The 2e/h journey

Brian Petley*
(formerly of the National Physical Laboratory)

* brian.petley@phys.org
NPL Beginnings

Bushy House at the National Physical Laboratory
An oscilloscope display of a solder-drop junction irradiated by 36 GHz microwaves
Essentially there were three aspects to the problems of measuring $2e/h$:

(i) getting from millivolts to volts
(ii) getting the voltage units from one country to another, and
(iii) comparing the Josephson $2e/h$ with $2e/h$ determined by independent measurements.
Comparison of 1969 results

• The published NPL result was: $483.593 \pm 93(100) \text{MHz/V}_{\text{NPL}}$

• In USA volts the UK result became: $483.597 \pm 7(10) \text{MHz/V}_{\text{NIST}}$

• The Pennsylvania result was: $483.597 \pm 6(12) \text{MHz/V}_{\text{NIST}}$

• Fractional difference: $(0.2\pm3.3) \times 10^{-6}$

• $2e/h$ from the rest of physics: $483.596 \pm 4(29) \text{MHz/V}_{\text{NIST-69}}$

• Fractional Difference: $(2.5\pm6.4) \times 10^{-6}$

• **2012** $2e/h$ recommended value: $483.597 \pm 870(11) \text{MHz/V}$
The Maintained and SI volts

Diagram showing changes in maintained and disseminated volt values over time, with points for NML (Australia), NPL (U.K.), BIPM, PTB (W. Germany), and NBS (U.S.A.). Key points include:

- 1969 INTERNATIONALLY AGREED CHANGES
- PRESENT ESTIMATE OF SI VOLT
- PROBABLE FUTURE CHANGE IN MAINTAINED VOLT
- JOSEPHSON EFFECT [(2e/h)V] / GHz

Graph parameters include:

- RELATIVE VOLTAGE µV
- TIME/YEAR (1968 to 1986)
- CHANGES IN THE DISSEMINATED VOLT
The Josephson constant

The value assigned in 1972 was:

\[ K_{J-72} = 483.594 \text{ MHz/V exactly} \]

And in 1990, following more accurate realisations of the volt, the value was reassigned as:

\[ K_{J-90} = 483.5979 \text{ MHz/V exactly} \]

The latter value pervades today. The ‘exact’ value of \( 2e/h \) is referred to as \( K_j \)
## Evolution in the Number of Josephson junctions in series

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Tunnel junctions in series</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>1 (≈2 mm square)</td>
</tr>
<tr>
<td>1972</td>
<td>2 (10 mV)</td>
</tr>
<tr>
<td>1977</td>
<td>Levinson – reduced barrier size to (≈2 μm)</td>
</tr>
<tr>
<td>1988</td>
<td>&gt;10 000 (1 V)</td>
</tr>
<tr>
<td>1992</td>
<td>20 238 (Nb, Al₂O₃ barriers, 10 V)</td>
</tr>
<tr>
<td>1995</td>
<td>400 (SNS, 1.7 μm square)</td>
</tr>
<tr>
<td>1997</td>
<td>32 768 (SNS, 1V, 2 μm)</td>
</tr>
<tr>
<td>2009</td>
<td>307 200 (SNS) up to 25 V.</td>
</tr>
</tbody>
</table>
A NIST Josephson array
The range of variables tested
(Woods and Solve, 2009)

<table>
<thead>
<tr>
<th>Josephson junction influence parameter</th>
<th>Parameter range tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step number</td>
<td>± 1 to ± 120</td>
</tr>
<tr>
<td>Number of junctions</td>
<td>1 to 307 000</td>
</tr>
<tr>
<td>Junction material</td>
<td>&gt;20 types (including normal metal barriers and arrays)</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>±0.15 mV to ±18.5 V</td>
</tr>
<tr>
<td>RF frequency</td>
<td>Few hundred kHz to 100 GHz</td>
</tr>
<tr>
<td>Temperature</td>
<td>2 K to 64 K</td>
</tr>
<tr>
<td>Overall limits</td>
<td>1 in $10^{10}$ to $10^{17}$</td>
</tr>
</tbody>
</table>
Results of comparisons to 2009 between national 10 volt Josephson apparatus (95% uncertainties), (Woods and Solve 2009)
But is it really $2e/h$?

There are three ways to answer this question at present.

1. **Comparison between Josephson junctions:** no effect to parts in $10^{17}$? (Includes tests of gravitational shifts.)

2. **Compare the Josephson $2e/h$ with that from the rest of physics,** currently $\sim 1$ in $10^8$. Possibilities still that there may be:
   - Nordtvedt - Charge Screening effects $\sim 1$ in $10^{11}$?
   - or Penin – vacuum polarisation QED magnetic field dependent effects $\sim 1$ in $10^{19}$?

3. **Another type of internally self consistent measurement** (known as the quantum triangle) - combines three methods $2e/h, h/e^2,$ and $e$. Present tests to a few parts in $10^7$. 
The Quantum Triangle

1. A Josephson voltage standard (JVS) driven at a frequency $f_j$ on the $n$th step produces a voltage:

$$U_{JVS} = nf_j/K_j \quad \text{with} \quad K_j = (2e/h)(1+\varepsilon_j)$$

2. A quantum Hall resistance standard (QHR) quantized on the $i$th plateau has a resistance

$$R_{QHR} = R_K/i \quad \text{with} \quad R_K = (h/e^2)(1+\varepsilon_K)$$

3. A single electron tunnelling current standard (SET) driven at a frequency $f_p$ produces a current:

$$I_{SET} = Q_Sf_S \quad \text{with} \quad Q_S = e(1+\varepsilon_S)$$

Since $I_{SET} = U_{JVS}/R_{QHR}$,

One can test whether:

$$(1+\varepsilon_S) = (1+\varepsilon_j)/2(1+\varepsilon_K)$$
The Kibble method falling coil method of measuring the Plank constant

(1) \( Bn90l = mg \)

(2) \( E_{90} = -\frac{d\Phi}{dt} = BnN \)

(3) \( E_{90}i_{90} = mgV \)

(4) \( f_j f_{j2} / K2J - 90R_{K-90} = mgV \)

(5) \( h = 4 / (KJ2 R_K) \)
The Josephson effects have given us:

A beautiful quantum effect in superconductivity

A new method of measuring a fundamental constant

Improved global accuracy for electrical measurements in science and technology: an every-day use of magnetic flux quantisation!

A likely major revision of the SI - in 2015? To a system based on ($^{133}$Cs)$_{hfs}$, c, h, e, k, $N_A$, lumen, and hence a system depending differently on $\alpha$ ($= \mu_0 c/[h/e^2]$)
THE END

or a new beginning?