Quantum suppression of conductance fluctuations in atomic-size contacts

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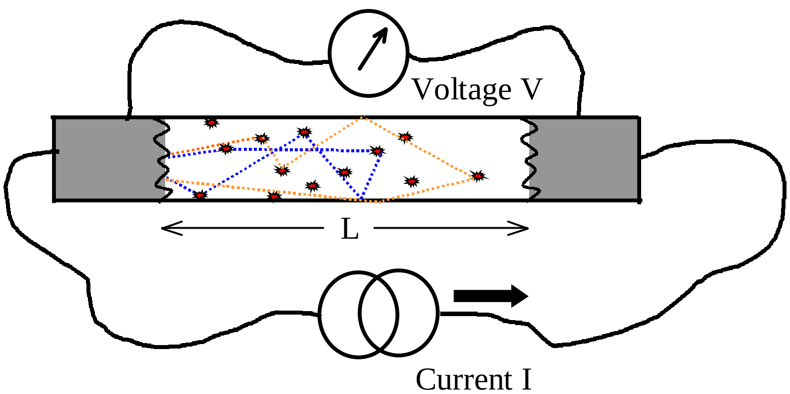
Universal Conductance Fluctuations



Requirement: $l_e \ll L \ll l_\varphi$

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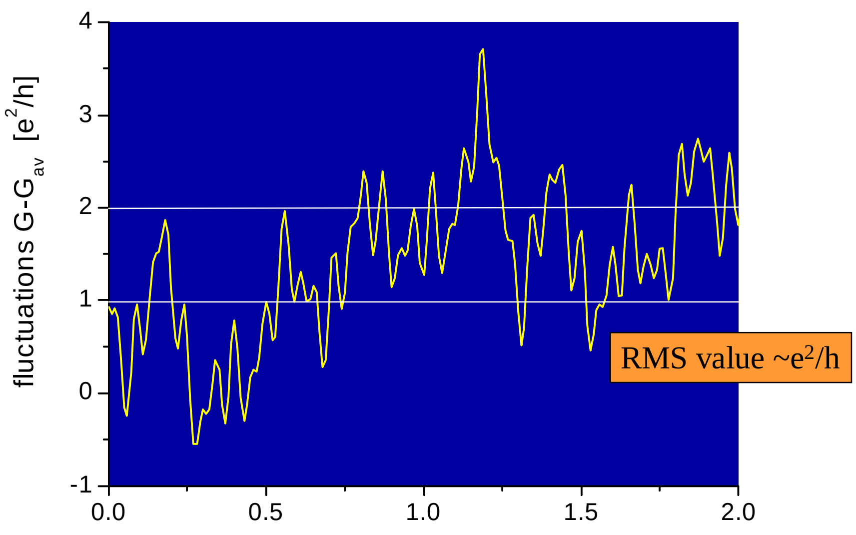
Universal conductance fluctuations



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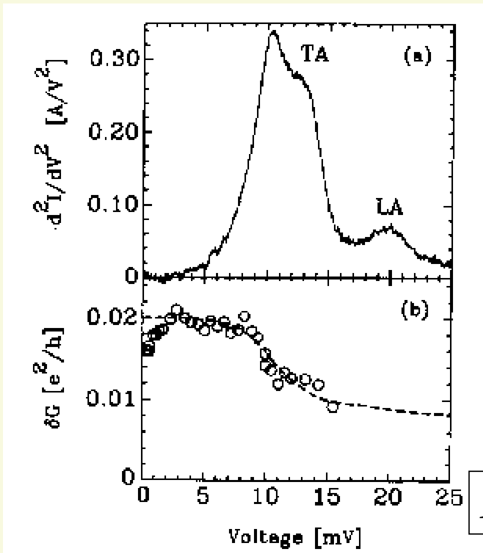
Conductance fluctuations in point contacts



$$\delta G \approx 1.6(e^2/h)\,a/l_e$$

Not universal

Ag, R=11 Ω (~$10^3 G_0$)

Holweg *et al.* Phys. Rev. Lett. **67** (1991) 2549

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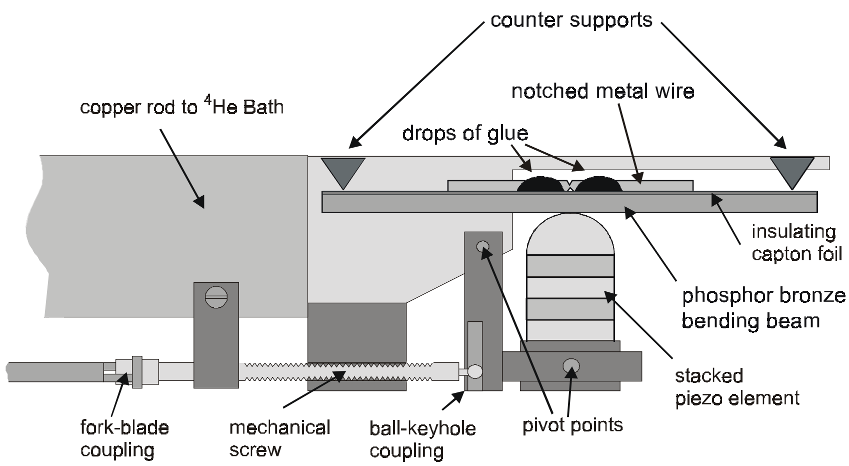
Mechanically Controllable Break Junction



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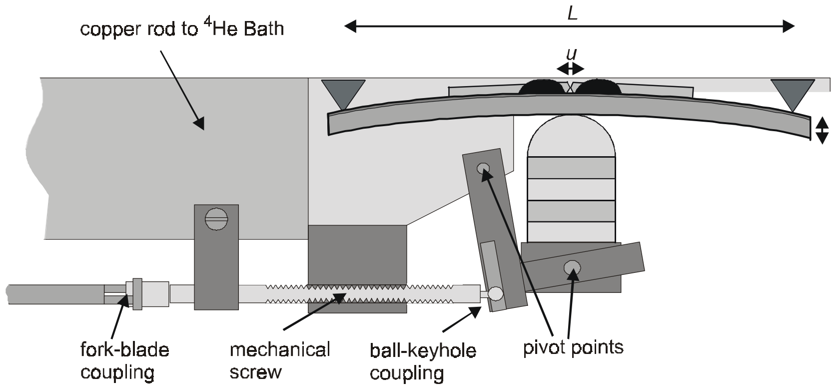
Mechanically Controllable Break Junction



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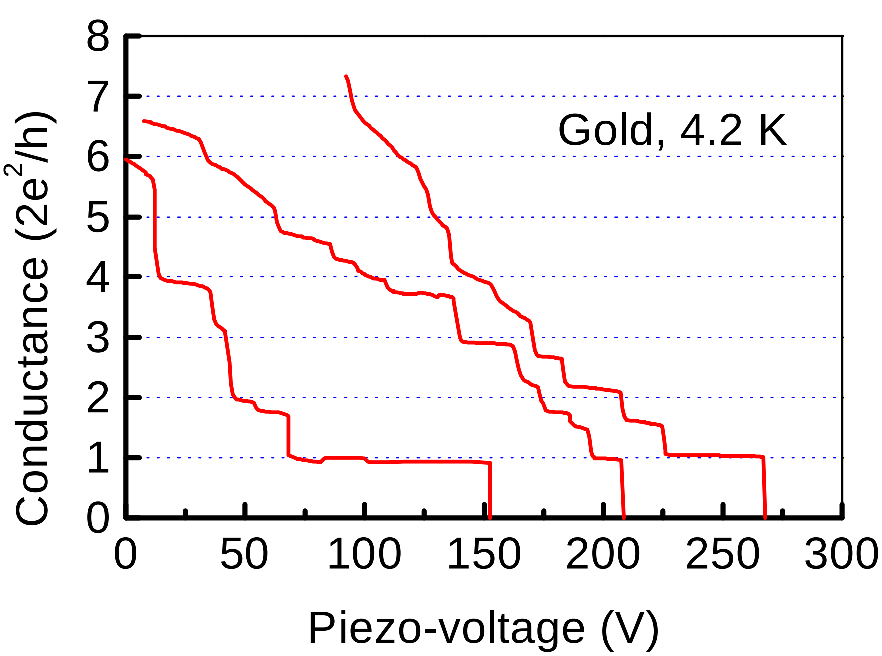

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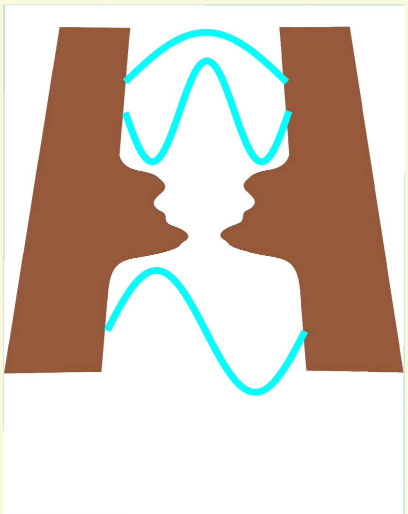
Quantum conductance (2 dimensions)



Incoming and reflected modes

Scattering at the contact

Transmitted modes

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Conductance is transmission

Vector of incoming waves from the left, on a basis of quantum modes: $\vec{i}_l$

Vector of outgoing waves to the right: $\vec{o}_r$

Matrix of transmission amplitudes: $\vec{o}_r = \hat{t}\vec{i}_l$

Landauer: $G = \frac{2e^2}{h}\mathrm{Tr}(\hat{t}^+\hat{t}) = \frac{2e^2}{h}\sum_n T_n$

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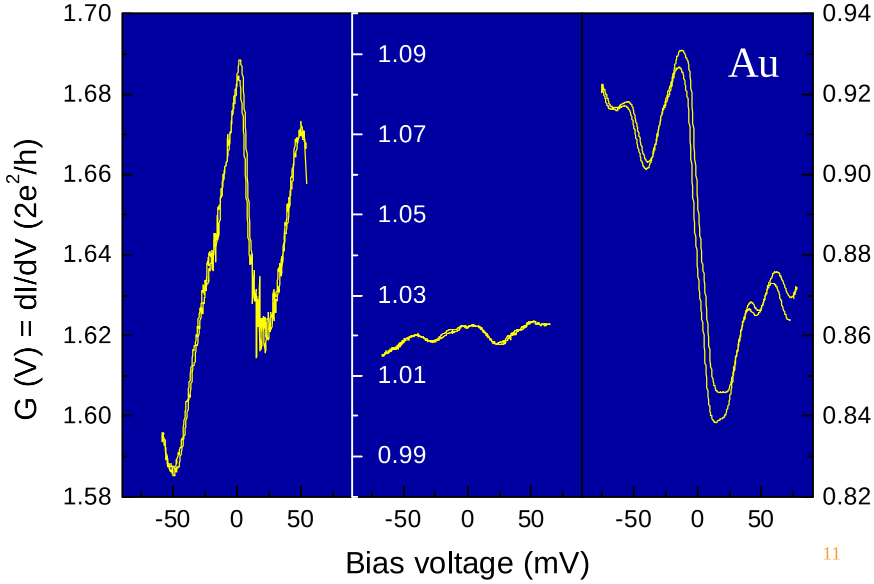
Examples for several settings of the conductance of the contact



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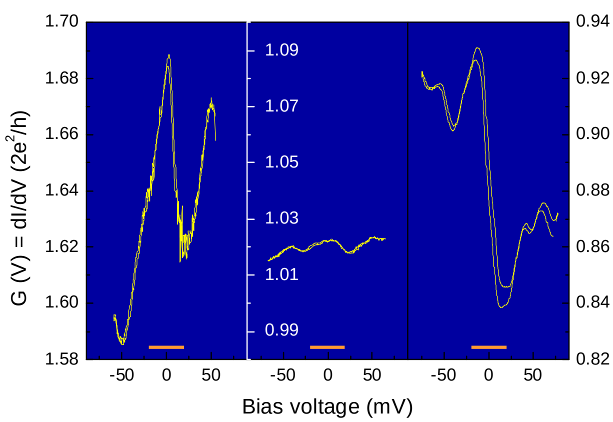
<u>Experimental approach to ensemble average</u>



- Large modulation voltage $V = V_{bias} + V_{mod}\sin(\omega t)$
- Fixed bias voltage (V_{bias}= 0) ; 20mV; 48 kHz
- Record G and dG/dV simultaneously

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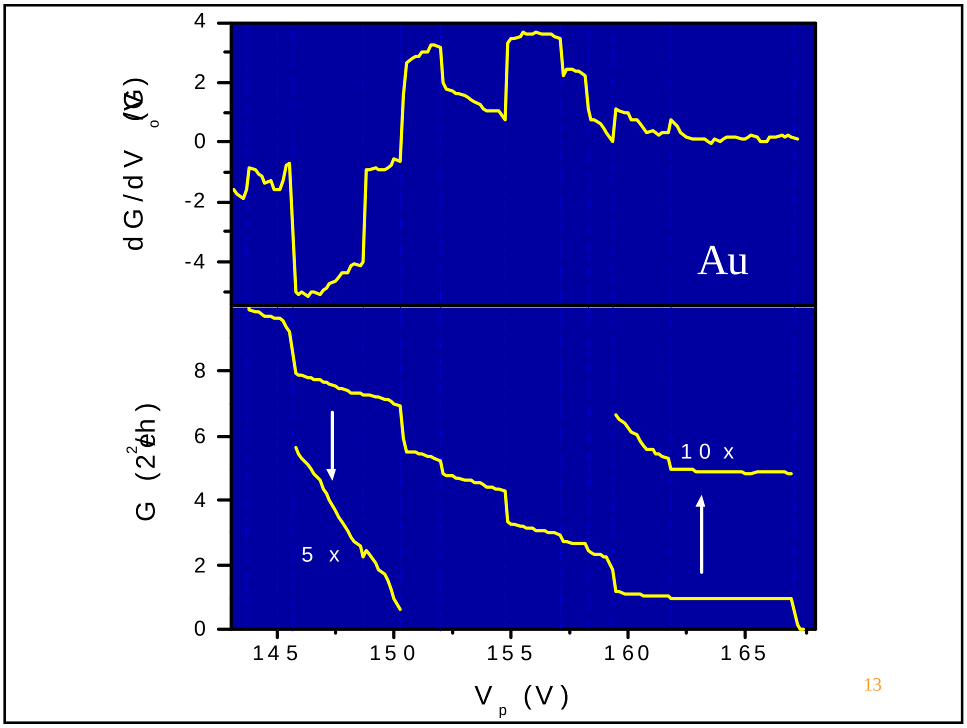
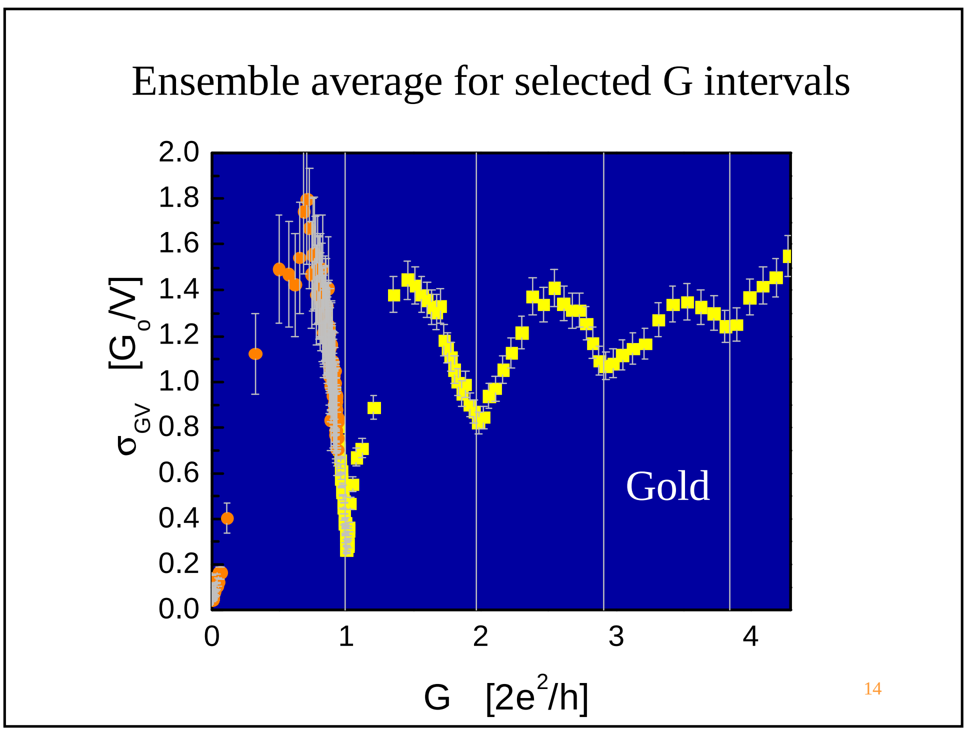


dG/dV (G/V)
4
2
0
-2
-4
Au
G (2e²/h)
8
6
4
2
0
10 x
5 x
145
150
155
160
165
V p (V)
13



Ensemble average for selected G intervals
σGV [Go/V]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Gold
0
1
2
3
4
G [2e²/h]
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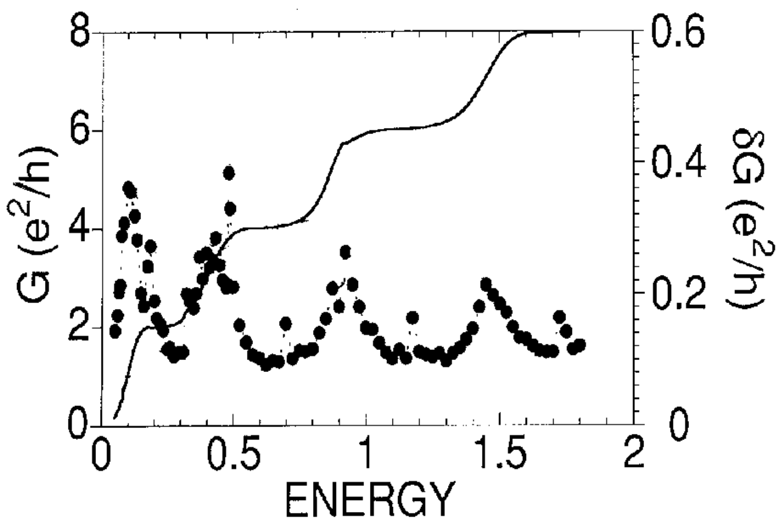
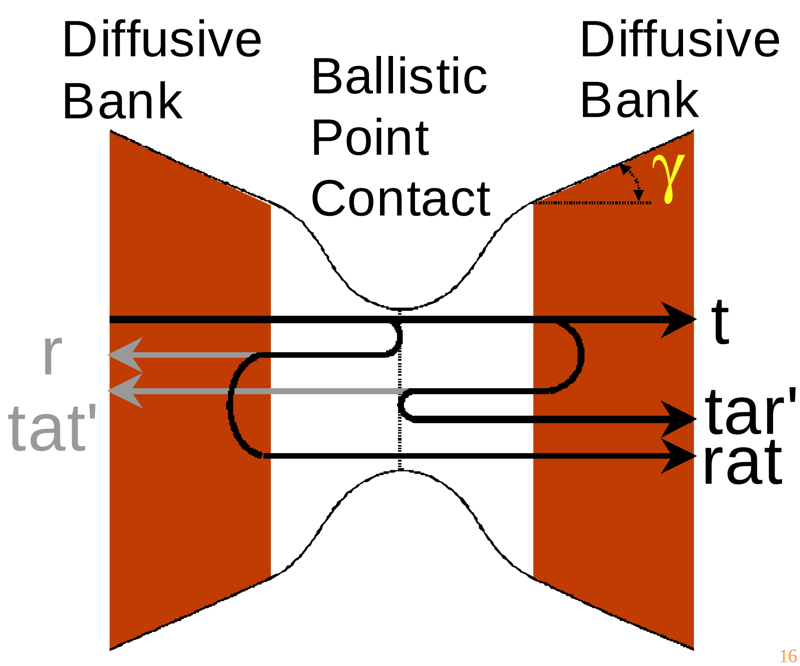
Model calculation



Maslov, Barnes & Kirczenow, Phys. Rev. Lett. **70** (1993) 1984



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Calculation of scattering corrections to G

Define $\sigma_{\mathrm{GV}} \equiv \left(\frac{\partial^2 I}{\partial V^2}\right)_{\mathrm{RMS}}$

$$I(V_0 + V_{\mathrm{mod}}\sin(\omega t)) = I(V_0) + \left(\frac{\partial I}{\partial V}\right)_{V_0}\sin(\omega t)$$

$$-\frac{1}{4}\left(\frac{\partial^2 I}{\partial V^2}\right)_{V_0} V_{\mathrm{mod}}^2\cos(2\omega t) + \cdots$$

$$I = \frac{2e^2}{h}\int_0^{eV}\mathrm{Tr}(\hat{t}^+\hat{t})\,dE$$

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Calculation of scattering corrections to G

(continued)

$$\mathrm{Tr}(\hat{t}^+\hat{t}) = \sum_{n=1}^{N} T_n\left(1 + \mathrm{Re}(a_{r_{nn}} r'_n + r_n a_{l_{nn}})\right)$$

$$\left\langle a_{r,l_{nn}}(E_1)\, a^*_{r,l_{nn}}(E_2)\right\rangle = \int_0^{\infty} P_{\mathrm{cl}}(\tau)\, e^{-i(E_1 - E_2)\tau/\hbar}\, d\tau$$

$$\sigma_{\mathrm{GV}} = \frac{2.71 e G_0}{\hbar k_{\mathrm{F}} v_{\mathrm{F}}\sqrt{1-\cos\gamma}}\left(\frac{\hbar/\tau_e}{eV_{\mathrm{mod}}}\right)^{3/4}\sqrt{\sum_{n=1}^{N} T_n^2(1-T_n)}$$

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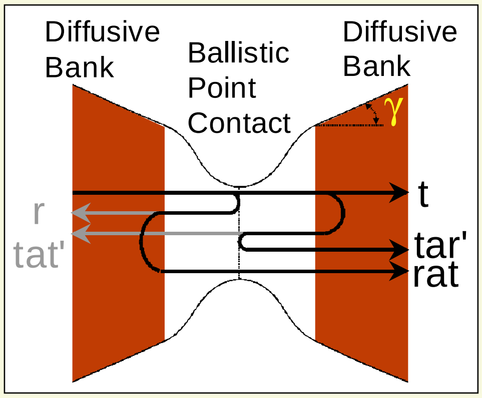
The probability per unit time to return to the contact, after a time τ, into a given mode *n, is*

$$P_{\rm cl}(\tau)=\frac{v_{\rm F}}{2\sqrt{3\pi}\,k_{\rm F}^{2}(D\tau)^{3/2}(1-\cos\gamma)}$$



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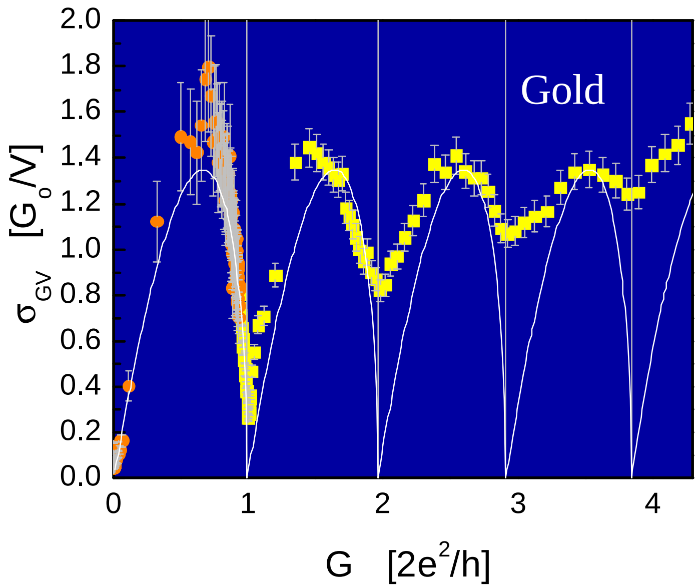
Model assuming channel saturation



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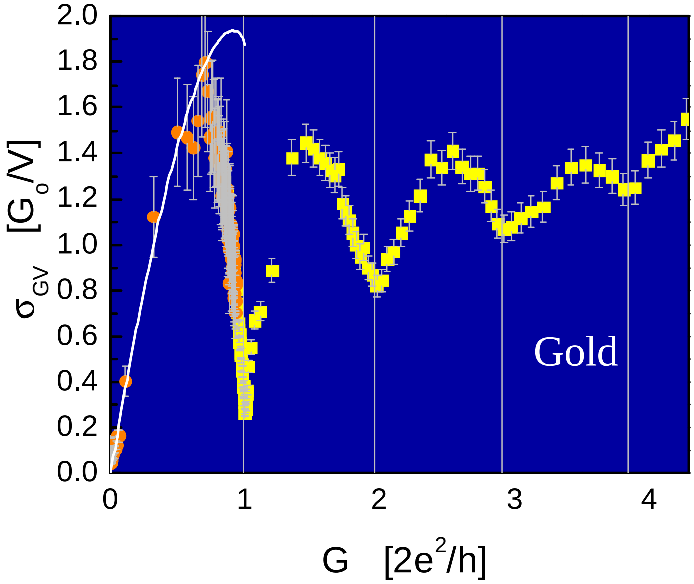
Assuming a random distribution of T_n
for two channels



$$G = G_0 \sum_{n=1}^{2} T_n ,$$

$$T_n \in [0,1]$$

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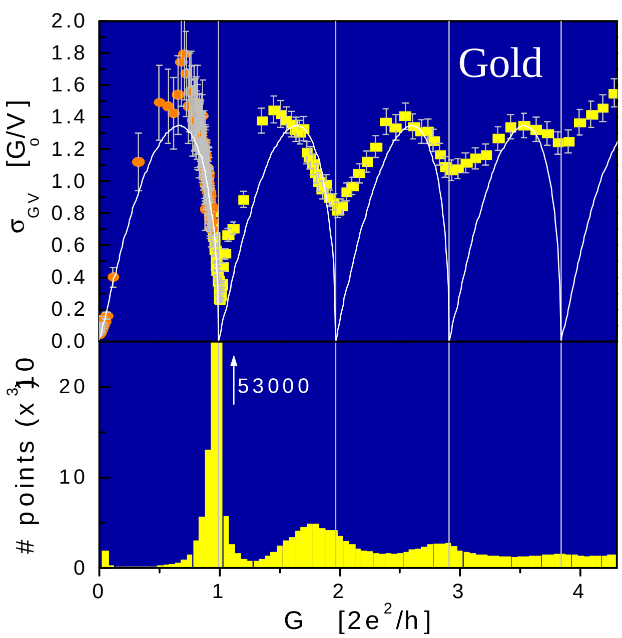

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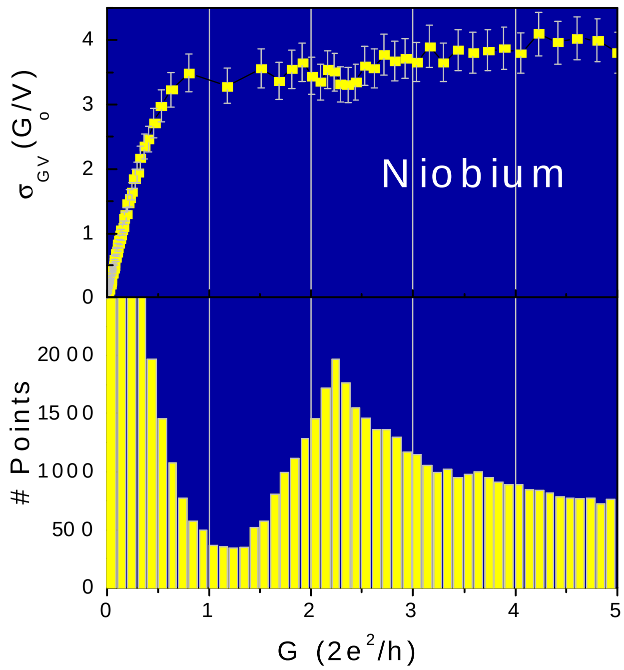

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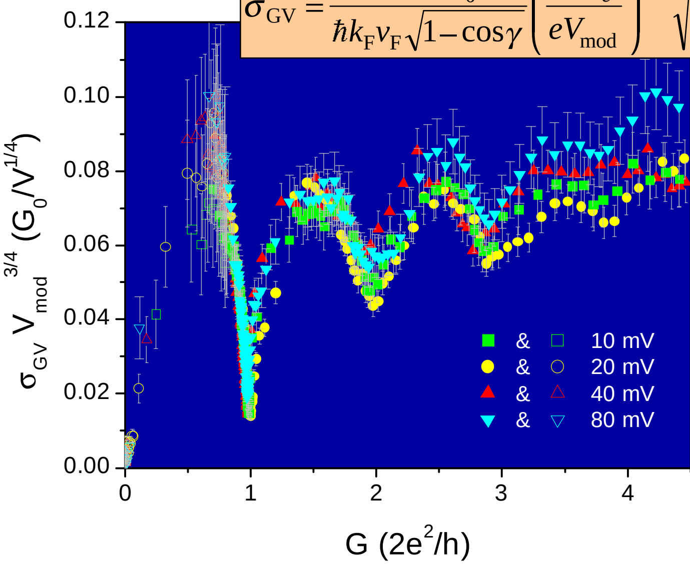
Test of the dependence on modulation amplitude

$$\sigma_{\mathrm{GV}} = \frac{2.71 e G_0}{\hbar k_{\mathrm{F}} v_{\mathrm{F}} \sqrt{1-\cos\gamma}} \left(\frac{\hbar/\tau_e}{e V_{\mathrm{mod}}} \right)^{3/4} \sqrt{\sum_{n=1}^{N} T_n^2 (1-T_n)}$$



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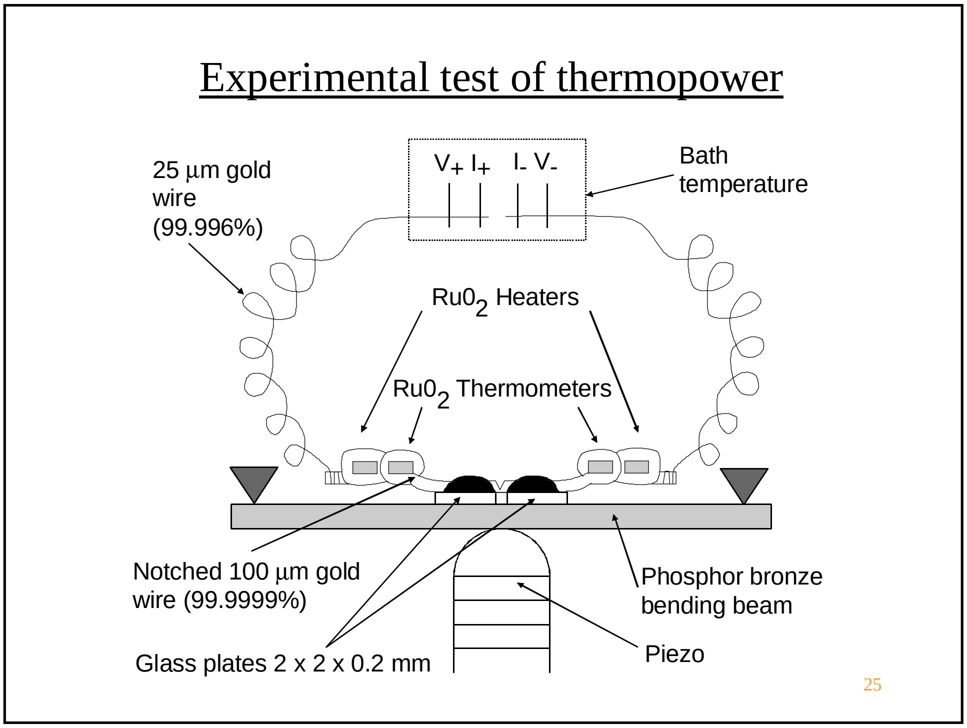
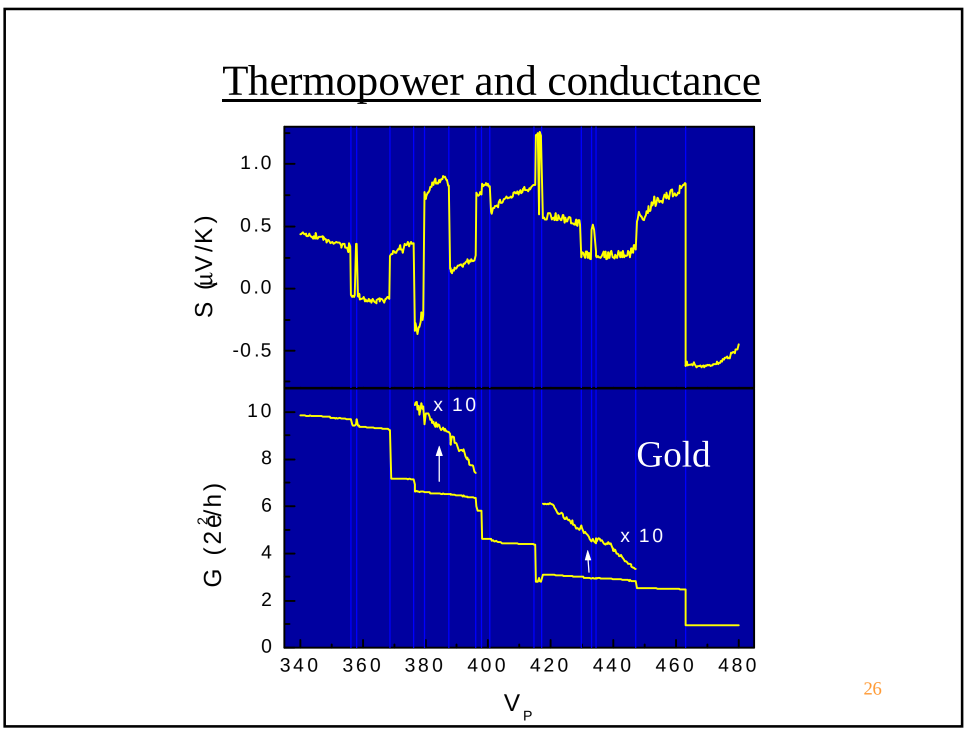

Experimental test of thermopower
25 µm gold wire (99.996%)
V+ I+ I- V-
Bath temperature
Ru0$_2$ Heaters
Ru0$_2$ Thermometers
Notched 100 µm gold wire (99.9999%)
Phosphor bronze bending beam
Glass plates 2 x 2 x 0.2 mm
Piezo
25


Thermopower and conductance
S (µV/K)
1.0
0.5
0.0
-0.5
G (2e²/h)
10
8
6
4
2
0
x 10
x 10
Gold
340 360 380 400 420 440 460 480
V$_P$
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Fluctuating contribution to the thermopower

(analogous to conductance fluctuations)

$$\sigma_S = \frac{c k_B}{e k_F l_e \sqrt{1-\cos\gamma}} \left(\frac{k_B \theta}{\hbar v_F / l_e} \right)^{1/4} \frac{\sqrt{\sum_{n=1}^{N} T_n^2 (1-T_n)}}{\sum_{n=1}^{N} T_n}$$

c=5.658 for $\Delta\theta/\theta \to 0$

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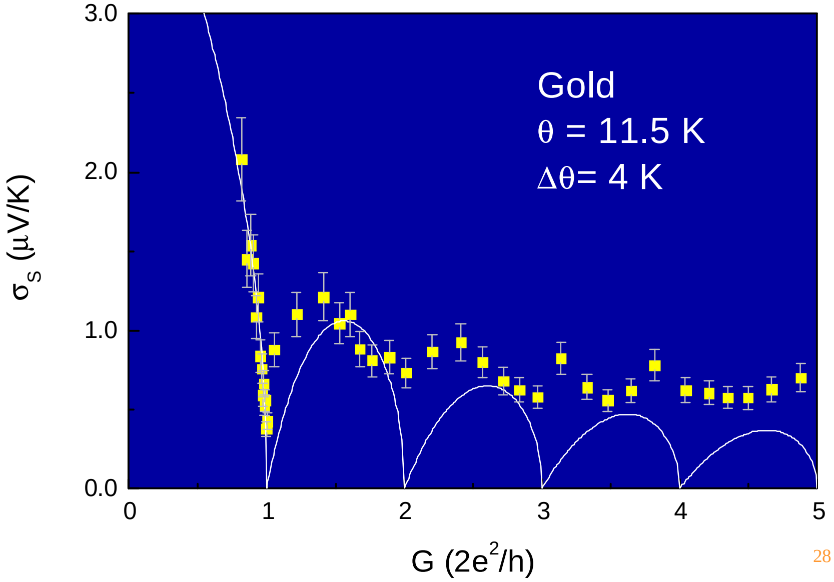
Standard deviation in thermopower



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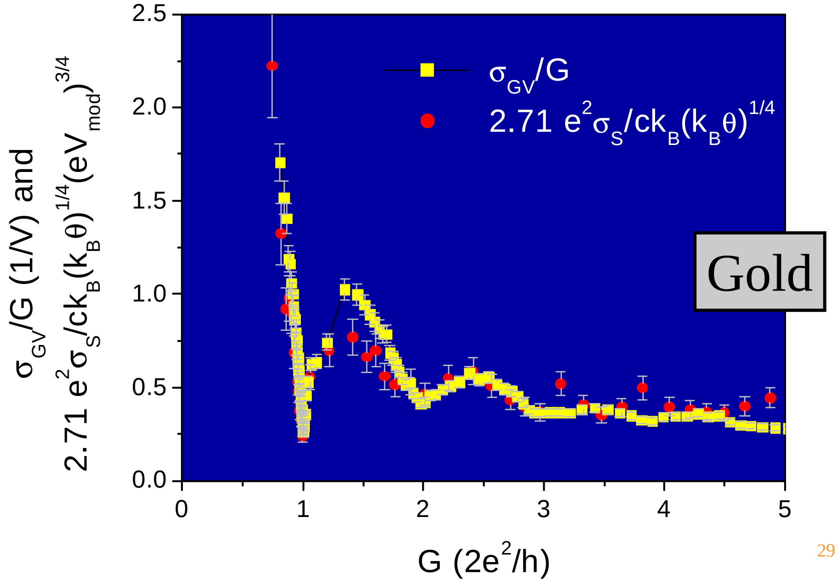
Scaling of thermopower and conductance fluctuations



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Conclusions

- For atomic-size contacts of monovalent metals we observe a quantum suppression of the fluctuations close to NG_0.
- Formulation in terms of scattering properties of the bare contact.
- Saturation of channel transmission (Cu,Ag,Au,Na,…).
- Fluctuations of the thermopower.
- Thermopower and conductance fluctuations are in quantitative agreement.

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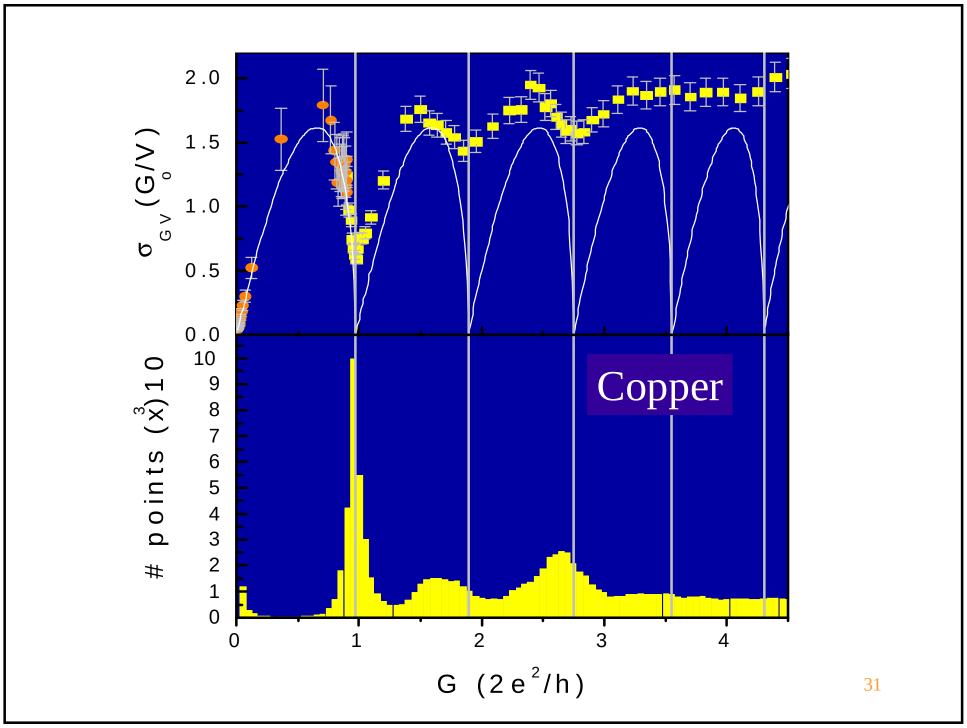
Copper
σ_{GV} (G_o/V)
points (x10^3)
G (2e^2/h)
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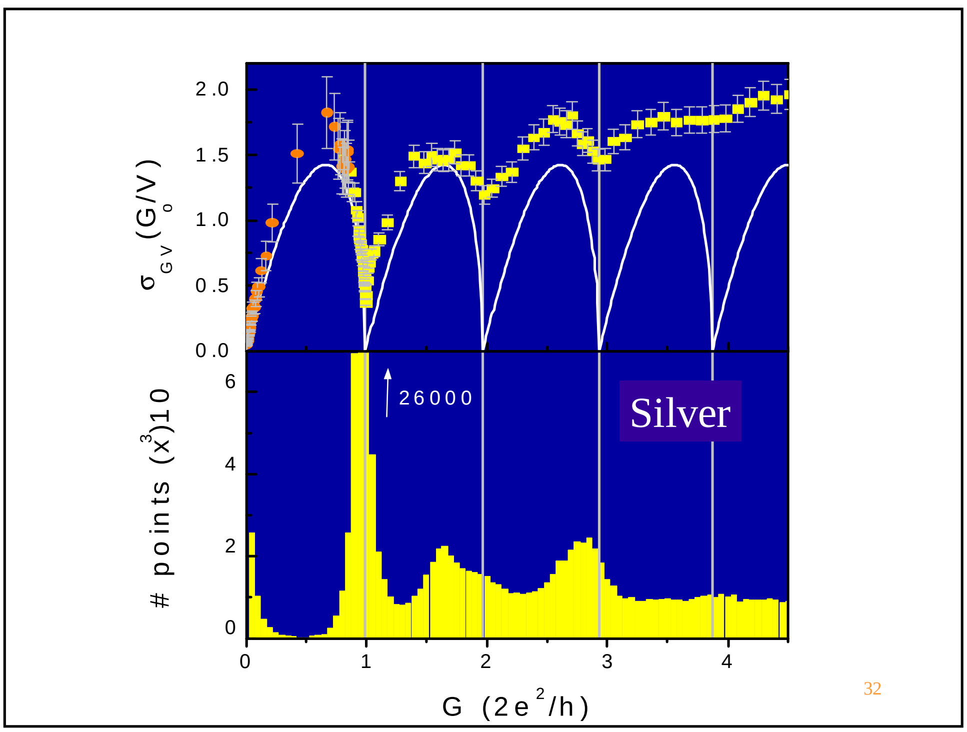
Silver
26000
σ_{GV} (G_o/V)
points (x10^3)
G (2e^2/h)
32

Series resistance

To lowest order

$$\left\langle \mathrm{Tr}(\hat{t}^{+}\hat{t}) \right\rangle = \sum_{n=1}^{N} T_n \left[1 - \sum_{m=1}^{N} T_m \left(\left\langle \left| a_{r_{mn}} \right|^2 \right\rangle + \left\langle \left| a_{l_{mn}} \right|^2 \right\rangle \right) \right]$$

$$\text{From shift}: \left\langle \left| a_{l,r_{mn}} \right|^2 \right\rangle \approx 0.005 \text{ for gold} \Rightarrow \ell_e = 6 \pm 1\text{nm}$$

From random matrix theory, perfectly transmitted channels:

$$\frac{\langle G \rangle}{G_0} = \frac{g}{1+(g+1)r} + \frac{1}{3}\left(\frac{(g+1)r}{1+(g+1)r} \right)^3$$

(Beenakker and Melsen, PRB **50** (1994), 2450)

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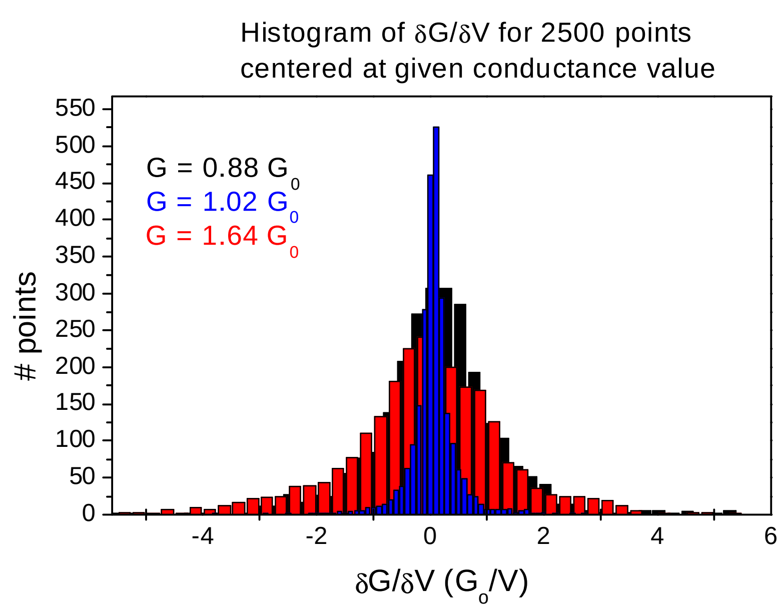

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Scaling of the two properties

$$\frac{\sigma_{\mathrm{GV}}}{G} = \sigma_{\mathrm{S}} \frac{2.71 e^2}{c k_{\mathrm{B}} \left(k_{\mathrm{B}}\theta\right)^{1/4} \left(eV_{\mathrm{mod}}\right)^{3/4}}, \quad G = G_0 \sum_{n=1}^{N} T_n$$

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