Two-valuedness against measurement: nine spin-based theories set against published bounds

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Abstract. In 1925 Pauli described the electron's extra quantum number as "a peculiar, classically non-describable two-valuedness" [1]. Many theories since have read that two-valuedness as something more: a rotating body, a circulating charge, an axis fixed at the source, motion along a hidden direction, a source of space-time torsion, or a field of its own. This paper sets each such theory beside the published measurements that bear on it. A neutron's wave returns after 716.8 ± 3.8° of precession, not the 360° of any rotating body, and silver atoms form two traces, not the band of a classical moment. Bell tests give $S = 2.697 \pm 0.015$ against the preset-axis limit of 2. No Yukawa deviation from inverse-square gravity is seen above 38.6 μm, and no Kaluza–Klein graviton below 2.3–4.6 TeV in the models searched. Of nine theories, two are contradicted within their stated scope (the rotating charged electron and the preset local axis); six are not contradicted, because the measurements do not reach their predictions, the theory fixes no number that a measurement contradicts, or it is empirically equivalent to quantum mechanics; and one, the "torsion fields", states no quantitative prediction to test. Bounds on the free parameters of these theories are listed with them. Entanglement is explained in words.

Keywords: two-valuedness; electron magnetic moment; neutron interferometry; Bell inequality; extra dimensions; torsion; Lorentz invariance; supersymmetry.

1. Introduction

Pauli introduced the electron's fourth quantum number as a label with two values and refused to give it a mechanical picture [1]. A few months later Uhlenbeck and Goudsmit proposed that the electron rotates about its own axis [2, 3], and the word "spin" has carried that picture since. The two-valuedness itself is beyond doubt. It splits a beam of silver atoms into two [4], it sets the electron's magnetic moment [5], and it makes a neutron's wave return only after two full turns of precession [6].

What remains open is which pictures of it survive measurement. Section 2 collects the measurements used throughout (Table 1). Section 3 tests nine theories built on a picture of two-valuedness against them (Table 2). Section 4 gives a reading of entanglement in words. In this paper "two-valuedness" names the measured quantity; "spin" appears only inside theory names, quotations and titles.

2. Measurements

2.1 No large fourth direction

If gravity could spread into a fourth spatial direction, its force would fall faster than the inverse square wherever that direction is open. The Eöt-Wash torsion balance finds the inverse-square law holding down to 52 μm. It excludes a gravitational-strength Yukawa interaction with a range above 38.6 μm at 95 % confidence [7]. At the Moon's distance, lunar laser ranging bounds any anomalous precession to $\delta\omega/\omega < 1.6 \times 10^{-11}$ [8].

2.2 No small curled direction, as far as it has been sought

A direction curled smaller than that range leaves the inverse square alone but brings a tower of heavy copies of every particle that travels in it [9]. None is seen. In high-mass diphoton events at 13 TeV, the first Kaluza–Klein excitation of the Randall–Sundrum graviton is excluded below 2.3 to 4.6 TeV, for couplings from 0.01 to 0.2 [10]. The bound holds for the named models only.

2.3 The electron: magnetic moment and size

A single electron in a Penning trap gives g/2 = 1.001 159 652 180 59 ± 0.000 000 000 000 13, a relative uncertainty of 0.13 parts per trillion [5]. Bhabha scattering at 183 and 189 GeV, combined over ALEPH, L3 and OPAL, sees no finite electron size; in a form-factor model it bounds an effective electron radius below 2.8 × 10^{-19} m at 95 % confidence [11].

2.4 Two beams and a wave that returns only after two turns

Silver atoms passing an inhomogeneous magnetic field land in two separate traces, not in one continuous band [4]. A neutron's wave turned in a magnetic field does not return to itself after one full turn (360°). It returns after two: 716.8 ± 3.8° [6], within one standard error of 720° and 94 standard errors from 360° (Figure 1).

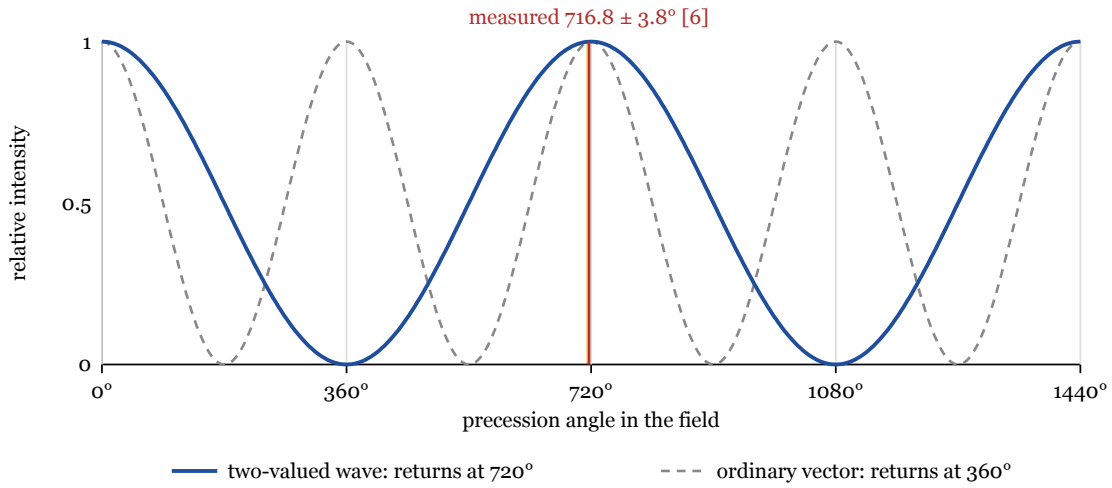


Figure 1. Neutron interferometry, schematic. Relative intensity in one output beam against the precession angle of the neutron's two-valuedness in a magnetic field. A two-valued wave (solid) returns to its starting intensity after 720°; an ordinary vector (dashed) would return after 360°. Red line and yellow band: the measured return, 716.8 ± 3.8° [6]. After 360° the polarisation direction is back where it started, but the wave has changed sign relative to the unrotated reference beam; the interference shows that sign. The curves are drawn for an ideal interferometer; the measured contrast was lower.

2.5 Bell correlations and no signalling

In the test of Clauser, Horne, Shimony and Holt [12], any pair whose two ends carry their own preset answers gives a number S of at most 2 [13]. This assumes that no influence passes between the ends and that the analyser settings are chosen independently of those answers. Quantum mechanics allows up to 2√2 ≈ 2.83 [14]. Freedman and Clauser first saw a violation, of a related inequality [15]. The measured CHSH values are:

- Aspect, Grangier, Roger: S = 2.697 ± 0.015 [16].
- Weihs et al., with the analysers switched while the photons were in flight: S = 2.73 ± 0.02 [17].
- Hensen et al., electrons in diamond 1.3 km apart, loophole-free: S = 2.42 ± 0.20 [18].
- Yin et al., from a satellite to two stations 1,203 km apart: S = 2.37 ± 0.09 [19].

All four central values lie between 2 and 2√2. They are not one number. Each apparatus has its own efficiencies, noise and state quality, so S belongs to the apparatus.

It is a theorem that what one end sees on its own cannot depend on the analyser setting chosen at the other [20, 21]. For a maximally entangled pair read with ideal analysers, each end alone reads 50/50 at every angle. Salart et al. bound any hidden influence between the ends to more than 10^4 times the speed of light [22]. That bound rests on their stated assumption that the Earth moves slower than 10^{-3} c in any privileged frame, and the reading of their test is contested [23].

In entanglement swapping [24, 25], a joint reading of two particles, one from each of two pairs, leaves the two far particles entangled although they never met. Ma et al. made that joint reading after the far particles had already been read. It sorted the earlier outcomes into correlated groups and changed none of them.

2.6 Torsion, polarised matter, and the speed of light

A torsion pendulum carrying about 10^{23} polarised electrons sees no anomalous torque from the Earth or the Sun. For ranges beyond 1 AU it bounds the dimensionless product of a monopole–dipole coupling, $g_P^e g_S^N$ in natural units, below 9.4×10^{-37} [26]. Polarised electrons in the Earth's mantle bound long-range dipole–dipole couplings further [27]. Read through the matching of torsion couplings to tests of Lorentz invariance, coupling-weighted combinations of 19 of the 24 independent components of a background space-time torsion are bounded, the most sensitive at the level of 10^{-31} GeV [28]. Photons from the burst GRB 090510, up to 31 GeV, arrived with no energy-dependent delay: $|\Delta t/\Delta E| < 30$ ms GeV^{-1} at 99 % confidence, which places the scale of any linear energy dependence of the speed of light, of either sign, above 1.2 Planck energies, under stated assumptions about the emission [29]. Equivalently, the dimensionless coefficient of such a term, in units of the inverse Planck energy, is below 0.83 in magnitude.

2.7 Supersymmetric partners at the LHC

With 139 fb^{-1} of 13 TeV proton collisions, ATLAS finds no excess in events with jets and missing transverse momentum. In simplified models with a massless lightest neutralino it excludes gluinos below 2.30 TeV and mass-degenerate first- and second-generation squarks below 1.85 TeV, at 95 % confidence [30].

Table 1. Measurements used in this paper.

Quantity	Measured value ± σ, or bound	Reference
Electron g/2	1.001 159 652 180 59 ± 0.000 000 000 000 13	[5]
Effective electron radius (form-factor model)	$< 2.8 \times 10^{-19}$ m (95 % CL)	[11]
Neutron return angle	716.8 ± 3.8°	[6]
Stern–Gerlach traces, silver atoms	two, separated	[4]
CHSH S (preset-axis limit 2)	2.697 ± 0.015; 2.42 ± 0.20 (loophole-free)	[16]; [18]
Yukawa range at gravitational strength	$< 38.6\ \mu$m (95 % CL)	[7]
First Randall–Sundrum graviton excitation	> 2.3–4.6 TeV (95 % CL, couplings 0.01–0.2)	[10]
Monopole–dipole coupling, $g_P^e g_S^N$	$< 9.4 \times 10^{-37}$ (range > 1 AU)	[26]
Background torsion (19 of 24 components, combinations)	most sensitive $\approx 10^{-31}$ GeV	[28]
Linear dispersion scale of light, either sign	> 1.2 Planck energies (99 % CL)	[29]
Gluino mass; light-squark mass	> 2.30 TeV; > 1.85 TeV (95 % CL, simplified models)	[30]

3. Spin-based theories tested against measurement

3.1 Criterion

A theory is *contradicted* when a measurement in Table 1 contradicts its stated prediction beyond the quoted error or outside the quoted confidence limit. It is *not contradicted* when no measurement does, either because

the measurements do not reach its predictions or because it predicts the same numbers as standard quantum mechanics. Where no quantitative prediction was found, this is said. Each result applies to the claim exactly as stated in its subsection, not to every theory that shares a name with it. Table 2 lists the results.

3.2 The spinning electron as a rotating charged body

Claim. The electron is a small charged body rotating about its axis, and its two-valuedness is that rotation [2, 3].
Measurements. (i) A rotating body returns to itself after 360°; the neutron's wave returns after 716.8 ± 3.8° [6]. (ii) A classical magnetic moment with random orientation spreads a beam into a band; silver atoms form two traces [4].
Result. Contradicted as a literal rotation. Pauli's two-valued quantum number, which this picture was meant to explain, is untouched.

3.3 Zitterbewegung as literal motion

Claim. The electron is a point charge circulating at the speed of light on a circle whose radius is half the reduced Compton wavelength, 1.93×10^{-13} m, and its two-valuedness is the angular momentum of that orbit [31]. The oscillation itself is a term in Dirac's equation, found by Schrödinger [32].
Measurement. Bhabha scattering sees no electron structure down to an effective radius of 2.8×10^{-19} m [11], about 7×10^{5} times smaller than the orbit. Whether the orbit picture predicts a scattering form factor of that size has not been calculated in the sources found, so this comparison does not decide it.
Result. Not contradicted; the measurements listed here do not decide it. The oscillating term of Dirac's equation is an interference between positive- and negative-energy components; it has been reproduced in a trapped-ion simulation of the equation [33], which is a simulation, not an observation on an electron.

3.4 A preset axis carried by each particle

Claim. Each particle of an entangled pair leaves the source carrying its own axis, and each analyser reads that axis locally. This is the class of local hidden-variable models of two-valuedness analysed by Bell [13].
Measurement. Any such model gives $S \leq 2$ [12]. Measured: $S = 2.697 \pm 0.015$, 46.5 standard errors above 2 [16]; $S = 2.42 \pm 0.20$ with the detection and locality loopholes closed together [18].
Result. Contradicted, under the assumptions of Bell's theorem: independent settings and no influence between the ends.

3.5 Motion along a compact extra dimension

Claim. Internal quantities of particles are motion along a closed extra direction of space [9]. Every particle that moves in that direction then has a tower of heavier copies, spaced by the inverse of its size, and gravity changes its law at distances near that size.
Measurements. No gravitational-strength Yukawa deviation above 38.6 μm [7]; no Randall–Sundrum graviton below 2.3 to 4.6 TeV [10].
Result. Not contradicted. The theory fixes no size for the closed direction, so no stated prediction is contradicted. The measurements exclude a gravitational-strength Yukawa range above 38.6 μm and, in the Randall–Sundrum models named, a first graviton excitation below 2.3 to 4.6 TeV; a version that fixes a size or mass inside those ranges would be contradicted.

3.6 Einstein–Cartan spin–torsion gravity

Claim. The intrinsic angular momentum of matter is a source of space-time torsion, as mass is a source of curvature [34].
Measurements. No anomalous torque on about 10^{23} polarised electrons [26]; background torsion combinations

bounded, the most sensitive near 10^{-31} GeV [28].
Result. Not contradicted. In this theory torsion does not propagate; it is confined to the inside of matter, and its effects become large only at densities far beyond any laboratory [34]. The measurements bound a background torsion field, which the theory does not predict.

3.7 "Torsion fields" from rotating bodies

Claim. Rotating bodies emit long-range fields that propagate faster than light and act with macroscopic strength on the two-valuedness of matter. These claims were made in the 1990s outside the peer-reviewed literature; no primary source reporting a measurement was found.
Measurements. The polarised-electron pendulum bounds any coupling between electron two-valuedness and the unpolarised matter of the Earth and Sun below 9.4×10^{-37} for ranges beyond 1 AU [26], and the mantle electrons bound long-range dipole–dipole couplings [27].
Result. No number stated. No quantitative prediction was found to set against these bounds. Any long-range coupling of electron two-valuedness to unpolarised matter beyond 1 AU must lie below the bound above.

3.8 Spin networks and a discrete space that slows light

Claim. Space is a network of discrete quanta whose edges carry SU(2) representation labels, the spins of the theory's name, of which one half is the smallest nonzero value [35]. In some versions the speed of light then depends on its energy at first order in its ratio to the Planck energy; in the version of Gambini and Pullin the sign depends on the photon's helicity [36].
Measurement. GRB 090510: no delay up to 31 GeV; a linear dispersion scale of either sign above 1.2 Planck energies, a coefficient below 0.83 in magnitude [29].
Result. Not contradicted. Neither the network theory [35] nor the Gambini–Pullin version [36] fixes the value of the coefficient, so no stated prediction is contradicted. The measurement bounds any linear dispersion coefficient below 0.83 in magnitude, for either sign, under the stated emission assumptions; a version that fixes a larger coefficient would be contradicted.

3.9 Supersymmetric partners

Claim. Each particle has a partner whose spin quantum number, in the theory's terms, differs by one half [37], and in the versions built to stabilise the weak scale these partners lie near 1 TeV.
Measurement. No gluino below 2.30 TeV and no light squark below 1.85 TeV in simplified models with a massless lightest neutralino [30].
Result. Not contradicted. The theory fixes no partner mass; a scale near 1 TeV is an expectation of naturalness, not a prediction of the theory. The search bounds gluinos and light squarks in the simplified models named; heavier partners, compressed spectra, other decay chains and a massive lightest neutralino are not excluded.

3.10 The Bohm–Schiller–Tiomno rotating fluid

Claim. The two-valued wave is a fluid whose internal rotation carries the two-valuedness, and particles follow its flow [38].
Measurement. None separates it from quantum mechanics. By construction it reproduces the statistics of the Pauli equation, including the 720° return [6] and the two Stern–Gerlach traces [4].
Result. Not contradicted. It is empirically equivalent to quantum mechanics for these measurements; the rotation it posits is not itself observed.

Table 2. Spin-based theories and the measurements that bear on them.

Theory (section)	Measurement	Result
Rotating charged electron (3.2)	716.8 ± 3.8°; two Stern–Gerlach traces	Contradicted

Theory (section)	Measurement	Result
Zitterbewegung as a literal orbit (3.3)	effective radius $< 2.8 \times 10^{-19}$ m against 1.93×10^{-13} m; no form-factor prediction found	Not contradicted (not decided)
Preset local axis (3.4)	$S = 2.697 \pm 0.015$; 2.42 ± 0.20 loophole-free	Contradicted
Compact extra dimension (3.5)	Yukawa $< 38.6\ \mu$m; RS graviton > 2.3–4.6 TeV	Not contradicted (no size fixed by the theory; bounds in named models)
Einstein–Cartan torsion (3.6)	torsion combinations $\approx 10^{-31}$ GeV; pendulum null	Not contradicted (beyond reach)
"Torsion fields" (3.7)	coupling $< 9.4 \times 10^{-37}$; no quantitative claim found	No number stated
Spin network with linear dispersion (3.8)	scale > 1.2 Planck energies; coefficient < 0.83	Not contradicted (coefficient not fixed by the theory; bound < 0.83)
Supersymmetric partners (3.9)	gluino > 2.30 TeV; squark > 1.85 TeV	Not contradicted (no mass fixed by the theory; bounds in simplified models)
Bohm–Schiller–Tiomno fluid (3.10)	none decides	Not contradicted (equivalent)

3.11 What the measurements leave

Each contradicted picture gives two-valuedness a mechanism made of something else, a body that turns or an axis that travels with the particle, and each predicts a number that a listed measurement contradicts. What survives every listed measurement is the property as Pauli stated it: two-valued, measured to 0.13 parts per trillion in the electron's moment, and returning after 720° rather than 360°. The not contradicted theories are not contradicted because the measurements do not reach them, because they fix no number that the measurements contradict, or because the measurements cannot separate them from quantum mechanics, not because a measurement supports them.

4. Entanglement in words

Two experimental facts set the picture. The ends agree more than any pair of preset answers could. Neither end can be used to signal the other [20, 21].

4.1 The picture

Take a single wave, one object, tied at two ends. Each particle is one end. The pair is not two things that carry copies of an answer. It is one thing with two places where it can be read. The two outcomes are two faces of one reading.

4.2 Why this matches the numbers

If each end kept its own copy of a shared value and read it separately, the result could not exceed $S = 2$. Each CHSH value in Section 2.5 refutes that, the first [16] by 46.5 standard errors. If the wave is read once for both ends, the correlation is the standard quantum one for the two analyser angles. The picture takes that rule from quantum mechanics as given and does not derive it. With ideal analysers, S then reaches the ceiling $2\sqrt{2}$. Noise, imperfect state preparation and, in tests that count every trial, detector loss bring S down to the measured 2.37 to 2.73.

4.3 Why no usable signal passes

A single reading of the whole wave fixes how the two outcomes relate. It does not fix either outcome on its own, so each end on its own sees a fair coin (for a maximally entangled pair). The correlation shows only

when the two records are brought together and compared. The joint reading describes the correlation; it carries nothing from one end to the other that either end could control or detect on its own.

4.4 Where the wave is tied

It is not tied to places. Yin et al. kept the correlation with the two ends 1,203 km apart, carried from a satellite [19]. The wave goes with the particles. The picture needs no extra direction of space and no hidden axis along which the pair is “connected”. The measurements of Sections 2 and 3 find no such direction in the ranges probed and exclude a preset local axis, and the picture works without either.

5. Conclusions

Nine theories that give two-valuedness a picture beyond Pauli’s were set against published measurements. Two are contradicted in their stated form and scope: the rotating charged electron and the preset local axis. Six are not contradicted: zitterbewegung as an orbit, which these measurements do not decide; Einstein–Cartan torsion, whose predictions lie beyond present reach; the compact extra dimension, the spin network and supersymmetry, which fix no number the measurements contradict, though the measurements bound their free parameters; and the Bohm–Schiller–Tiomno fluid, which is empirically equivalent to quantum mechanics. The “torsion fields” state no quantitative prediction to set against a measurement. In every contradicted case the decisive number is a published measurement with its error and confidence level.

Data availability

No new data were generated. All values are taken from the cited publications; the arithmetic in Sections 2 and 3 (ratios and standard-error distances) is reproducible from Table 1 with the CODATA 2018 constants.

Competing interests

The author declares no competing interests.

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