table 12.22

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	120°	1	—
0°	240°	1	—
120°	120°	1	—
120°	240°	1	—
120°	0°	1	—
240°	240°	1	—
240°	0°	1	—
240°	120°	1	—

*P***o = 1**

This result, if compared with that of Table 12.15, is bewildering, but, as you will see, the following Tables represent another good reason for undermining Mermin's argument.

In order to demonstrate a violation of the simple Bell's Theorem, we are going to start by assigning to each detector 5 directions separated by 72° and, after, 15 directions separated by 24° (Tables 12.23-12.24).

Table 12.23

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	72°	3/5	2/5
0°	144°	1/5	4/5
0°	216°	1/5	4/5
0°	288°	3/5	2/5

*P***o** = 13/25 = **0,52** < 5/9

The above Table is the same as Table 12.17, which concerns pairs of loops of the hexahedron.

Table 12.24

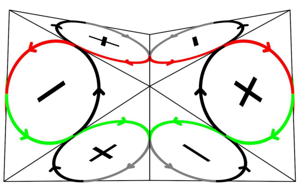
M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	—
0°	24°	3/5	2/5
0°	48°	1/5	4/5
0°	72°	1/5	4/5
0°	96°	2/5	3/5
0°	120°	1	—
0°	144°	3/5	2/5
0°	168°	1/5	4/5
0°	192°	1/5	4/5
0°	216°	3/5	2/5
0°	240°	1	—
0°	264°	3/5	2/5
0°	288°	1/5	4/5
0°	312°	1/5	4/5
0°	336°	3/5	2/5

*P***o** = 13/25 = **0,52** < 5/9.

As you can see, both Tables 12.22 and 12.23 imply *P***o** = **0,52**, which represents a clear violation of the simple version of Bell's Theorem established by Mermin.

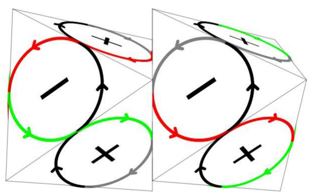
We will now go on dealing with even numbers of directions: first, six directions separated by 60°, and then 24 separated by 24°, as shown in Tables 12.25-12.26.

Figures 12.49-50 will help to understand that the results obtainable by joint measurements of spin on **a** and **b** will all be **S** (+ +, − −) if the two detectors M1 and M2 are rotated by 60°, 180° or 300° with respect to each other,[36] while the results will all be **O** (+ −, − +) if they are rotated by 0°, 120° or 240°, as shown in Table 12.22. Then we will obtain the same result choosing any number of directions that is a multiple of six, for example 24 separated by 15°, as in Table 12.23.



a **b**

Fig 12.49



a **b**

Fig. 12.50

In figure 12.49, **a** and **b** are in the spin singlet state, while in figure 12.50 they are rotated by 60° with respect to each other. If in these two different configurations **a** and **b** are rotated by

[36] In figures 12.49 - 50 we follow the equivalent procedure explained in section 8, figures 12.13-15 (leaving both detectors oriented in the same way and rotating the loop **b** with respect to **a** around the *x*-axis by the chosen angles).

120° or 240° with respect to each other, the result obtained will be equivalent to the initial configuration.

Table 12.25

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	–
0°	60°	–	1
0°	120°	1	–
0°	180°	–	1
0°	240°	1	–
0°	300°	–	1

*P***o** = *P***s** = 1/6x3 = ½

Table 12.25 includes the same six combinations of Table 12.20 and, although being different for what concerns the numerical values of each outcome (since Table 12.20 refers to the properties of pairs of loops ***LC*** $LC_{3/4}$ **of the hexahedron** in the spin singlet state), it implies the same final result: *P***o** and *P***s** are equally ½, as also predicted by QM.

Table 12.26

M1	M2	Probability **O** Outcome	Probability **S** Outcome
0°	0°	1	–
0°	15°	3/4	1/4
0°	30°	1/2	1/2
0°	45°	1/4	3/4
0°	60°	–	1
0°	75°	1/4	3/4
0°	90°	1/2	1/2
0°	105°	3/4	1/4
0°	120°	1	–
0°	135°	3/4	1/4
0°	150°	1/2	1/2
0°	165°	1/4	3/4
0°	180°	–	1
0°	195°	1/4	3/4
0°	210°	1/2	1/2
0°	225°	3/4	1/4
0°	240°	1	–
0°	255°	3/4	1/4
0°	270°	1/2	1/2
0°	285°	1/4	3/4
0°	300°	–	1
0°	315°	1/4	3/4
0°	330°	1/2	1/2
0°	345°	3/4	1/4

If, in the same experiments we execute a large number of runs, assigning to each detector 24 directions separated by 15°, the probabilities of obtaining **O** and **S** results are:

*P***o** = *P***s** = 1/24x12 = **1/2**

This experiment (as well as the others examined above, in which pairs of loops of the hexahedron are involved), even though in agreement with QM, highlights a clear conflict with Mermin's argument.

Indeed, on the one hand Mermin follows a purely classic reasoning, being convinced that it suits quantum physics experiments, the effects of which derive from an unknown logic (or from unintelligible postulates), on the other hand the experimental versions which have been here proposed (the second and the third) take into consideration a model of the electron which, having well-defined properties, gives us the opportunity of denying the validity of the uncertainty and the quantum-states-superposition principles at the basis of QM.

PART 5

14. “***Entanglement*”, “*incompatible measurements of spin*” and "*indeterminism*" *are here substituted by intelligible concepts based on additional well-defined variables and determinism.***

We recall the attention to paragraph 2 in which we have imagined a source capable of emitting pairs of particles in the spin-1/2 singlet state, **a** and **b**, respectively directed towards a detector vertically oriented and a detector horizontally oriented.

The experimental setup is now sketched in figures 12.51 and 12.52, where you can see a pair of particles simulated by a pair of loops $LC_{3/4}$ of the hexahedron, two detectors labelled “M1” and “M2” and two observers, A situated on the left sector and B on the right sector.

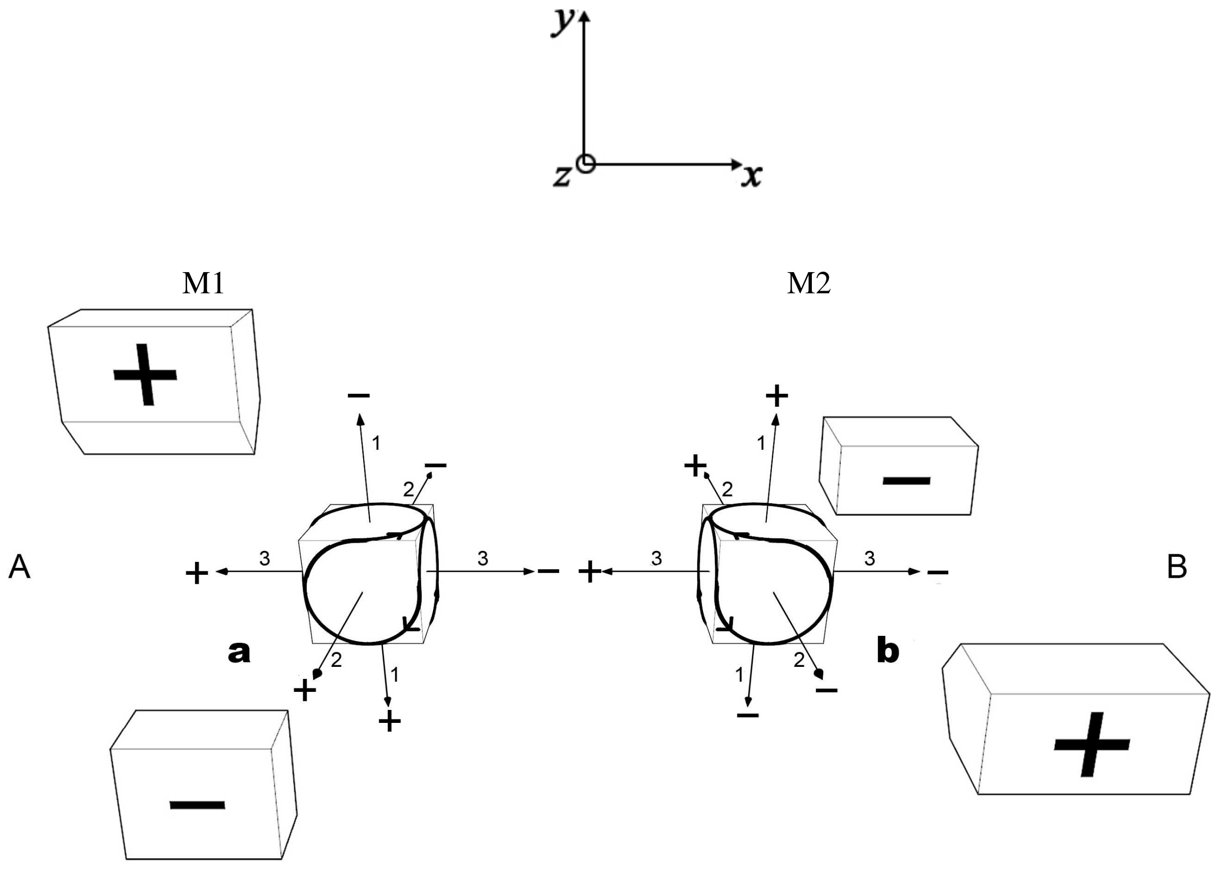


Fig. 12. 51*a*
scenario n°1

(**a**'s **DSA**=1), A will measure spin $s=y^+$ (**b**'s **DSA**=2), B will measure spin $s=z^+$

More simply, observer A will measure **a** spin *up*, while observer B will measure **b** spin left.

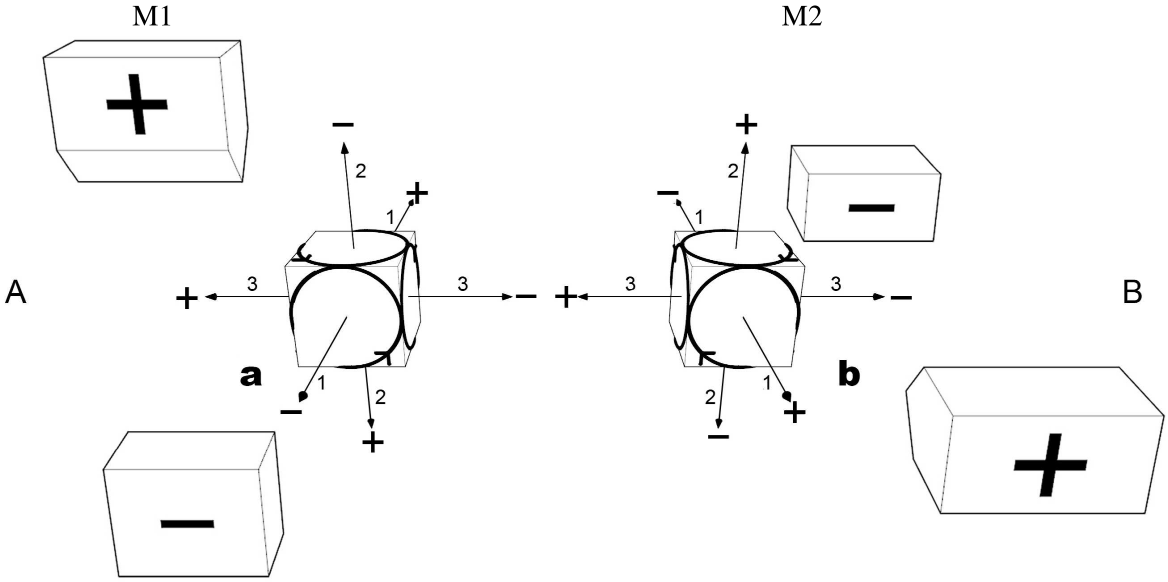


Fig. 12. 51*b*
scenario n°2
(**a**'s **DSA**=2), A will measure spin s=y^+ (**b**'s **DSA**=1), A will measure spin s=z^-

(here, the pair of loops **a** and **b**, with respect to the scenario n°1, are rotated by 90° clockwise about the positive direction of the *x*-axis: thus, the configuration has changed and, while observer A will again measure **a** spin *up*, observer B will now measure **b** spin *right;* note that the pair of loops of figure 12.51*a* would assume other different configurations if again rotated clockwise about the positive direction of the *x*-axis, a first time by 180°and a second time by 270°).

In the example sketched in the above figure, imagine that observer A measures **a**'s spin, *s*, along the *y*-axis, and finds $s_y = s+$. According to the principals of quantum theory, **b**'s spin will be in the state $| s-\rangle$. In the other sector, if observer B decides to measure **b**'s spin along the same axis, he will find $s_y = s-$ with probability *P*=1. But what happens if B decides to measure **b**'s spin along the *z*-axis? He will have probability ½ to find $s_z = s+$ and. probability ½ to find $s_z = s-$. Supposing that B finds $s_z = s+$ (spin *left*), he would deduce that **a**'s spin is now in the state *s*−, i.e. *s* right⟩. But such a supposition is meaningless if referred to the above figures 12.46, since the particle is going to be, or has already been, measured by a S-G vertically oriented.

We will have the same situation with a pair of loops of the octahedron in the spin singlet state.

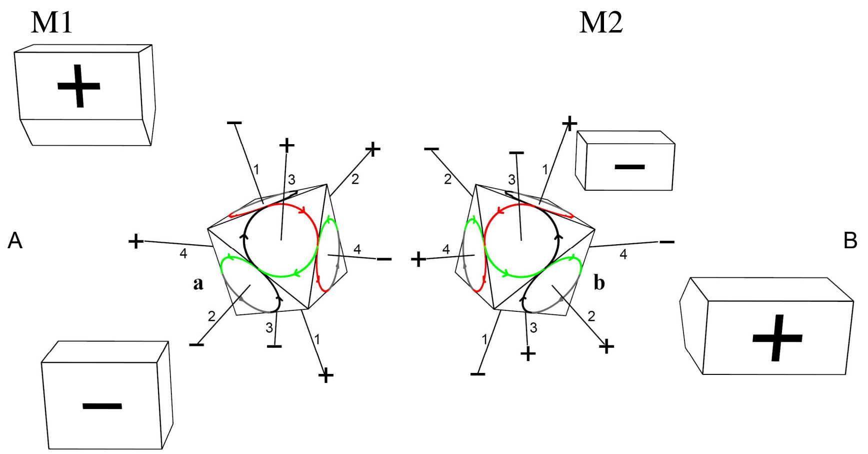


Fig. 12.52*a*
scenario n°1
(**a**'s **DSA**=1), A will measure spin s=y^+ (**b**'s **DSA**=2), B will measure spin s=z^-

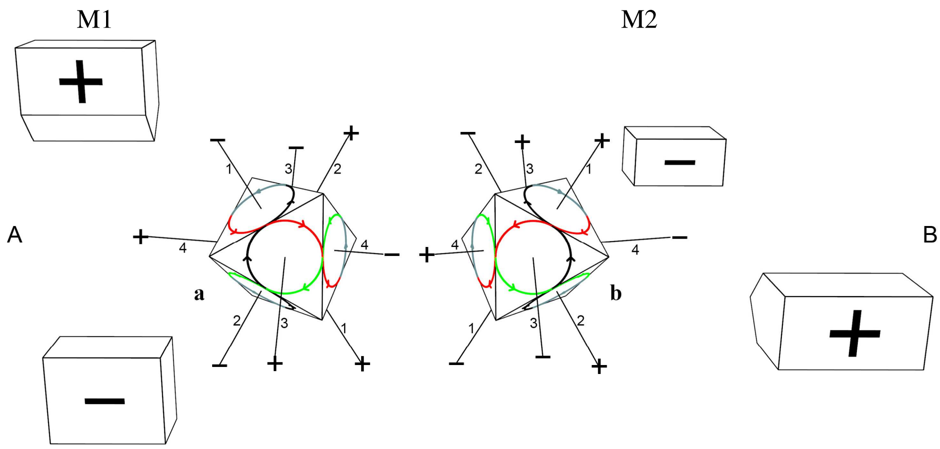


Fig. 12.52*b*
scenario n°2
(**a** and **b**, with respect to scen. n°1, are rotated by 25° clockwise around the positive direction of the *x*-axis)
(**a**'s **DSA**=1), A will measure spin $s=y^+$ (**b**'s **DSA**=2), A will measure spin $s=z^-$

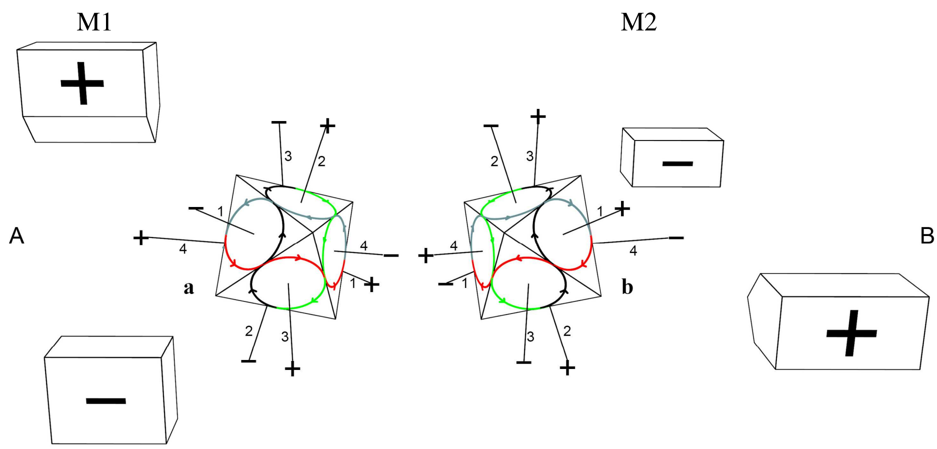


Fig. 12.52*c*
scenario n°3
(**a** and **b**, with respect to scen. n°1, are rotated by 60° clockwise around the positive direction of the *x*-axis)
(**a**'s **DSA**=2), A will measure spin $s=y^-$ (**b**'s **DSA**=3), A will measure spin $s=z^+$

In conclusion, we have to say that each observer has probability ½ to measure either the spin $s+$ or $s-$ for the simple reason that he doesn't know which of the possible scenerios is given when he is effectively going to measure the spin.

It should now be clear that, if you consider more reasonable a model of the electron based on the explicit properties illustrated in the above figures, your conclusion is that probabilities are not ontic. In fact, those figures are telling you that **a** and **b** "know" how to react with their respective detectors, no matter how A and B decide about their orientation.

15. ***A rational explanation of Stern-Gerlach-type experimental results***.

A collimated beam of silver atoms[37] vaporized in an oven is directed towards a detector containing a Stern-Gerlach apparatus, which is here oriented along the *y*-axis and has its inhomogeneous magnetic field intensity increasing from the negative component up to ihe positive component. The detector has one entrance on the left and two exits on the right which are labelled "+" and "−"(figure 12.53). The beam will be split into two beams of equal intensity. The spin *s* of the electrons belonging to the upper beam will be denoted with "*sy* = *s*+", and with "*sy* = *s*−" the spin of the electrons belonging to the lower beam.

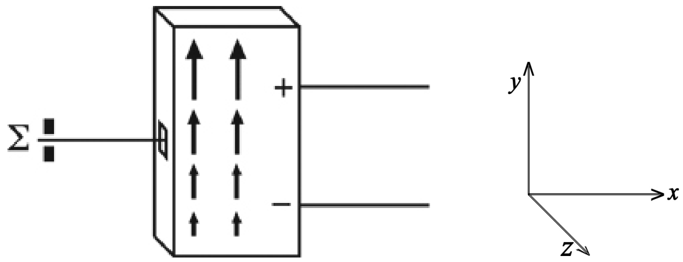


Fig. 12.53

A beam of electrons is here simulated by a sequence of *n* **loops** ***LC*¾ of the hexahedron** (figure 12.54). The use of loops $LC_{1/4}$ would substantially lead to same results (the only difference would consist in the inversion of the signs in one of the three spin axes).

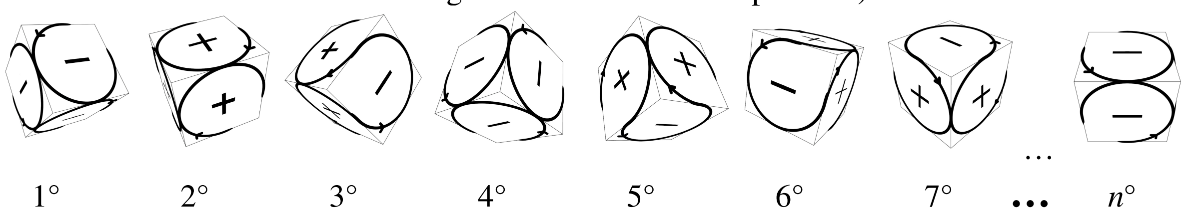


Fig. 12.54

(beam of loops $LC_{3/4}$ of the hexahedron, each spinning about three axes)

We are now going to describe, in three phases, one of the possible paths of a single loop directed towards a sequence of three detectors, labelled "M1", "M2", "M3" (the first and the third oriented along the *y*-axis and the second along the *z*-axis, as in figures 12.61 and 12.69) ,

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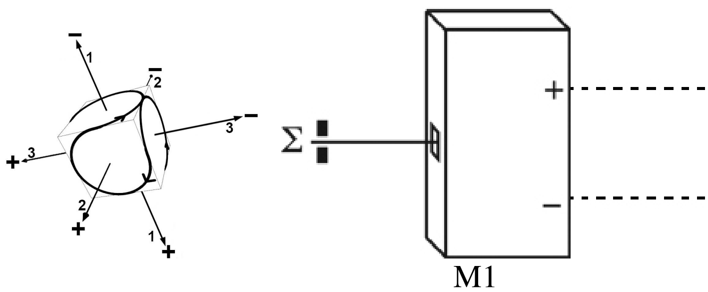


Fig. 12.55

You can see, on the left of figure 12.56, a loop in one of its possible spatial orientations directed towards M1, which is the first of three detectors in sequence:

---

[37] In a physical system such as a silver atom, its magnetic moment is associated to the magnetic angular momentum (spin) of the outmost electron.

1st phase - The loop, while crossing M1 with its **DSA** n°**1**, will be subject to a precession movement about the direction of the S-G magnetic field B (here along the *y*-axis)[38]. The **DSA**, jointly with the loop and its **spin axes 2 and 3** will rotate about B.

Although the precession movement concerns the whole loop, in order to avoid an almost complicate illustration, the following figure 12.56 will show only the double cone described by the **DSA** precession about B.

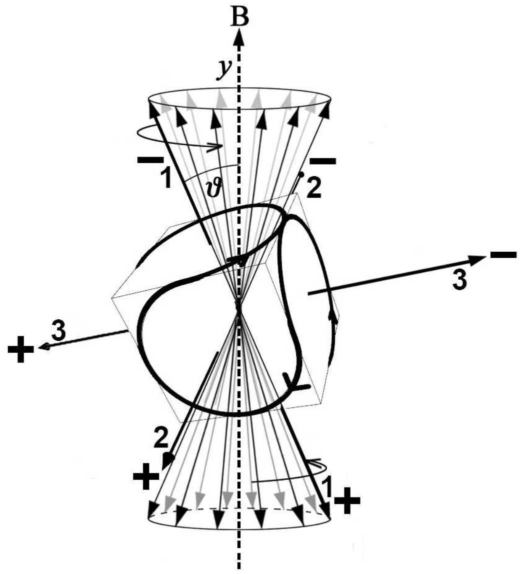


Fig. 12.56
(the **DSA 1**, while crossing M1, precesses about B, that is the direction of the S-G magnetic field)

At the end of this phase, the loop's spin component, if measured, would be found $s_y = s^+$. Hence, the loop enters into M2 (figure 12.57).

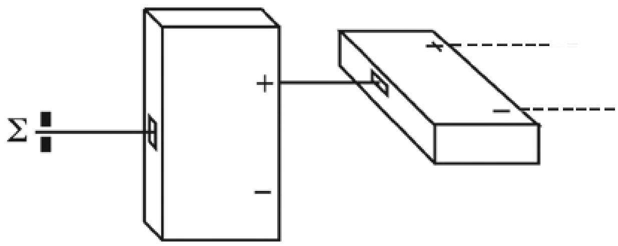


Fig. 12.57

2nd phase – The loop passes through M2, and its **DSA** will be one of the two axes 2 and 3, each with probability ½ of having the negative pole facing either the positive or the negative component of the S-G apparatus. Thus, the loop will have probability 1/4 to assume one of four possible main spatial orientations.[39] We suppose that the loop, once inside M2, has the axis **2** as **DSA** (see figure 12.58). This will precess about the direction of the S-G magnetic field B, which is now along the *z*-axis, while the whole loop with its **spin axes 1 and 3** will also precess about it.

---

[38] The angle ϑ formed between the direction of the DSA and the *y*-axis will be maintained unchanged until the loop passes through M2.

[39] The probability of obtaining one of the four possible main orientations depends on the lengths of the S-G magnet and on the loop's velocity.

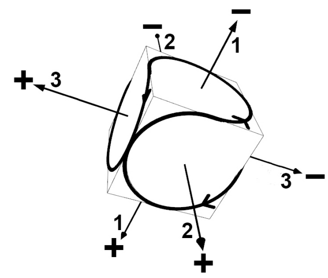


Fig. 12.58
(the loop enters M2 with the **DSA 2**)

The *z* component of spin, if it were measured at the end of this phase, would be found $s_z = s^+$; hence the loop enters into M3 (figure 12.59)

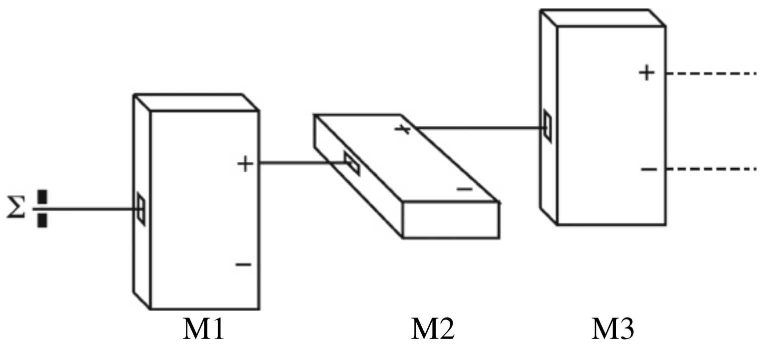
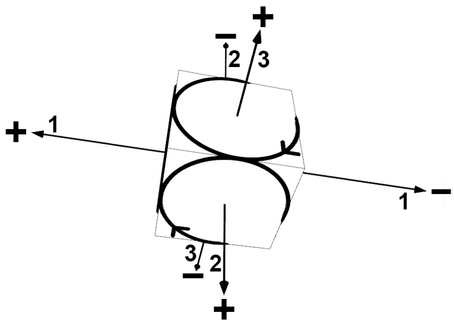


Fig. 12.59

3rd phase – We suppose that the loop, once inside M3, has its **DSA 3**, as in figure 12.60. The precession will be about B (again along the *y*-axis), while the **spin axes 1 and 2** will rotate about it;



. Fig. 12.60

but the loop's precession movement is no longer relevant in this last phase, since its *y* component of spin is now going to be measured and found $s_y = s^-$ (figure 12.61). In other words, the loop will emerge from the negative channel of M3.

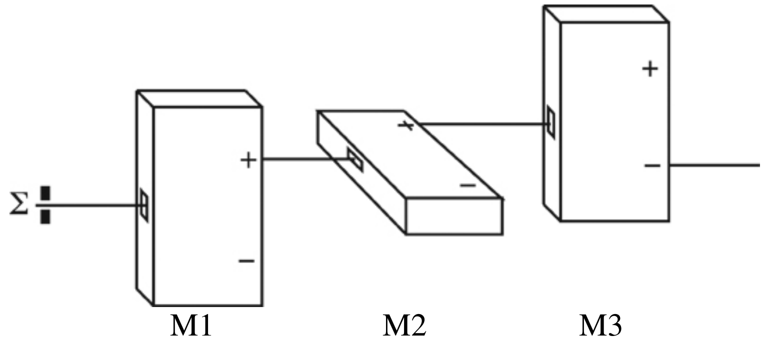


Fig. 12.61

We will provide an analogous description, this time dealing with a beam of electrons simulated by **loops of the octahedron** randomly oriented (figure 12.62).

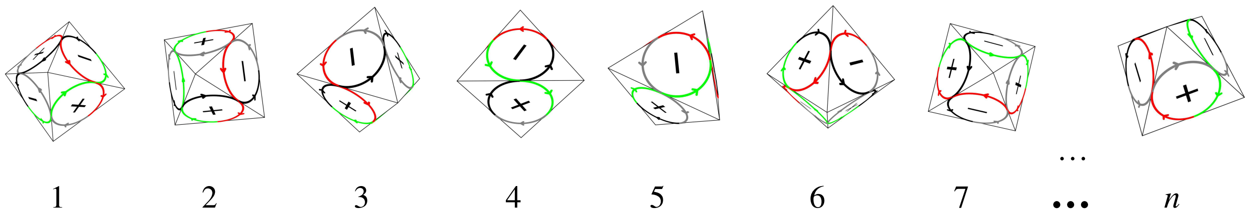


Fig. 12.62

(beam of loops 4-$LC_{1/3}$ of the octahedron, each spinning about four axes)

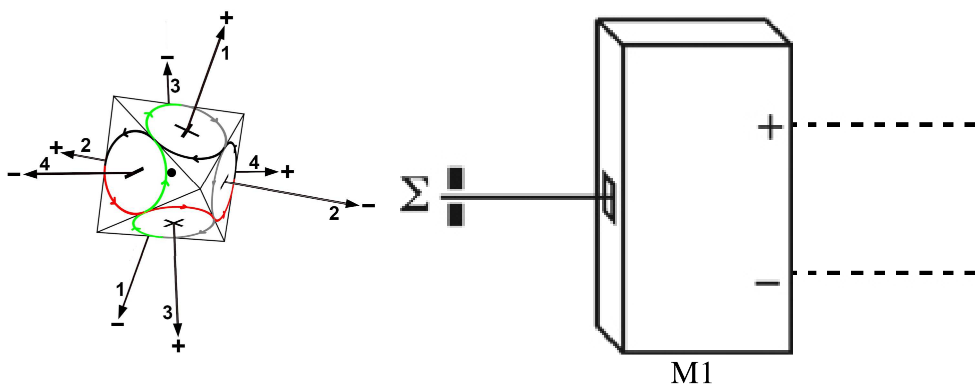


Fig. 12.63

The above figure illustrates a source which emits, though a collimator, a loop towards the entrance of M1. The loop should be positioned on the right of the source but, in order to be visualized in all details, it is here shown on the left.

1st phase - The loop, once entered M1 with the **DSA 1**, will precess about the direction of the S-G magnetic field B(y) (figure 12.64), and the loop with its **spin axes 2, 3 and 4** will rotate about it too.

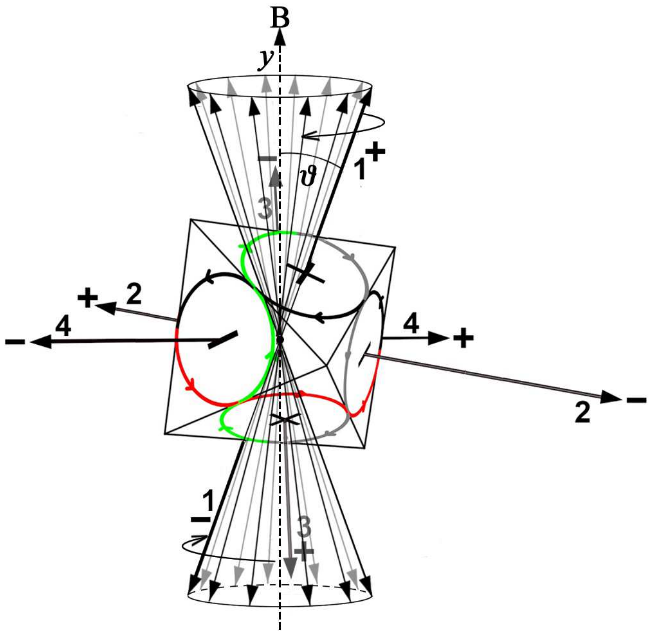


Fig. 12.64
(precession of **DSA 1** about B)

2nd phase – The loop enters into M2 (figure 12.65) and its **DSA** will be one of the axes 2, 3 or 4, each with probability ½ of having the negative pole facing either the positive or the negative component of the S-G magnet (horizontally positioned). Therefore, the loop has probability 1/6 to assume one of six possible orientations.

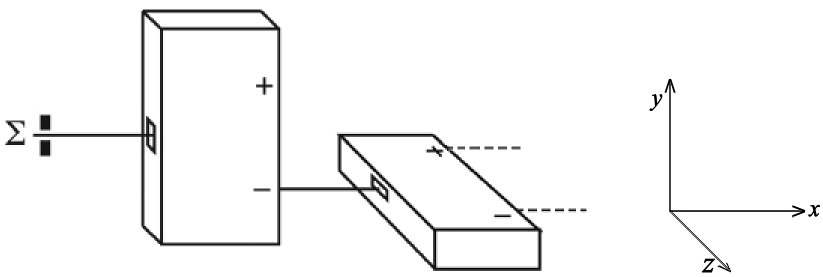


Fig. 12.65

We suppose that inside M2 the loop's **DSA** is the axis **4**, as illustrated in figure 12.66. This, jointly with the loop's **spin axes 1, 2 and 3**, will precess about B, which is oriented along the *z*-axis.

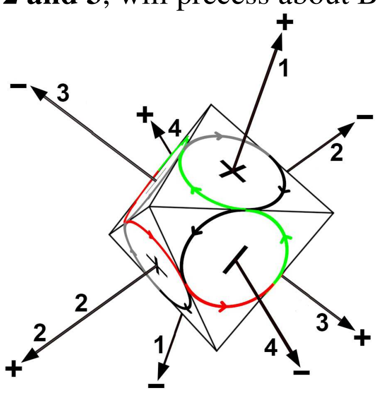


Fig. 12.66

The spin component of the loop, if measured, would be $s_z = s^-$, so that it will emerge from the negative channel of M2 and proceed moving towards M3 (figure 12.67).

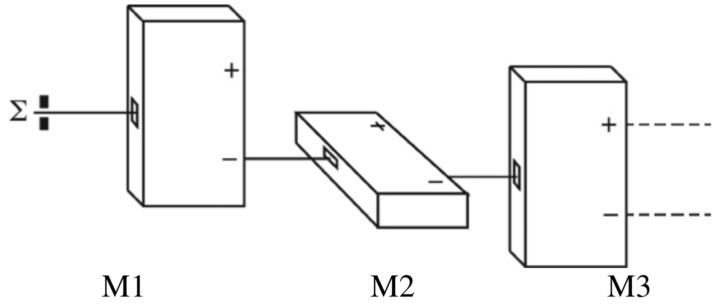


Fig. 12.67

3rd phase – We suppose that the loop, as soon as it is inside M3, has the **DSA 2** precessing about B(y) (figure 12.68).

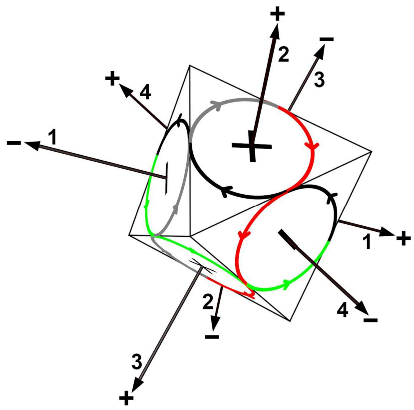


Fig. 12.68

If a measurement is now effectuated, the loop's spin will be found $s_y = s^-$, for it will clearly emerge from the negative channel of M3 (figure 12.69).

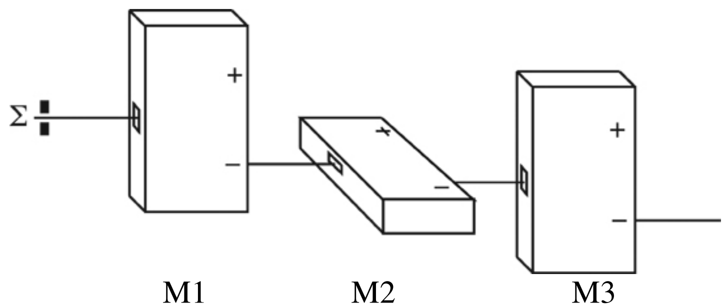
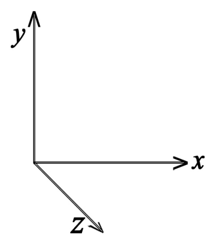


Fig. 12.69



Since in each phase, the loop has equal probability ½ to emerge either from the positive or the negative channel of the detector M3, we can come to the conclusion that a beam of *n* loops (with *n* very large), if directed towards three detectors in sequence, as illustrated in figure 12.70, will emerge from M3 being split into two beams of equal intensity, each constituted by *n*/8 loops. In this example, ¾ of the original loops will be dispersed out of the negative channels of M1 and M2, more precisely, ½ out of the negative channel of M1 and ¼ out of the negative channel of M2.

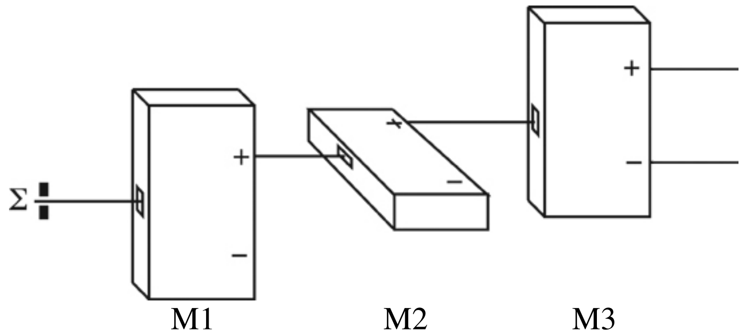


Fig. 12.70

16. ***Conclusions***.

The second and third versions of the EPRB-type experiment described in this paper provide two different sets of statistical predictions, which concern the results obtainable by joint measurements of spin on pairs of electron-positron in the singlet state emitted from a common source. This experiment, even though difficult to execute, has a *scientific value*, since its predictions might be confirmed in agreement either with the hypothetical properties of the spherical loop of the hexahedron (based on the probabilities resulting from Tables 12.17 – 12.21), or with the properties of the spherical loop of the octahedron, based on the probabilities deriving from Tables 12.22 – 12.26 (other loops may be considered interenting referring to "Onde...Sferiche" (Spherical...Waves) described in chapter X of my book, yet unpublished, *A New Image of Reality*. (a few chapters, included Onde...Sferiche are available ob my web site <www.carloroselli.com>),

It is to be hoped that, in the near future, technology may reach a sufficient level of efficiency for executing the experiment in the same way conceived by Mermin, with the only difference that the orientations of the two detectors may be regulated along more than three directions, according to the Table one wants to refer to.

Supposing that one of the two experimental versions were confirmed and supposing that the properties of one of above two loops were accepted by the scientific community as a model for the electron for being more reasonable than the actual point-like model, then the principles on which QM are founded would have to be reviewed, and the irrational notion of “quantum states superposition” removed in favour of the classical concept of “quantum states mixture”, as explained in section 14 (figures 12.51-55).

In any case, what I mainly hope is that the new ideas here proposed may somehow stimulate physicists ceativity and offer them an opportunity for reconsidering the foundations of quantum physics and its anomalies and paradoxes, most likely responsible for the long lasting stagnation of the current scientific paradigm. In general, scientists don’t seem inclined to risk a radical change of some of the principles on which mathematics, logic and physics theories are founded, even though they are rather accustomed to coexist with paradoxes and their metamorphic peculiarity, and are not interested in searching for their origin, maybe because considered nonexistent or impossible to reach (this argument has been widely discussed in chapter III). Therefore, I'm going to stress my impression that the reason behind all the unsuccessful attempts to unify General Relativity and Quantum Mechanics may be attributed in part to such an attitude of scientists and in part to lack of radically new concepts and principles.-

Appendix 1

The Thirteen Loops LV derived from the platonic curves.

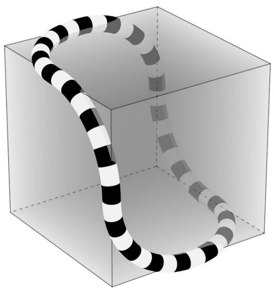


Fig. 10.65

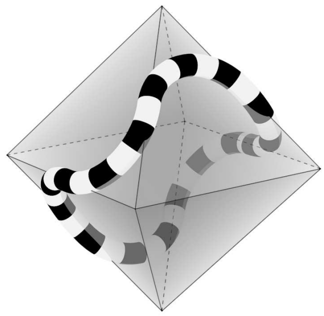


Fig. 10.66

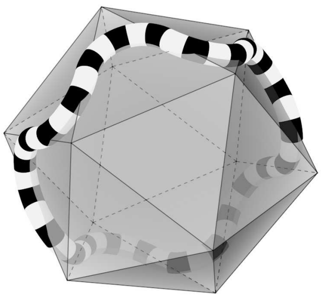


Fig. 10.67

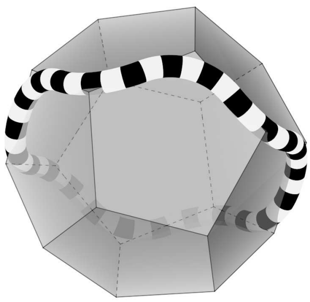


Fig. 10.68

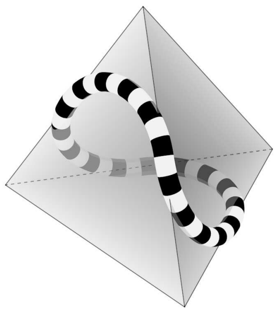


Fig. 10.69

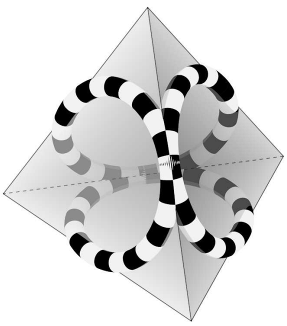


Fig. 10.70

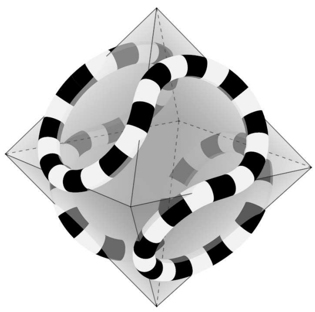


Fig. 10.71

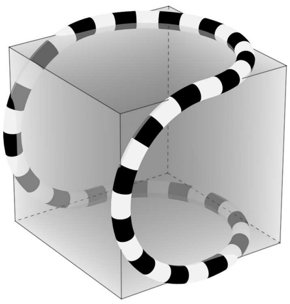


Fig. 10.72

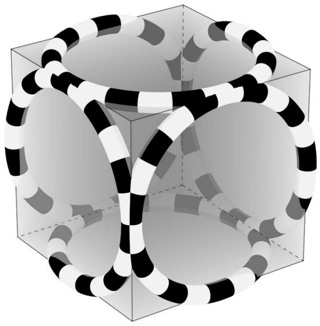


Fig. 10.73

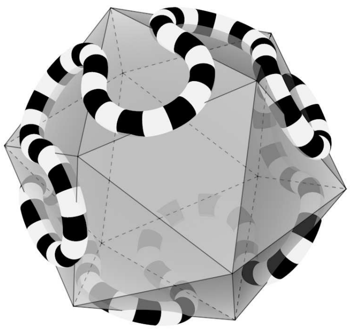


Fig. 10.74

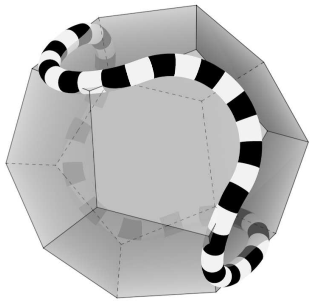


Fig. 10.75

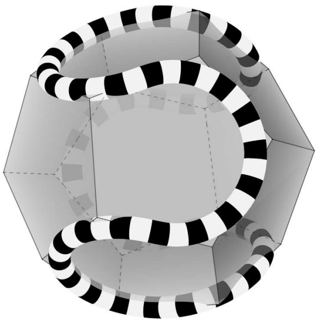


Fig. 10.76

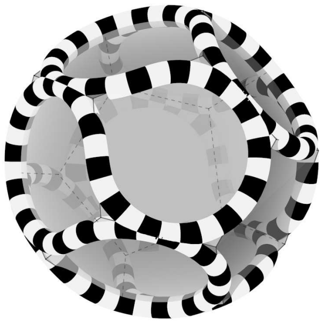


Fig. 10.77

Appendix 2

***Calculation of probabilities P_O* and *P_S*, *depending on the angles chosen for the directions of the four S-G devices, two situated on the left sector and two on the right sector (as in figure 12.2)*.**

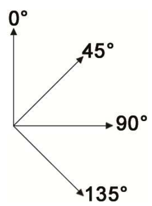
We are now going to calculate the probabilities, P_O and P_S, for each of the first three configurations of the pairs of loops $LC_{2/3}$ of the tetrahedron (see figures 12.6 to 12.8),[40] depending on how we decide to orientate the two pairs of S-G devices, *a*, *a*' and *b*, *b*', respectively situated in the left and in the right sector of the experimental apparatus. We will examine two cases.

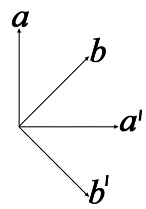
Case n°1 - we have (*a*^*b*) = (*a*'^*b*) = (*a*'^*b*') = 45° and (*a*^*b*') = 135°, as sketched in figure 12.2.

In the following description, the two tetrahedrons (on which, for simplicity, the respective loops have been omitted) are positioned perpendicularly to the direction of the *x*-axis along which they move, with **a** in the back (randomly directed towards *a* or *a*') and **b** in the front (as well randomly directed towards *b* or *b*').

[40] The other three configurations (figures 12.9 to 12.11) are not taken into account, since they would give the same results as the first ones.

As you can see, the angle $A\hat{O}B$ of 120° of **a** has been purposely divided into eight equal parts, each of 15°. In this way, it will be quite simple to show the rotation of **b**, with respect to **a**, of a given angle. In the following example, when **b** is rotated by 45° with respect to **a**, as in figure 12.19, it means that the two loops are now oriented each other in such a way that the probabilities concerning their respective spin results will be calculated on the basis of two different fractions: 3/8 and 5/8. On the other hand, when **b** is rotated by 135°, as in figure 12.20, the probabilities will be calculated on the basis of two other different fractions: 1/8 and 7/8.





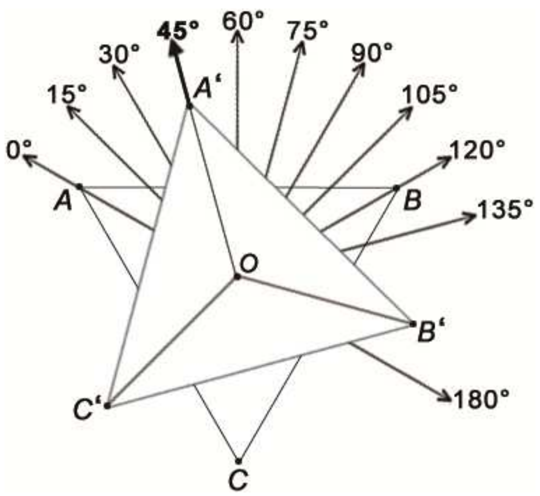


Fig. 12.19

(**b**, which is in the front, is rotated by 45° with respect to **a,** which is in the back)

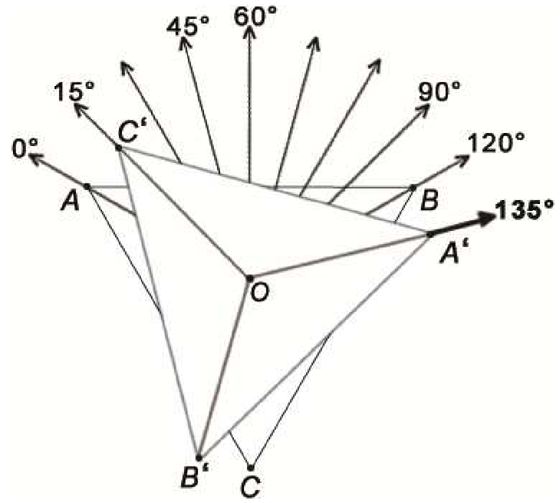


Fig. 12.20

(**b** is rotated by 135° with respect to **a**)

Table 12.7

Calculation of probabilities, *P***o** and *P***s**, for each of the 3 configurations with $(a \wedge b) = (a' \wedge b) = (a' \wedge b') = 45°$		
1st config.	− −, *P***s** = 3/8	− +, *P***o** = 5/8
2nd config.	− +, *P***o** = 3/8	− +, *P***o** = 5/8
3rd config.	+ +, *P***s** = 5/8	− +, *P***o** = 3/8

Since here the number of tests is three (one for each configuration), subtracting from the sum of all the values of P_O the sum of all the values of P**s**, and then dividing by 3, we will obtain the correlation function

$$E(a, b) = E(a', b) = E(a', b') = 1/3\ \Sigma(P_O - P_S) = 1/3(9/4 - 3/4) = ½ \qquad (10)$$

Table 12.8

Calculation of probabilities, *P*o and *P*s, for each of the 3 configurations with $(a\wedge b') = 135°$		
1st config.	– –, *P*s = 7/8	– –, *P*s = 1/8
2nd config.	+ +, *P*s = 7/8	+ –, *P*o = 1/8
3rd config.	+ –, *P*o = 7/8	+ +, *P*s = 1/8

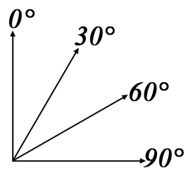
from which the correlation function is

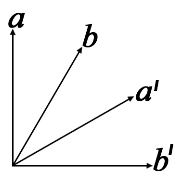
$$E(a, b') = 1/3\Sigma(P_{\mathbf{O}} - P\mathbf{s}) = 1/3(1 - 2) = \mathbf{-\ 1/3}, \qquad (11)$$

so that, according to (6), from (10) and (11) we will have:

$$Q = 1/2 + 1/2 + 1/2 - 1/3 = \mathbf{11/6.} \qquad (12)$$

Case n°2 – we have $(a\wedge b) = (a'\wedge b) = (a'\wedge b') = 30°$ and $(a\wedge b') = 90°$ (see graphs and figures 12.21 - 12.22).





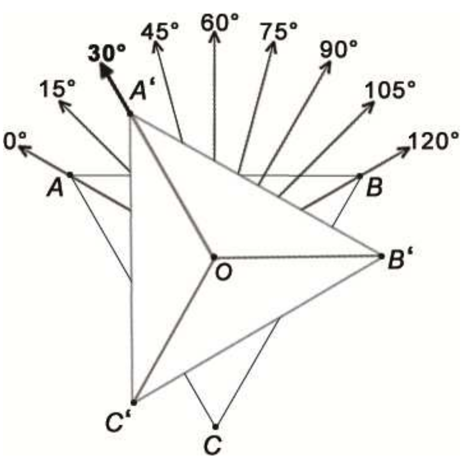


Fig. 12.21

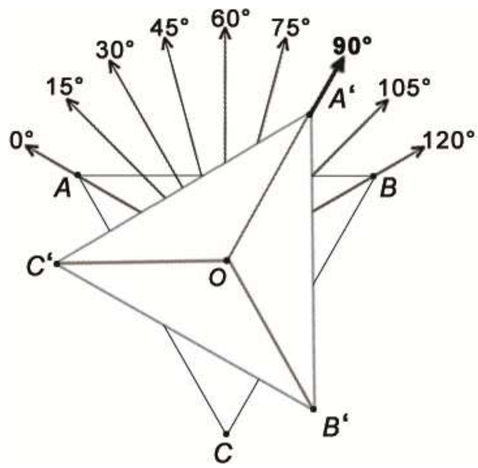


Fig. 12.22

Table 12.9

Calculation of probabilities, Po and Ps, for each of the 3 configurations with $(a\wedge b) = (a'\wedge b) = (a'\wedge b') = 30°$		
1st config.	− −, Ps = 1/4	− +, Po = 3/4
2nd config.	+ +, Ps = 1/4	+ −, Po = 3/4
3rd config.	+ −, Po = 1/4	+ −, Po = 3/4

from which the correlation function is

$$E(a, b) = E(a', b) = E(a', b') = 1/3 \sum(P_O - Ps) = 1/3(5/2 - 1/2) = \mathbf{2/3} \qquad (13)$$

Table 12.10

Esiti Possibili	calcultations of Po and Ps for each of the 3 configurations with $(a\wedge b') = 90°$	
1st config.	+ −, Po = 1/4	+ +, Ps = 3/4
2nd config.	− +, Po = 1/4	− −, Ps = 3/4
3rd config.	+ −, Po = 1/4	+ −, Po = 3/4

and the correlation function is

$$E(a, b') = 1/3\sum(P_O - Ps) = 1/3(3/2 - 3/2) = \mathbf{0}, \qquad (14)$$

so that from (13) and (14) we will obtain:

$$Q = 2/3 + 2/3 + 2/3 - 0 = \mathbf{2} \qquad (15)$$

This manuscript requires to be revised; notes and references need to be completed.

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