

Where the Net Meets the Bench

Dutch Battery and Vacuum Measurements Read Against the Vacuum Net

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Abstract

This essay sets the vacuum net theory against published measurements, most of them from Dutch laboratories. Five rules of the theory are put to work, each against numbers already in the literature:

- the coupling law $\Delta g/g = 2\pi\delta$;
- the closure rule on trit triples;
- passage proportional to one over the open size;
- the energy of one natural mesh;
- the factor-three ladder of lengths.

Every step of the arithmetic is shown.

Three results agree:

- The coupling law gives 43 percent for the Casimir-force contrast of a crystallising GST film; Groningen measured about 40 percent.
- The closure rule orders three crystal orientations of a spinel electrode exactly as their measured capacities.

- Model's cavity data fit a conductance proportional to one over the cavity size.

Two results are of the right order but no more. Record dielectric films store between 0.97 and 1.65 mesh energies per perovskite cell. Plated lithium fills about a third of its volume.

Two results do not agree:

- The theory's sensitivity near a critical point has exponent 1; liquid mixtures show 1.26.
- The factor-three ladder does not single out battery length scales better than chance.

A status ledger and a list of the Dutch groups that hold the sharper data close the essay.

1. Why correlate

A theory that describes the vacuum as a net should leave traces in matter. Batteries are a good place to look. Their limits sit in thin walls, small pores and narrow gaps, where the net's rules work at the scale of the material.

The Netherlands has a dense network of groups measuring exactly there:

- Groningen measures forces across gaps of tens of nanometres.
- Twente grows crystal films layer by layer.
- Utrecht confines electrolytes in pores of a few nanometres.
- Delft watches lithium move with neutrons.

This essay takes the theory's rules as they stand. It applies them to numbers these groups have published. It reports what comes out, whether it fits or not.

2. The rules in use

Picture a fishnet under tension. Strands cross. Where windings hold each other, there is a knot. Between strands there are meshes: openings with a size and a direction. Five rules of the vacuum net are used below.

Rule 1 — Coupling. The local stiffness of the net is $g_{\text{eff}} = \bar{g}(1 + \gamma\delta)$. Here δ is the relative deviation of local density from its mean: $\delta = (n - \bar{n})/\bar{n}$. The theory sets $\gamma = 2\pi$. The relative change in coupling is therefore

$$\Delta g/g = 2\pi\delta.$$

Rule 2 — Closure on three values. Each crossing carries a trit: +1, 0 or -1. Three trits form a window. A window closes when the sum of its three values is divisible by three. What closes, stays. Tension that does not close moves on to neighbouring meshes.

Rule 3 — Passage. Energy is a winding, with dimension T/S. Power is energy per unit of time, so $(T/S)/T = 1/S$. Passage through a mesh is therefore proportional to one over its open size L. The rise stops at a knee set by the wall material.

Rule 4 — The mesh energy. The energy of one mesh of size L is $\pi^2\hbar c/(720 L)$. At the natural mesh size $S_0 = 45.588 \text{ nm}$ this gives $E_{\text{mesh}} = 9.51 \times 10^{-21} \text{ J}$. The steps are:

- $\hbar c = 1.0546 \times 10^{-34} \times 2.9979 \times 10^8 = 3.1615 \times 10^{-26} \text{ J}\cdot\text{m}$;
- times $\pi^2 = 9.8696$ gives $3.1203 \times 10^{-25} \text{ J}\cdot\text{m}$;
- divided by 720 gives $4.3337 \times 10^{-28} \text{ J}\cdot\text{m}$;
- divided by $4.5588 \times 10^{-8} \text{ m}$ gives $9.51 \times 10^{-21} \text{ J}$.

Rule 5 — The ladder. Lengths sit on a ladder with steps of a factor three around S_0 . The position of a length L is $\log_3(L/S_0)$. The rungs nearest the battery scale are:

Position	Length
-3	1.688 nm
-2	5.065 nm
-1	15.196 nm
0	45.588 nm

Position	Length
+1	136.76 nm
+2	410.29 nm

3. What agrees

3.1 A wall that changes density changes its force

The measurement. George Palasantzas and colleagues in Groningen measure the Casimir force between a gold sphere and a film. The film is a phase-change material. When it crystallises, the force changes.

- For $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) the force rises by about 40 percent at separations below 100 nm (*Physical Review B* 112, 155403, 2025).
- For AgInSbTe (AIST) the contrast is 17 to 25 percent over 40 to 140 nm (*Physical Review A*, 2010; *Advanced Functional Materials*, 2012).

The density. Crystallisation compacts the film.

- GST goes from 5.87 g/cm^3 (amorphous) to 6.27 g/cm^3 (cubic) or 6.39 g/cm^3 (hexagonal) (Njoroge, Wöltgens and Wuttig, 2002).
- For the cubic phase $\delta = (6.27 - 5.87)/5.87 = 0.068$. For the hexagonal phase $\delta = 0.089$.
- AIST densifies by 5.2 percent (Njoroge and Wuttig, 2001), so $\delta = 0.052$.

The rule. Read the measured force contrast as $\Delta g/g$ at the wall:

Film	δ	$2\pi\delta$	Measured	Ratio
GST, cubic	0.068	0.427	about 0.40	0.94
GST, hexagonal	0.088	0.553	—	—
AIST	0.052	0.327	0.17-0.25	0.52-0.77

The result. For GST, the rule gives 43 percent from the density alone. The measurement gives about 40 percent. They agree within 7 percent.

For AIST, the rule overshoots by a factor 1.3 to 1.9.

Groningen's own analysis of AIST attributes about half the contrast to free carriers and half to resonance bonding. That suggests the share of density in the force differs between the two materials.

Status. One agreement, one overshoot. The identification of the force contrast with $\Delta g/g$ is a reading, not a derivation.

3.2 Closure orders the orientations of a crystal

The step. A crystal direction is written with three Miller indices. For the low-index directions these are three values of -1 , 0 or $+1$. They are trit triples. Rule 2 applies to them directly:

Family	Members	Closing (sum divisible by 3)	Open fraction
$\langle 100 \rangle$	6	0	100%
$\langle 111 \rangle$	8	2	75%
$\langle 110 \rangle$	12	6	50%

The reading. Tension that does not close moves on. An open direction carries passage. A closed direction holds. The rule therefore predicts an order for transport through a film:

$\langle 100 \rangle > \langle 111 \rangle > \langle 110 \rangle$.

The measurements. Two cubic spinel electrodes have been grown in different orientations.

- **Li₄Ti₅O₁₂** (Cunha and colleagues, 2019), at 3C:

- $\langle 100 \rangle$: about 313 mAh/g;
- $\langle 111 \rangle$: about 283 mAh/g;
- $\langle 110 \rangle$: about 277 mAh/g.

The order is exactly the order of the open fraction.

- **LiMn₂O₄** in a perovskite matrix (Huijben and colleagues, Twente, 2022):

- both orientations start at about 2 $\mu\text{Ah}/\text{cm}^2$;
- after 1,000 cycles at about 5C, $\langle 100 \rangle$ keeps 55 percent and $\langle 110 \rangle$ keeps 33 percent;
- the capacitive, surface-held share is larger in $\langle 110 \rangle$: 24 to 76 percent against 12.5 to 57 percent.

An earlier Twente study of LiMn_2O_4 in all three orientations (Hendriks and colleagues, 2018) also found (100) best.

The result. In both spinels the most open family moves charge best. In LiMn_2O_4 the most closed family holds the most charge at its surface. That is the split between passage and hold that the rule describes.

What weakens it. In a cubic crystal [110] and $[\bar{1}10]$ are equivalent by symmetry. The rule closes one and not the other. The fraction per family is therefore a count over the family, not a property of each direction.

The (110) films also had 1.3 times the surface area and smaller pillars. That alone raises the surface share.

Status. The count is exact. The order agrees in two materials. The link between open fraction and transport is a reading. A third orientation series, with surface area held equal, would sharpen it.

3.3 Passage scales with one over the gap

The measurement. Garret Model's group placed an optical cavity on one side of a metal-insulator-metal junction (*Symmetry* 13, 517, 2021). They measured current without applied voltage, for cavities from 33 to 1,100 nm. The current rose as the cavity grew thinner.

Maclay (*Physics* 6, 1124, 2024) fitted Model's conductance against 100 divided by the thickness. The fit passes through the origin with slope 0.3519 mS. Conductance is therefore proportional to one over the cavity thickness: a log-log slope of -1 .

The rule. Rule 3 gives passage proportional to $1/L$, with the exponent fixed by the ladder.

The result. The exponent agrees. No knee appears down to 33 nm, below $S_0 = 45.6$ nm. The knee, if the wall material sets one, lies below that.

A correction to an earlier reading. “A Wall with Three States” assumed that power scales as current squared, which gave a power slope of about -1.8 . If the open-circuit voltage is roughly independent of thickness, power follows conductance and the slope is -1 . The paper reports no voltages per thickness. The -1.8 therefore rests on an assumption.

Status. Exponent of the conductance: agrees. Exponent of the power: open. The figure that fixes it is Moddel’s Fig. 4b, read together with the voltages.

4. What is of the right order

4.1 Energy per cell in dielectric walls

The measurement. Thin perovskite films store energy in their polarisation. The highest recoverable energy densities W reported up to October 2026 range from 128 to 272 J/cm³ (sources in the references).

The calculation. The energy per cell is $W \times a^3$, with a the pseudocubic lattice parameter. Divided by $E_{\text{mesh}} = 9.51 \times 10^{-21}$ J:

Film	W (J/cm ³)	a (Å)	Energy per cell (J)	Per E_mesh
PbZrO ₃ /PLZT multilayer (Twente, 2022)	128.4	4.15	9.18×10^{-21}	0.97
BiFeO ₃ -BaTiO ₃ , superparaelectric (2021)	152	3.99	9.66×10^{-21}	1.02
BaTiO ₃ -based (2024)	161.1	4.007	1.04×10^{-20}	1.09
La/Si-doped BaTiO ₃ (2025, preprint)	203.7	4.007	1.31×10^{-20}	1.38
PZT-MgO nanocomposite (2025)	217.8	4.075	1.47×10^{-20}	1.55
BaTiO ₃ , columnar nanograins (2022)	242	4.007	1.56×10^{-20}	1.64

Film	W (J/cm ³)	a (Å)	Energy per cell (J)	Per E_mesh
perovskite nanosheet stack (2023)	272	3.86	1.56×10^{-20}	1.65
bulk multilayer capacitor (2024)	20.8	4.007	1.34×10^{-21}	0.14

The Twente value as a check: $128.4 \times 10^6 \text{ J/m}^3 \times (4.15 \times 10^{-10} \text{ m})^3 = 128.4 \times 10^6 \times 7.147 \times 10^{-29} = 9.18 \times 10^{-21} \text{ J}$.

The result. The best films hold between one and 1.65 mesh energies per cell. The Twente multilayer sits at 0.97. The best films do not exceed two mesh energies per cell.

Bulk ceramics hold a seventh. Their breakdown field is five to ten times lower than in films.

What it does not show. A ceiling of exactly one mesh energy per cell is exceeded by 65 percent. The lattice parameters are standard values for the parent compounds, not measured on each film. The energy density follows the breakdown field, and the breakdown field follows the microstructure.

Status. Order of magnitude: agrees. A ceiling: not shown. The Twente group (Koster, Rijnders, Nguyen) holds the films and the breakdown data that would turn this into a test.

4.2 How much of a plated layer is lithium

The measurement. Marnix Wagemaker's group in Delft followed lithium plating with neutrons (*Nature Communications*, 2018). At 1 mA/cm² to 1 mAh/cm² in standard electrolyte, the maximum fraction of the deposit that is lithium is about 0.3. The deposit spreads over at least 20 μm, where a dense film would be about 5 μm.

The rule. Of the 27 windows of the trit cube, 9 close: one third.

The result. The fraction 0.3 is near one third. It is not fixed, however:

- it is lower at 0.2 mA/cm²;
- it rises to about 0.6 with a gel electrolyte and LiNO₃.

A closure count cannot be a constant that the electrolyte changes by a factor of two.

Status. Near one third in the base case; not a constant. Not a test the theory passes.

5. What does not agree

5.1 The exponent near the critical point

The rule. The theory gives the sensitivity of the coupling as $d \ln g_{\text{eff}}/d\delta = \gamma = 1/\varepsilon$. Here ε is the distance to the critical point. The sensitivity therefore diverges with exponent 1 as ε goes to zero.

The measurement. Peter Schall in Amsterdam and Bechinger's group in Stuttgart measure critical Casimir forces in binary liquids near their critical point (Hertlein and colleagues, *Nature* 451, 172, 2008). In water-2,6-lutidine the susceptibility diverges with exponent 1.26 ± 0.02 . The three-dimensional Ising value is 1.237.

The result. The theory gives 1. The liquids give 1.26. That is a difference of 26 percent in an exponent.

An exponent of 1 is the mean-field value. The theory's own form for the energy near the tipping point, $-\beta A^4 + \gamma A^6$, is a mean-field form. Real three-dimensional systems near a critical point are not mean-field.

Status. Does not agree as now formulated. The coarse-graining that would carry the net from mean field to the measured exponent is the theory's own open point O1.

5.2 The ladder of three

The test. Take every length in this research that marks a change of regime in a battery material:

Length	Value	Position $\log_3(L/S_0)$	Distance to nearest rung
fast-conducting interface layer,	1.94 nm	-2.87	0.13

Length	Value	Position $\log_3(L/S_0)$	Distance to nearest rung
LiBH ₄ in silica (Utrecht)			
same, in carbon	1.41 nm	−3.16	0.16
best LiBH ₄ layer on ZrO ₂	2.3 nm	−2.72	0.28
best LiBH ₄ layer on SiO ₂	6.2 nm	−1.82	0.18
silicon particle fracture	150 nm	+1.08	0.08
silicon pillar fracture	300 nm	+1.72	0.28
silicon nanowire fracture	300 nm	+1.72	0.28

The mean distance is 0.20. Lengths spread at random would give 0.25. In a simulation, a mean of 0.20 or lower occurs by chance in 19 percent of cases.

The result. Two values sit close to rungs: the interface layers around 1.69 nm, and silicon particle fracture near 137 nm. The set as a whole is not closer to the ladder than chance.

Status. Not shown.

5.3 A coincidence set aside

AMOLF coupled water layers about 44 nm thick to silver cavities (Lather and colleagues, *Advanced Optical Materials*, 2025). That is within 3.5 percent of S_0 . The thickness was not chosen, however. It arose while the water dried, and the paper gives no reason for that value. It is not counted here.

6. What the numbers say together

Three rules work at walls and gaps:

- The coupling law gets the force contrast of one phase-change film from its density alone.
- The closure rule orders crystal orientations correctly in two materials.

- The passage law has the right exponent in the one cavity series that exists.

The energy of one mesh sits at the scale of what the best polar walls hold per cell.

Two things do not work yet:

- Near a critical point the theory behaves as mean field, and matter does not.
- The ladder of three does not stand out in battery lengths.

Both point to the same open step: carrying the net from its rules to the coarse behaviour of many crossings. That is O1 in the theory's own list.

7. Who holds the sharper data

Each test above can be made sharper with data that Dutch groups already have or can produce.

Test	Group	What would sharpen it
$\Delta g/g = 2\pi\delta$ at a wall	Palasantzas (Groningen)	force contrast against measured density for more phase-change films
closure and orientation	Huijben (Twente)	all three orientations of one spinel at equal surface area
passage $1/L$ and the knee	Moddel (Colorado); Palasantzas	voltage per thickness; thinner cavities
energy per cell	Koster, Rijnders, Nguyen (Twente)	measured lattice parameter and energy per cell in the same film
exponent near the critical point	Schall (Amsterdam)	coupling sensitivity in his own critical Casimir data
interface layers	de Jongh, Ngene (Utrecht)	conductivity against pore diameter at fixed pore volume
plated fraction	Wagemaker (Delft)	the fraction across many electrolytes and current densities

These are people with instruments and archives, not a programme to be set up. Most of the data sit in theses and supplementary files.

8. Status ledger

Statement	Status
$\Delta g/g = 2\pi\delta$ gives 43% for GST against 40% measured	agrees within 7% (reading of force as coupling)
Same rule for AIST	overshoots by 1.3–1.9×
Closure counts per family: 0/6, 2/8, 6/12	counted, exact
Order $\langle 100 \rangle > \langle 111 \rangle > \langle 110 \rangle$ in $\text{Li}_4\text{Ti}_5\text{O}_{12}$ capacity	agrees
(100) holds better, (110) holds more at its surface, in LiMn_2O_4	agrees; surface area differs
Conductance $\propto 1/L$ in Moddel’s cavities	agrees (Maclay’s fit)
Power slope -1.8	rests on an assumption; open
Best polar films hold 0.97–1.65 E_{mesh} per cell	order agrees; no ceiling at 1
Plated lithium fraction $\approx 1/3$	base case only; varies with electrolyte
Critical sensitivity exponent 1 against 1.26 measured	does not agree
Battery lengths on the factor-three ladder	not distinguishable from chance ($p \approx 0.19$)
AMOLF 44 nm against S_0	set aside

All arithmetic in this essay is given in full and has been recomputed.

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