From Electrical Engineering to Quantum Physics: The Case of Nishina Yoshio

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Beginning of QM in Japan

- **Yukawa Hideki**
- **Tomoanga Sin-itiro**
- **Sakata Shoichi**
- **Esaki Reona**
- **Nambu Yoichiro**

Nishina Yoshio 1890-1951

- The first generation of Japanese quantum physicist
- Essential in introducing quantum mechanics into Japan
- Trained as an electrical engineer

Nishina Yoshio's earlier career

- 6th higher school: Engineering
- Tokyo Imperial University: College of Engineering, Dept. of Electrical Engineering
- 1918 Riken and Grad School
- 1921 Europe
- 1923 Copenhagen
- 1928 Return to Japan

Goal of the paper

Possible connections between electrical engineering and quantum mechanics in Japan

Argument

- **Electrical engineering was one of the bases for quantum physical research to be motivated, legitimized, and sustained in Japan.**

- **It prepared at least one important figure in quantum physics research in Japan through its conceptual affinity.**

Larger project

- **Quantum mechanics in socio-cultural context in Japan**
  - 1. social-institutional levels
  - 2. conceptual-cultural levels.

Social and institutional levels

- **What social and institutional resources supported development of atomic/nuclear physics in Japan**
  - What were personal motivations for physicists?
  - What legitimized such research in society?
  - How was such research sustained in society?

Conceptual dimension

- **What were conceptual and cultural resources available**
  - Pedagogical traditions
  - Conceptual resources in related disciplines

Background considerations

- **Perception of values of atomic physics was different in early 20th century Japan (they did not expect atomic power/bomb)**
- **Did not know what kind of knowledge and training would be needed for atomic physics research**

Note 1

- **Focus on the first generation**
- **As for the second generation, different considerations would be necessary**

Notes 2

- **Mathematical physics and engineering (as in the case of the Sommerfeld school).**
- **Spectroscopy and X-ray**

- **1930s: Cosmic ray research and airplane**
- **1940s: Atomic bomb project**

Outline of the paper

- **Social and cultural background**
- **Conceptual connections**
  - Electrical engineering education that Nishina received
  - Quantum physics research of Nishina
    - Derivation of Klein–Nishina formula

Ⅰ. Socio-cultural background

1. Primacy of Engineering

- **Engineering had higher priority and more prestige than physics in early 20th century Japan**
- **Modernization of Japan since the Meiji Era (1868-)**
  - Early inclusion of engineering in higher education: The Imperial college of engineering
  - Need of engineers to build modern infrastructure

2. Atomic theory and Electron

- **Atomic physics as a basis of electrical engineering**
  - Physics provided basic understanding of electric theory
  - Electron was the main focus of atomic physics as it was introduced into Japan in early 20th century
  - Education and training (textbooks)
  - Physicists' self-description (Popular writings)

Nagaoka Hantaro (1865-1950)

- **Tokyo Imperial University**
- **Saturnian model of atom**

- ***Studies of Electricity Today (1912)***
  - Popular account of electricity studies
  - Includes atomic physics

Mizuno Toshinojo (1861-1944)

- **Imperial University of Kyoto**
- **More focused on electron**
- ***The Electron Theory* (1912)**

Aichi Keiichi (1880-1923)

- **Theoretical physicist at Tohoku Imperial University**
- ***Autobiography of an Electron* (1923)**
  - Popular account of atomic physics

Physics and electricity

- **Connecting physics with electricity**
- **Seeking popular support and interest**
- **Education of electrical engineers or teachers of electrical engineering**
- **Research related to electricity**

Study of Electron

- **Nishina's early career was consistent as a pursuit of knowledge about electron**
- **Commented by his relatives about his stay in Europe as "research of electron"**

Ⅱ. Physical and Conceptual

Question

- What Nishina learned from electrical engineering
- How could that be related to quantum physics conceptually

1. Nishina’s EE training

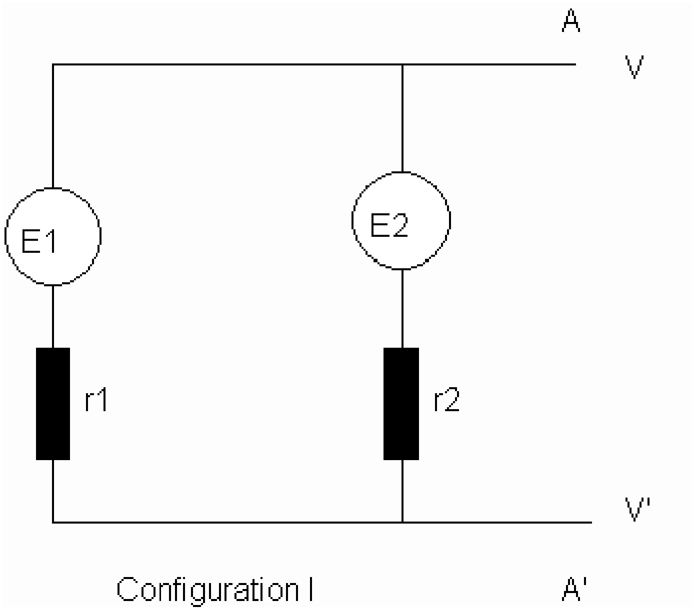
Ho Hidetaro (1882-1931)

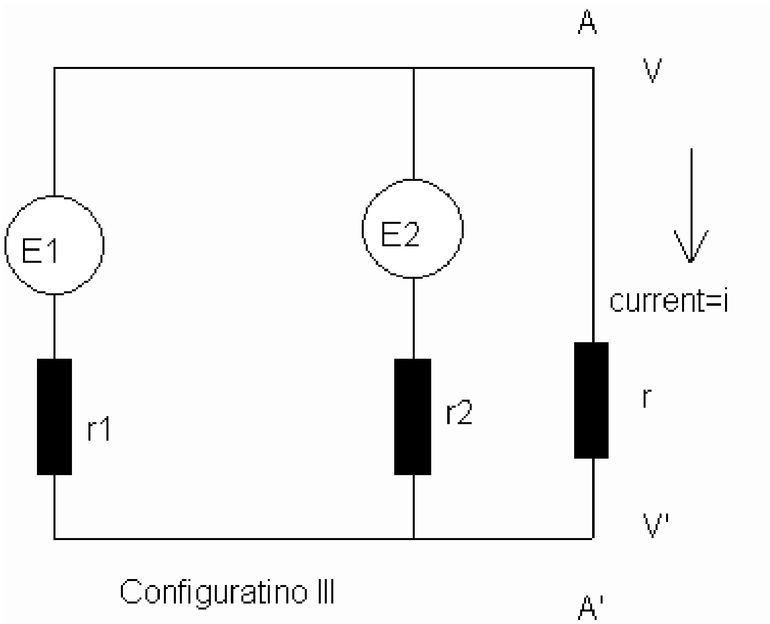
- Professor of electrical engineering at Tokyo Imperial University and Nishina’s first advisor
- Introduction of Steinmetz’ theory of alternating current theory to Japan
- Ho-Thévenin’s theorem

Steinmetz

- **Charles Proteus Steinmetz 1865-1923**
- **Theorization of alternating current**

Ho-Thévenin's theorem



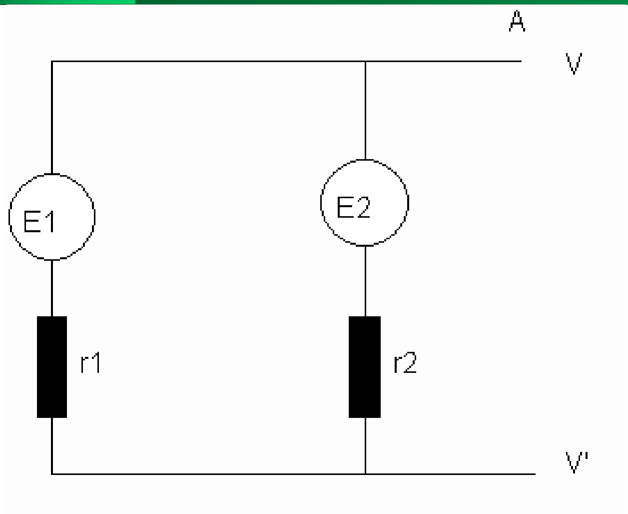


$$I = \frac{V - V'}{R + r}$$

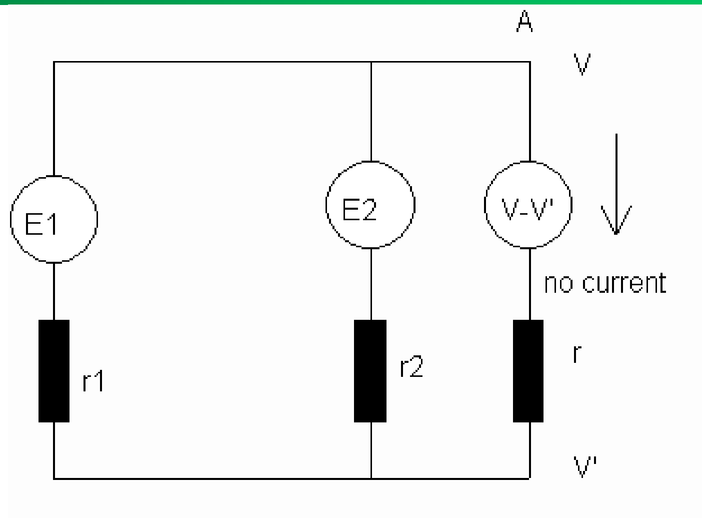
Principle of Superposition

- **Principle of Superposition in Electrical Circuit**
  - Configuration A: voltage source E_1 at A but none at B
  - Configuration B: voltage source E_2 at B but not A
  - Configuration C: voltage source E_1 at A and E_2 at B
  - The solution to configuration C by adding up the solutions to Configurations A and B

Ho-Thévenin's theorem



Configuration I



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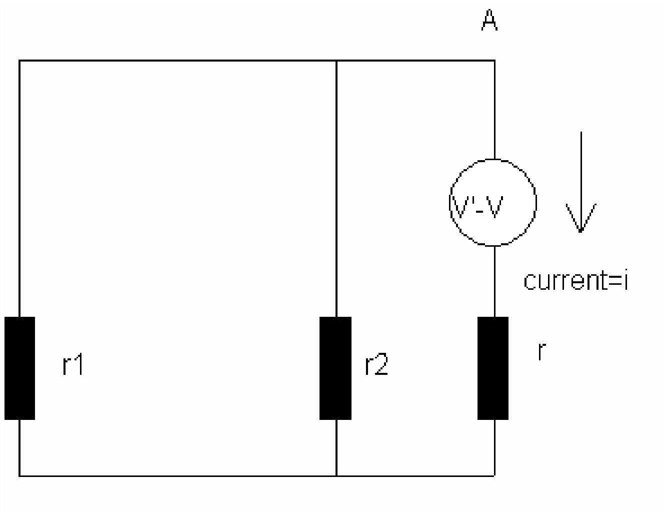

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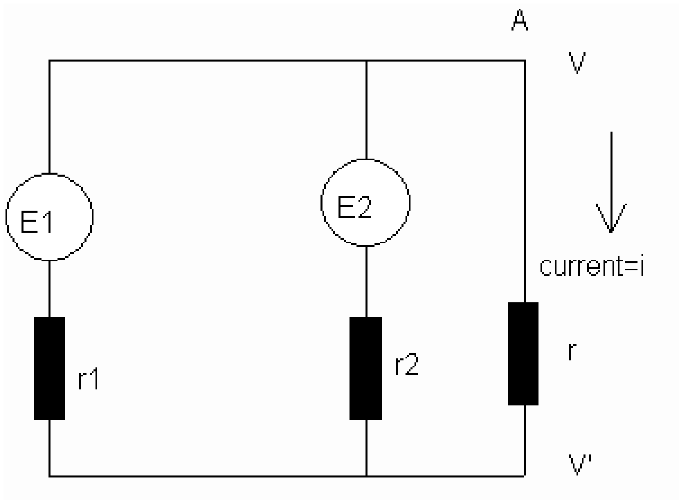

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2. Nishina’s B. A. Thesis

- **“Effects of Unbalanced Single-Phase Loads on Poly-Phase Machinery and Phase Balancing,” B. A. Thesis, Tokyo Imperial University, 1918.**
- **The question of how unbalanced loads would affect an alternator, a motor, or a rotary transformer in poly-phase system.**
- **Applied the principle of superposition**

  “An unbalanced polyphase system can be resolved into two balanced components of opposite phase rotations, one positive and the other negative”

3. QM and Superposition

- **The principle of superposition in QM**
- **Dirac's textbook**
- **Japanese translation in the 1930s (by Tomonaga and others)**

4. The Klein-Nishina formula

- **Klein & Nishina, “Über die Streuung durch freie Elektronen nach der neuen relativstischen Quantendynamik von Dirac,” *Zeitschrift f`ür Physik*, 52, 853-868.**
- **Earliest application of Dirac’s theory**
- **Experimental confirmation**
- **Includes negative energy contributions (I. Waller, 1930)**

Klein-Nishina formula

- **Yazaki, Y. (1992). "How was the Klein-Nishina formula derived?: Based mainly on the source materials of Y. Nishina in RIKEN," *Kagakushi Kenkyu*, 31, (I) 81-91; (II)129-137 (in Japanese).**

Outline of Derivation

- **Semiclassical treatment of Compton scattering following Gordon and Dirac, using Dirac's relativistic theory of electron**

1. **Solutions of Dirac equation for a free electron and an electron in a monochromatic radiation**
2. **Current density**
3. **Vector potential and Magnetic field vector**
5. **Intensity**

Dirac Equation

$$\left[p_0+\frac{e}{c}A_0+\rho_1\left(\boldsymbol{\sigma},\mathbf{p}+\frac{e}{c}\mathbf{A}\right)+\rho_3 mc\right]\phi=0$$

$$\sigma_1=\begin{Bmatrix}0&1&0&0\\1&0&0&0\\0&0&0&1\\0&0&1&0\end{Bmatrix},\ \sigma_2=\begin{Bmatrix}0&-i&0&0\\i&0&0&0\\0&0&0&-i\\0&0&i&0\end{Bmatrix},\ \sigma_3=\begin{Bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{Bmatrix},$$

$$\rho_1=\begin{Bmatrix}0&0&1&0\\0&0&0&1\\1&0&0&0\\0&1&0&0\end{Bmatrix},\ \rho_2=\begin{Bmatrix}0&0&-i&0\\0&0&0&-i\\i&0&0&1\\0&i&0&0\end{Bmatrix},\ \rho_3=\begin{Bmatrix}1&0&0&0\\0&1&0&0\\0&0&-1&0\\0&0&0&-1\end{Bmatrix}.$$

Free electron solutions

$$\varphi_0(p) = u(\mathfrak{p})\, e^{\frac{i}{\hbar}[Et - (\mathfrak{p}\mathfrak{r})]}, \qquad \psi_0(p) = v(\mathfrak{p})\, e^{-\frac{i}{\hbar}[Et - (\mathfrak{p}\mathfrak{r})]}, \tag{4}$$

$$u(\mathfrak{p})\left(E/c + \rho_1(\boldsymbol{\sigma}\mathfrak{p}) + \rho_3 mc\right) = 0$$
$$\left(E/c + \rho_1(\boldsymbol{\sigma}\mathfrak{p}) + \rho_3 mc\right)v(\mathfrak{p}) = 0.$$

$$u(\mathfrak{p}) = u^*(\mathfrak{p})S(\mathfrak{p}),\; v(\mathfrak{p}) = S^{-1}(\mathfrak{p})v^*(\mathfrak{p})$$

$$\left.\begin{aligned} u_1^*(\mathfrak{p}) &= a_1\, e^{i\delta_1(\mathfrak{p})}, & u_2^*(\mathfrak{p}) &= a_2 e^{i\delta_2(\mathfrak{p})}, \\ v_1^*(\mathfrak{p}) &= a_1\, e^{-i\delta_1(\mathfrak{p})}, & v_2^*(\mathfrak{p}) &= a_2\, e^{-i\delta_2(\mathfrak{p})}. \end{aligned}\right\} \tag{21}$$

Incoming radiation

$$\mathfrak{A} = \mathfrak{a} e^{i\nu\left(t - \frac{(\mathfrak{n}\mathfrak{r})}{c}\right)} + \bar{\mathfrak{a}} e^{-i\nu\left(t - \frac{(\mathfrak{n}\mathfrak{r})}{c}\right)}, \tag{22}$$

Solutions

$$\varphi(\mathrm{p}) = \varphi_0(\mathrm{p})\left\{1 + f(\mathrm{p})e^{i\nu\left(t-\frac{(\mathrm{nr})}{c}\right)} + \bar{f}(\mathrm{p})e^{-i\nu\left(t-\frac{(\mathrm{nr})}{c}\right)}\right\},$$

$$\psi(\mathrm{p}) = \left\{1 + g(\mathrm{p})e^{i\nu\left(t-\frac{(\mathrm{nr})}{c}\right)} + \bar{g}(\mathrm{p})e^{-i\nu\left(t-\frac{(\mathrm{nr})}{c}\right)}\right\}\psi_0(\mathrm{p}).$$

$$f(\mathrm{p}) = \frac{e}{2h\nu(E/c - (\mathrm{np}))}\{2(\mathrm{ap}) + h(\boldsymbol{\sigma\eta}) - ih\rho_1(\boldsymbol{\sigma\varepsilon})\},$$

$$\bar{f}(\mathrm{p}) = -\frac{e}{2h\nu(E/c - (\mathrm{np}))}\{2(\mathrm{ap}) + h(\boldsymbol{\sigma\bar{\eta}}) - ih\rho_1(\boldsymbol{\sigma\bar{\varepsilon}})\},$$

$$g(\mathrm{p}) = -\frac{e}{2h\nu(E/c - (\mathrm{np}))}\{2(\mathrm{ap}) + h(\boldsymbol{\sigma\eta}) + ih\rho_1(\boldsymbol{\sigma\varepsilon})\},$$

$$\bar{g}(\mathrm{p}) = \frac{e}{2h\nu(E/c - (\mathrm{np}))}\{2(\mathrm{ap}) + h(\boldsymbol{\sigma\bar{\eta}}) + ih\rho_1(\boldsymbol{\sigma\bar{\varepsilon}})\},$$

Electric and current density

$$\mathfrak{J} = ec\Phi\varrho_1\sigma\Psi = ec\int\int\varphi(\mathfrak{p})\,\varrho_1\sigma\psi(\mathfrak{p}')\,d\mathfrak{p}\,d\mathfrak{p}'. \qquad (29)$$

$$\begin{aligned}\mathfrak{J} = \mathfrak{J}_0 + ce\int\int d\mathfrak{p}\,d\mathfrak{p}'\,\{u(\mathfrak{p})\,[\varrho_1\sigma g(\mathfrak{p}')\\ + f(\mathfrak{p})\,\varrho_1\sigma]\,v(\mathfrak{p}')\,e^{\frac{i}{h}\left[(E+h\nu-E')t-\left(\mathfrak{p}+\mathfrak{n}\frac{h\nu}{c}-\mathfrak{p}'\right)\mathfrak{r}\right]}\\ + \text{konjugiert komplexes Glied}\}. \qquad (30)\end{aligned}$$

Outgoing radiation

Outgoing radiation (According to Gordon)

From initial state *u(p) v(p)* to *u(p’) v(p’)*

$$\mathfrak{A}(\mathfrak{p},\mathfrak{p}') = \frac{(2\pi h)^3}{r}\,\frac{1}{\sqrt{\Delta\Delta'}}\left\{e^{i\nu'\left(t-\frac{r}{c}\right)}\, u(\mathfrak{p})\,[\varrho_1\,\boldsymbol{\sigma}\, g(\mathfrak{p}') + f(\mathfrak{p})\,\varrho_1\,\boldsymbol{\sigma}]\, v(\mathfrak{p}') + \text{konjugiert komplexes Glied}\right\}, \quad (36)$$

Magnetic field

$$\mathfrak{H}_0 = \frac{(2\pi\hbar)^3 c^2 \nu'}{2mc^2 r\left(\nu-\nu'+\frac{2mc^2}{\hbar}\right)} \sqrt{\frac{E'\nu'}{mc^2\nu}} \left\{ d\left(\frac{1}{\nu}(\mathbf{n}'\boldsymbol{\varepsilon})(\nu'-\nu)[\mathbf{n}'\mathbf{n}] - \nu'\left(\frac{1}{\nu}+\frac{1}{\nu'}\right)^2 \frac{mc^2}{\hbar}[\mathbf{n}'\boldsymbol{\varepsilon}]\right)\right.$$

$$-i\Bigg[\left(\frac{1}{\nu'}-\frac{1}{\nu}\right)\Bigg((\mathfrak{s},\mathbf{n}\nu'-\mathbf{n}'\nu')((\mathbf{n}'\boldsymbol{\varepsilon})\mathbf{n}-(\mathbf{n}\mathbf{n}')\boldsymbol{\varepsilon}) + \left(\nu-\nu'+\frac{2mc^2}{\hbar}\right)((\mathfrak{s}\mathbf{n}')\boldsymbol{\varepsilon}-(\mathbf{n}'\boldsymbol{\varepsilon})\mathfrak{s})\Bigg)$$

$$\left.+\frac{2}{\nu}(\boldsymbol{\varepsilon}\mathbf{n}')((\mathbf{n}\nu-\mathbf{n}'\nu')+(\nu'-(\mathbf{n}\mathbf{n}')\nu)\mathfrak{s}) - \left(\frac{1}{\nu}-\frac{1}{\nu'}\right)((\mathbf{n}[\boldsymbol{\varepsilon}\mathfrak{s}])\nu[\mathbf{n}'\mathbf{n}]+\nu'(\mathbf{n}'[\mathbf{n}\boldsymbol{\varepsilon}])[\mathbf{n}'\boldsymbol{\varepsilon}])\Bigg]\right\} e^{i\nu\left(t-\frac{r}{c}\right)} + c.c.$$

$$\mathfrak{s} = u(\mathbf{p})\boldsymbol{\sigma} v(\mathbf{p}'),\quad \bar{\mathfrak{s}} = u(\mathbf{p}')\boldsymbol{\sigma} v(\mathbf{p}),$$

$$d = u(\mathbf{p}) v(\mathbf{p}'),\quad \bar{d} = u(\mathbf{p}') v(\mathbf{p}).$$

Intensity

$$\overline{\mathfrak{D}_0^2} = \frac{e^4}{m^2 c^4 r^2}\left(\frac{\nu'}{\nu}\right)^3 \left\{\left(\frac{\nu}{\nu'} + \frac{\nu'}{\nu}\right)\varepsilon^2 - 2(\mathfrak{n}'\varepsilon)^2\right\}.$$

Result

$$\bar{I} = J_0 \frac{e^4}{2\,m^2\,c^4\,r^2}\,\frac{1+\cos^2\Theta}{\left(1+\alpha(1-\cos\Theta)\right)^3}\left(1+\alpha^2\,\frac{(1-\cos\Theta)^2}{(1+\cos^2\Theta)\left(1+\alpha\,(1-\cos\Theta)\right)}\right). \quad (60)$$

Archival research

- **Yazaki, Y. (1992). "How was the Klein-Nishina formula derived?: Based mainly on the source materials of Y. Nishina in RIKEN,"** ***Kagakushi Kenkyu*****, 31, (I) 81-91; (II)129-137 (in Japanese)**

Initial/final states and Average

$$\mathfrak{A}(\mathfrak{p}, \mathfrak{p}') = \frac{(2\pi h)^3}{r} \frac{1}{\sqrt{\Delta \Delta'}} \Big\{ e^{i\nu'\left(t-\frac{r}{c}\right)} u(\mathfrak{p}) [\varrho_1 \boldsymbol{\sigma} g(\mathfrak{p}')$$

$$+ f(\mathfrak{p}) \varrho_1 \boldsymbol{\sigma}] v(\mathfrak{p}') + \text{konjugiert komplexes Glied} \Big\}, \quad (36)$$

$$u(\mathfrak{p}')\, \alpha\, v(\mathfrak{p}) \cdot u(\mathfrak{p})\, \beta\, v(\mathfrak{p}'),$$

Calculating average

◆**Assumptions**

– The final state contains two independent state with the same strength (superposition)

– Take average over phase

$$u^*(p) = (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} e^{i\delta_1(r)} \\ 0 \\ 0 \\ 0 \end{pmatrix} + (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} 0 \\ e^{i\delta_2(r)} \\ 0 \\ 0 \end{pmatrix} = (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} e^{i\delta_1(r)} \\ e^{i\delta_2(r)} \\ 0 \\ 0 \end{pmatrix},$$

$$v^*(p) = (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} e^{-i\delta_1(r)} \\ 0 \\ 0 \\ 0 \end{pmatrix} + (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} 0 \\ e^{-i\delta_2(r)} \\ 0 \\ 0 \end{pmatrix} = (2\pi\hbar)^{-\frac{3}{2}} \begin{pmatrix} e^{-i\delta_1(r)} \\ e^{-i\delta_2(r)} \\ 0 \\ 0 \end{pmatrix}.$$

Results

$$\overline{u(\mathfrak{p}')\,\boldsymbol{\sigma}\,v(\mathfrak{p}')} = 0, \tag{51}$$

$$u(\mathfrak{p}')\,v(\mathfrak{p}') = u^*(\mathfrak{p}')\,v^*(\mathfrak{p}') = 2\,(2\,\pi\,h)^{-3}. \tag{52}$$

Conclusion

Electrical Engineering and QM

- **No causal claim**
  - It would be ridiculous to claim that Nishina worked on quantum mechanics because he studied electrical engineering