Correlations of wave intensities and particle numbers.
Thoughts on the 50th anniversary of G. Györgyi's death.

Sándor Varró,
[Wigner RCP] Budapest. ELI-Attosecond, Szeged, Hungary.

**Varró S, Correlations of wave intensities and particle numbers. Thoughts on the 50th anniversary of Géza Györgyi's death.
[Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] File:"Varro_S_Talk_A_ISMD_2023_GyorgyiG_v_1.ppt"**

Outline.

- Introduction. Motivation. HBT and Györgyi G.
- Sketch on family and school. Some research results of Györgyi G.
- Translations of classic works to Hungarian. History.
- HBT treated by Györgyi G. with discrete calssical probability.

Varró S, Correlations of wave intensities and particle numbers. Thoughts on the 50th anniversary of Géza Györgyi's death.
[Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] File:"Varro_S_Talk_A_ISMD_2023_GyorgyiG_v_1.ppt"

Györgyi G, Fluctuations and correlations of bundles of rays, on the basis of the particle picture. Fizikai Szemle,1962. (12. évf.) 5. sz. 146–152. (in Hungarian).

Györgyi G, Sugárnyalábok ingadozásai és korrelációja a részecske-kép alapján. Fizikai Szemle,1962. (12. évf.) 5. sz. 146–152. [Újra közölve: Fizikai Szemle, 2015. (65. évf.) 7–8. sz. 252–258.]

IRODALOM

1. *A. Ádám, L. Jánossy, P. Varga*, Acta Phys. Hung. *4*, 301 (1955); lásd még: *Jánossy Lajos, Náray Zsolt* Fiz. Szemle, *8*, 3 (1958).
2. *E. Brannen, H. I. S. Fergusson*, Nature, *178*, 481, (1956).
3. *R. Hanbury Brown, R. Q. Twiss*, Nature, *177*, 27 (1956); *R. Q. Twiss, A. G. Little, R. Hanbury Brown*, Nature, *180*, 324 (1957).
4. *L. Jánossy*, Il Nuovo Cimento *6*, 111 (1957); *12*, 369 (1959); *G. Graff, L. Jánossy*, Acta Phys. Hung. *10*, 291 (1959).
5. *E. M. Purcell*, Nature, *178*, 1449 (
6. *Rényi Alfréd*, Valószínűségszámít Bp. 1954.
7. *S. I. Wawilow*, Die Mikrostruktu demie-Verlag, Berlin, 1954.

Photons do not split.

Note added in proof. It would appear to the authors, and also to Prof. Jánossy (private communication), that if such a correlation did exist, it would call for a major revision of some fundamental concepts in quantum mechanics. This was, of course, the reason why these experiments were performed.

[1] Hanbury Brown, R., and Twiss, R. Q., *Nature*, **177**, 27 (1956).
[2] Ádám, A., Jánossy, L., and Varga, P., *Acta Phys. Hungary*, **4**, No. 4, 301 (1955).
[3] Brannen, E., Hunt, F. R., Adlington, R. H., and Nicholls, R. W., *Nature*, **175**, 810 (1955).

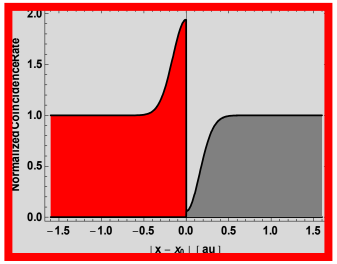
S. V., Correlation in thermal neutron beams. SZFI Seminar. 09. Feb. 2010.
To the memory of Géza Györgyi, on the occasion of the 80ies anniversary of his birthday.

Photon bunching, Fermion antibunching.

FIZIKAI SZEMLE

XII. ÉVFOLYAM

1962. 1. sz. 146-152. oldal



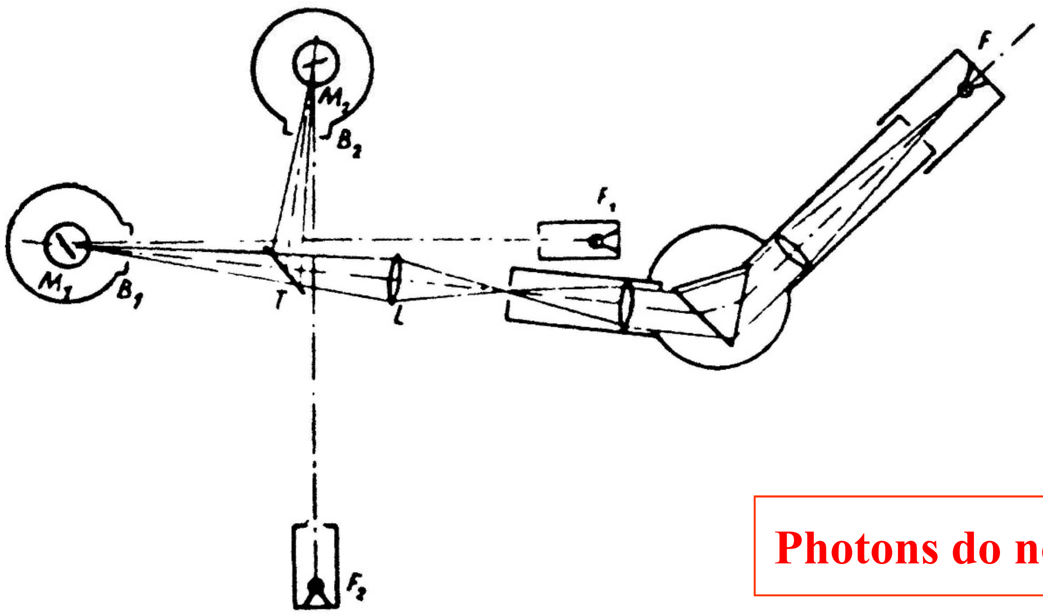
Sugárnyalábok ingadozásai és korrelációja a részecske-kép alapján.
[Fluctuations and correlations of bundles of rays, on the basis of the particle picture.]

$$\overline{(\Delta n)^2} = \bar{n}\left(1 + \bar{n}/z\right) \qquad \overline{(\Delta n)^2} = \bar{n}\left(1 - \bar{n}/z\right)$$

…"The explanation is straightforward. We have seen that the photons 'like' to bunch in an elementary phse spece cell; this led to the hypernormal fluctuations. In case of electrons, just such a bunching is forbidden by the Pauli principle (Fig. 4c). ... This character of their nature explains that their fluctuations stay below the normal value, and, if we performed the coincidence experiment shown in Fig. 1, then, on the basis of assumiing independence, provided the condition (2) is satisfied, we would receive less coincidence as the accidental ones."

Györgyi Géza
Központi Fizikai Kutató Intézet,
Elméleti Fizikai Laboratórium

John F. Clauser, Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect. Phys. Rev. D 9, 853-860 (1974). [Jánossy's 'Photon experiments' (1954-57): **Photons do not split.** They interfere individually with themselves.]



Photons do not split.

FIG. 1. Experimental arrangement of Ádám, Jánossy, and Varga. Light from source F is focused through a monochromator onto photomultipliers M_1 and M_2 via beam splitter T. (Figure after Ádám, Jánossy, and Varga.)

Jánossy L and Náray Zs 1957, The interference phenomena of light at very low intensities. *Acta Phys. Hung*. 7 403-425. Jánossy L and Náray Zs 1958 Investigations into interference phenomena at extremely low light intensities by means of a large Michelson interferometer. *Suppl. Nuovo Cimento* 9 588.

Ádám A, Jánossy L and Varga P 1954 Coincidences of photons, progressing in coherent beams of light (In Hungarian: Koherens fénynyalábokban haladó fotonok koincidencái.) *Magyar Fizikai Folyóirat* 2, 499 (1954).

Ádám A, Jánossy L and Varga P 1955, Beobachtungen mit dem Elektronenvervielfacher an kohärenten Lichtstrahlen. *Annalen der Physik* 16, 408-413 (1955). In Russian: *Acta Phys. Hung* .4, 301-305 (1955)

Hanbury Brown and Twiss [1956]

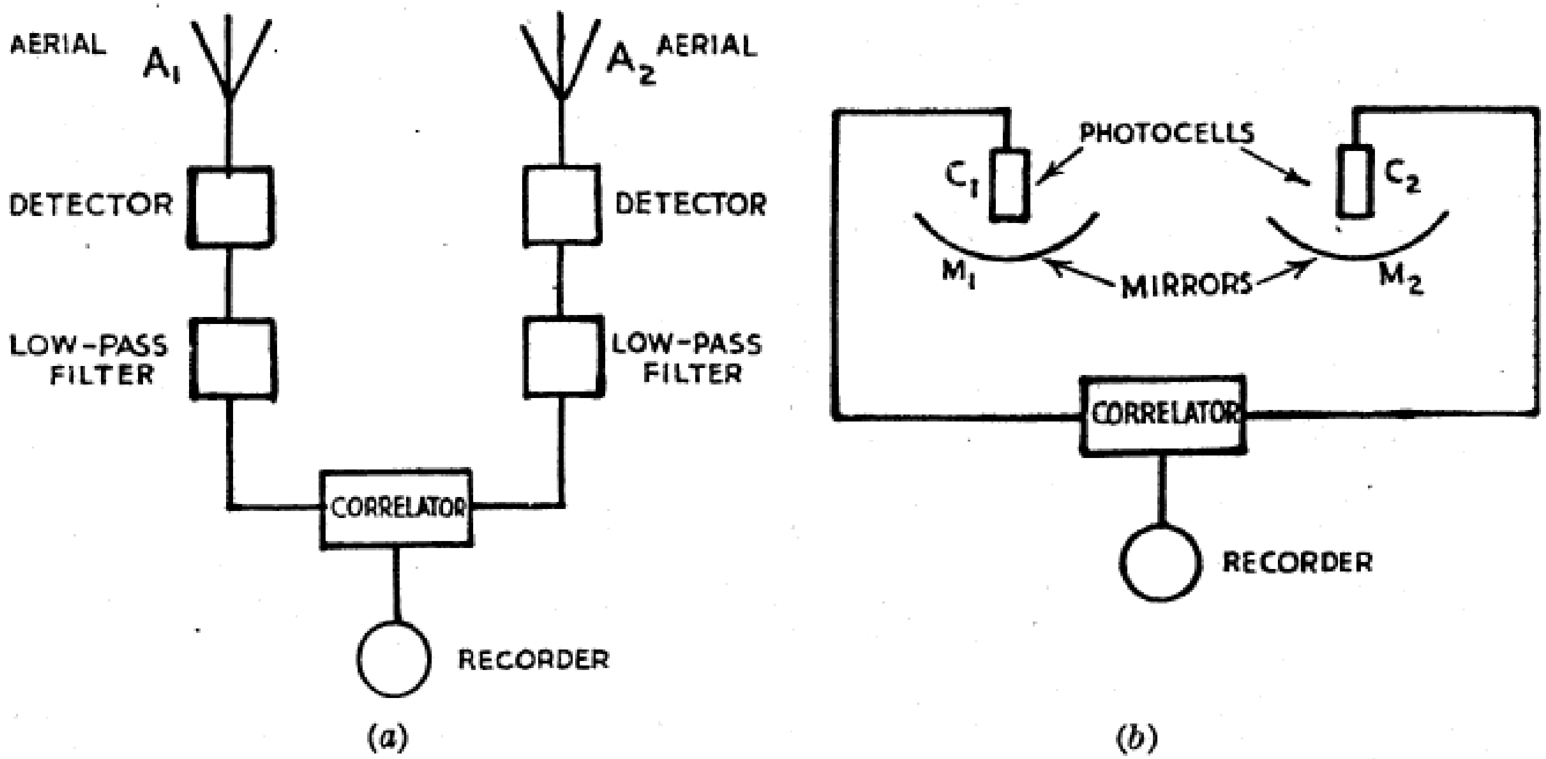


Fig. 1. A new type of radio interferometer (*a*), together with its analogue (*b*) at optical wave-lengths

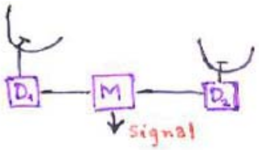
R. Hanbury Brown and R. Q. Twiss, Correlation between photons in two coherent beams of light. Nature Vol. 177., No. 4496. pp. 27-29 (1956).

Two-photon correlations. Photoelectric mixing.

R. GLAUBER: Quantum Optics and Heavy Ion Physics.
(Quark Matter 2005, Budapest, 2005).

R. Hanbury Brown + R.Q. Twiss

Intensity interferometry



$$E(r t) = E^{(+)}(r t) + E^{(-)}(r t)$$

$$E^{(+)}(r t) \sim e^{-i\omega_k t}$$

$$E^{(-)}(r t) \sim \{E^{(+)}(r t)\}^{*}$$

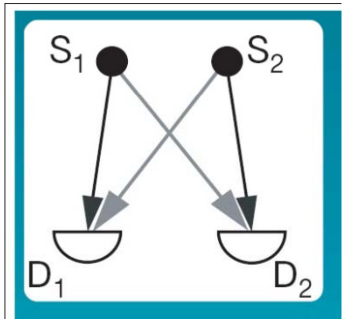
Ordinary (Amplitude) interferometry measures $G^{(1)}(r t\, r' t') \equiv \langle E^{(-)}(r t)\, E^{(+)}(r' t') \rangle_{av.}$

Intensity interferometry measures

$$G^{(2)}(r t\, r' t'\, r' t'\, r t) = \langle E^{(-)}(r t)\, E^{(-)}(r' t')\, E^{(+)}(r' t')\, E^{(+)}(r t) \rangle$$

Two-photon dilemma **?**

UGO FANO: Quantum Theory of Interference Effects in the Mixing of Light from Phase-Independent Sources.
Am. J. Phys. 29, 539-545 (1961)



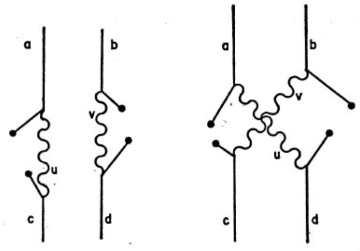


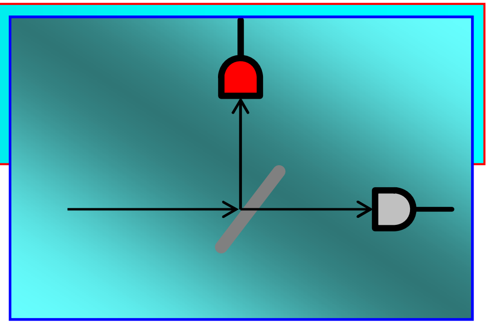
FIG. 1. Lowest-order diagrams representing light emission by a pair of atoms and its absorption by another pair of atoms. The heavy dots indicate ground-state lines.

$$P_c(t) = \left\langle | D_{c,a}(t) + D_{c,b}(t) |^2 \right\rangle$$
$$= \left\langle | D_{c,a}(t) |^2 + | D_{c,b}(t) |^2 \right\rangle$$
$$= P_{c,a}(t) + P_{c,b}(t)$$

$$P_{cd}(t) = \left\langle | D_{c,a}(t) D_{d,b}(t) + D_{d,a}(t) D_{c,b}(t) |^2 \right\rangle$$

S. V., The role of self-coherence in correlations of bosons and fermions in linear counting experiments. Notes on the wave-particle duality; *Fortschritte der Physik – Progr. Phys.*; 59, No. 3–4, 296-324 (2011).

$$\langle I(t)I(t+\tau)\rangle$$



Intensity Correlation ~ Energy Fluctuation

$$\langle I_1(t+\tau)I_2(t)\rangle = G_{12}^{(2)}(\tau) = I_1 I_2 \pm |G_{12}^{(1)}(\tau)|^2$$

Goldberger, Lewis & Watson [1963]: −

$$g^{(2,2)}(0) = \frac{\langle \hat{a}^+\hat{a}^+\hat{a}\hat{a}\rangle}{\langle \hat{a}^+\hat{a}\rangle^2} = 1 + \frac{(\Delta n)^2 - \bar{n}}{(\bar{n})^2} = 1 + \frac{(\Delta E_1)^2 - h\nu \bar{E}_1}{(\bar{E}_1)^2}$$

$$g_{cl}^{(2,2)}(0) = 1 + \frac{(\Delta E_1)^2}{(\bar{E}_1)^2}$$

Jordan & Klein [1927]: +

Jordan & Wigner [1927]: −

Coherent state

$$(\Delta n)^2 = \bar{n}$$

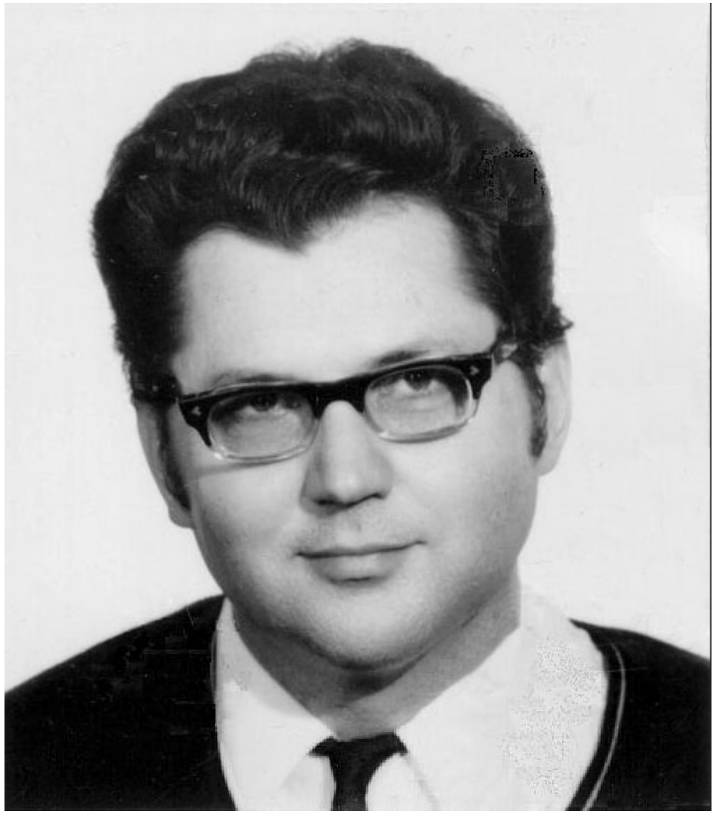
$$g^{(2,2)}(0) = 1 = g_{cl}^{(2,2)}(0)$$

Thermal state

$$(\Delta n)^2 = (\bar{n})^2 + \bar{n}$$

$$g^{(2,2)}(0) = 2 = g_{cl}^{(2,2)}(0)$$

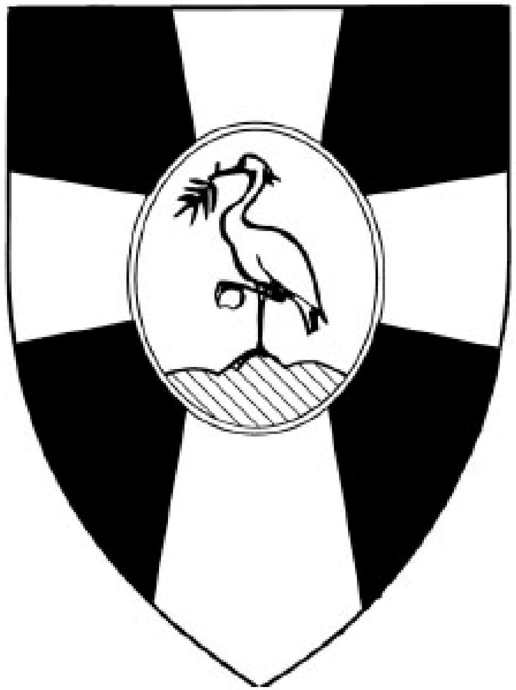
An oustanding and exceptional theoretical physicist.



GYÖRGYI Géza
[1930 okt 8 – 1973 aug 24]

Györgyi Géza érett kutató korában.
Számítógépes grafika, fénykép alapján.

Right Figure is a computer graphics based on the left photo of Györgyi G., copied from the book: KOVÁCS László, GYÖRGYI GÉZA. Egy kivételes elméleti fizikusi életpálya 1930 – 1973. (Magyar Tudománytörténeti és Egészségtudományi Intézet, Budapest 2016) An exceptional life of a theoretical physicist.

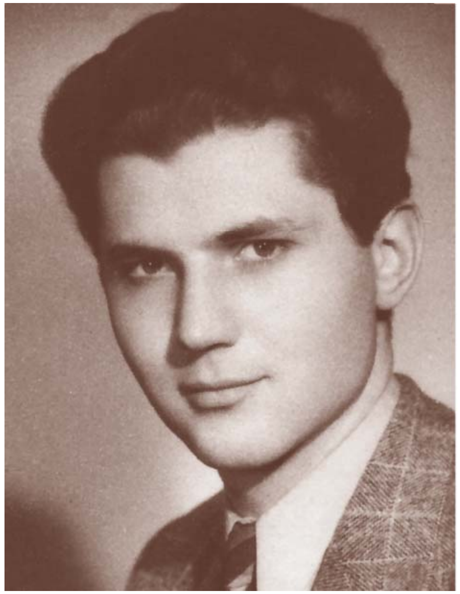


A gimnázium címere

A ciszterci rend címere

Györgyi Géza az iskola kapujában

Cisterci Rend Gimnáziuma. Györgyi G. At the gate of the gymnasium. Pictures copied from the book: KOVÁCS László, GYÖRGYI GÉZA. Egy kivételes elméleti fizikusi életpálya 1930 – 1973. (Magyar Tudománytörténeti és Egészségtudományi Intézet, Budapest 2016) An exceptional life of a theoretical physicist.



GYÖRGYI Géza
[1930 okt 8 – 1973 aug 24]

ZIMÁNYI (Györgyi) Magdolna
[1934 nov 29 – 2016 márc 27]

ZIMÁNYI József
[1931 dec 5 – 2006 szept 26]

Outstanding intellectual surroundings both in the family and at the university.

„A Györgyi-Giergl család három évszázada" – elnevezésű kiállítás egyik kurátora. (Zimányi Magdolna Dr. Györgyi Géza röntgenorvos és Zámor Magda lánya, Györgyi Kálmán iparművész unokája.)

DIE BEWEGUNG DES ENERGIEMITTELPUNKTES UND DER ENERGIE-IMPULS-TENSOR DES ELEKTRO-MAGNETISCHEN FELDES IN DIELEKTRIKA

Von

G. GYÖRGYI

ZENTRALFORSCHUNGSINSTITUT FÜR PHYSIK, BUDAPEST

(Vorgelegt von K. F. Novobátzky. — Eingegangen: 18. II. 1954.)

Es werden die Bewegungsgesetze des Massenmittelpunktes der elektromagnetischen Energie und des mit dem elektromagnetischen Feld in Wechselwirkung stehenden Dielektrikums untersucht. Es ergibt sich, dass der Abrahamsche Energie-Impuls-Tensor mit den üblichen Begriffen der Mechanik und mit dem Satz von der gleichförmigen Bewegung des Massenmittelpunktes eines geschlossenen Systems in Einklang steht.

Györgyi G, The motion of the centre of energy and the energy-momentum tensor of the electromagnetic field in dielectrics. Act. Phys. Hung. 4, 133-143 (1954). Discussion of the „Abraham – Minkowski problem".

IL NUOVO CIMENTO Vol. LIII A, N. 3 1° Febbraio 1968

Kepler's Equation, Fock Variables, Bacry's Generators and Dirac Brackets (*).

G. GYÖRGYI (**)

International Atomic Energy Agency
International Centre for Theoretical Physics - Trieste

(ricevuto il 7 Luglio 1967)

Summary. — A formulation of the Kepler problem, manifestly invariant with respect to the SO_4 and $SO_{3,1}$ groups, respectively, is given in terms of the Fock variables and their canonical conjugates; one is led to introduce a new time parameter, proportional to the eccentric anomaly. A transformation of the dynamical variables performed in order to get back the standard time t leads in a natural way to Bacry's generators. A manifestly $SO_{4,2}$ symmetric formulation of the problem is given. The concept of the Dirac bracket is used to establish a connection with the usual three-dimensional description.

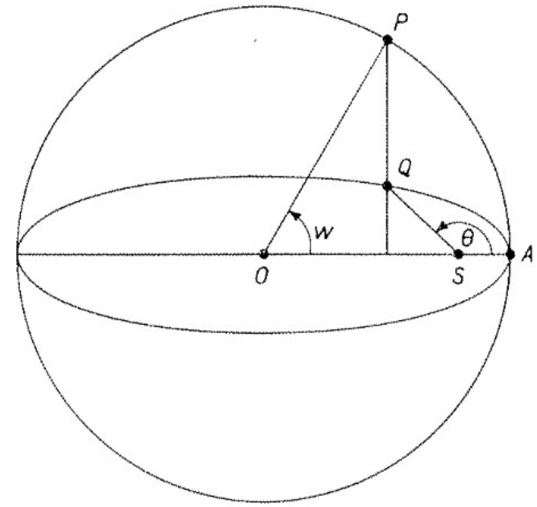
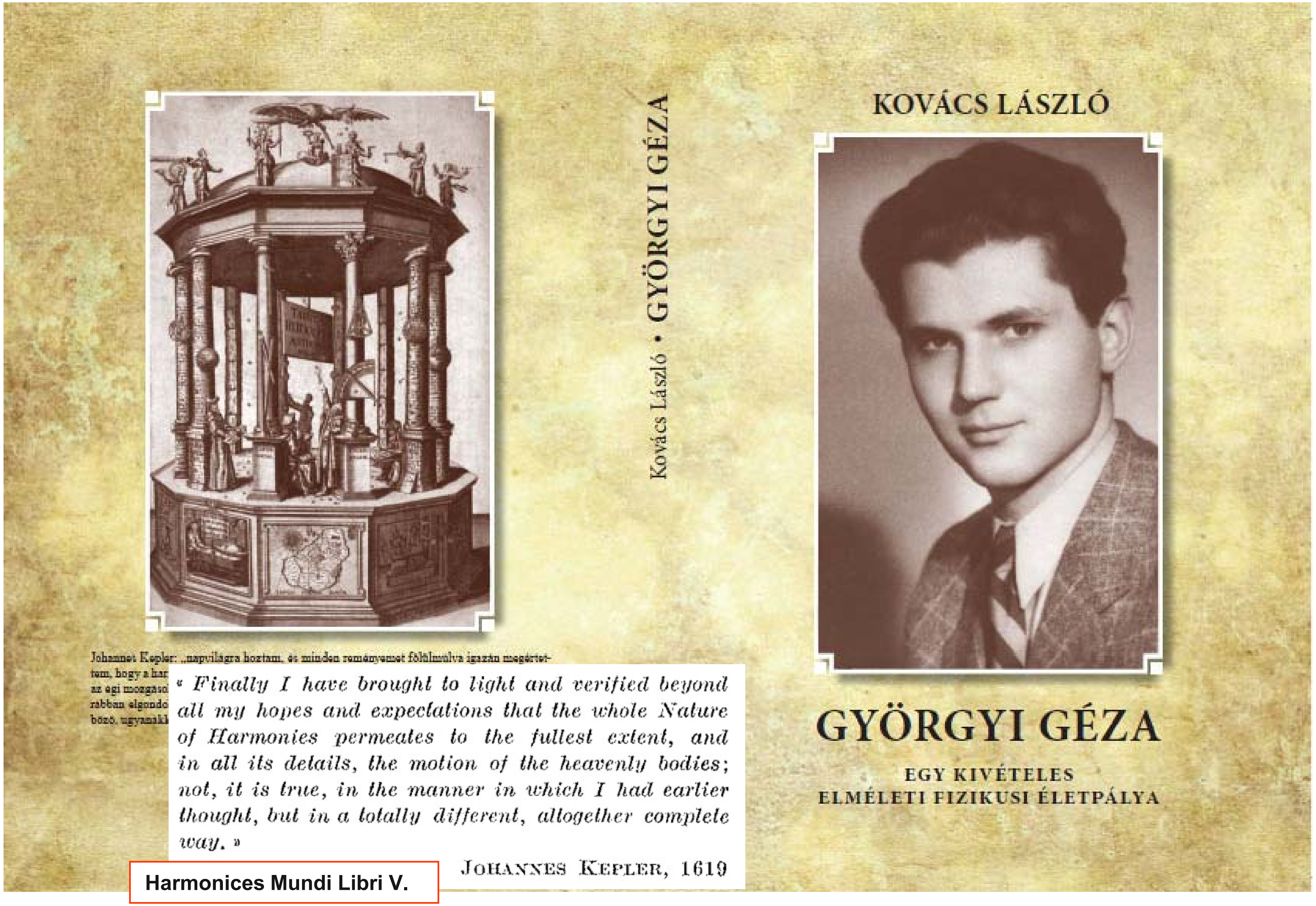


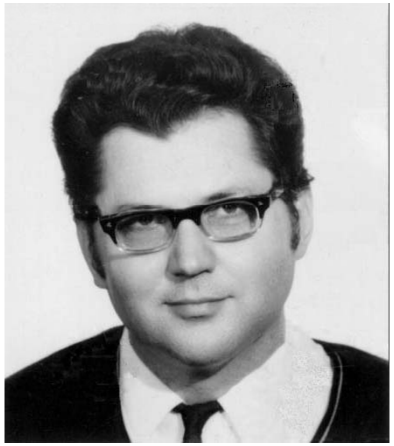
Fig. 1.

Györgyi G, Kepler's equation, Fock variables, Bacry's generators and Dirac brackets. Il Nuovo Cim. 53, 717-736 (1968). Group considerations;SO(4), SO(3,1)...



The cover of the book: KOVÁCS László, GYÖRGYI GÉZA. Egy kivételes elméleti fizikusi életpálya 1930 – 1973. **(Magyar Tudománytörténeti és Egészségtudományi Intézet, Budapest 2016) „An exceptional life of a theoretical physicist". Back cover: Johannes Kepler, Tabula Rudolphiane 1627 . Quote Kepler.**

Györgyi Géza Díj. [Györgyi G. Prize.]



A Györgyi Géza Díjat a KFKI Részecske- és Magfizikai Kutatóintézet, a Wigner Fizikai Kutatóközpont jogelődje alapította.
1996-ban osztották ki először.

[Note. The first prize winner. 1996. CSÖRGŐ Tamás.
Bevezette az LCMS koordináta rendszert, amely a Bose-Einstein korrelációs kísérleti és elméleti kutatások standard eszközévé vált a nagyenergiás nehézion fizikában.]

A. AHIJEZER, V. BERESZTYECKIJ

KVANTUM ELEKTRO DINAMIKA

AKADÉMIAI KIADÓ, BUDAPEST

Az eredeti mű adatai

А. И. АХИЕЗЕР, В. Б. БЕРЕСТЕЦКИЙ

КВАНТОВАЯ ЭЛЕКТРОДИНАМИКА

Издание второе переработанное

Государственное издательство физико-математической литературы, Москва 1959

Oroszból fordította

GYÖRGYI GÉZA

és

NAGY KÁROLY

Lektorálta

MARX GYÖRGY

Szerkesztette

NAGY KÁROLY

A védőborítót és kötéstervet készítette

HÚTH ISTVÁN

PRINTED IN HUNGARY

Akhiezer and Berestetzky, Quantum Electrodynamics. Hungarian translation by G. Györgyi and K. Nagy.

Hungarian translations by Györgyi G. of Wigner 's works [ ]. 1931 – 1959 – 1979.

E. P. Wigner, *Gruppentheorie und ihre Anwendungen auf die Quantenmechanik der Atomspektren*. (Friedrich Vieweg und Sohn, Braunschweig, 1931)

E. P. Wigner, *Group Theory and its Application to the Quantum Mechanics of Atomic Spectra*. (Academic Press, New York and London, 1959)

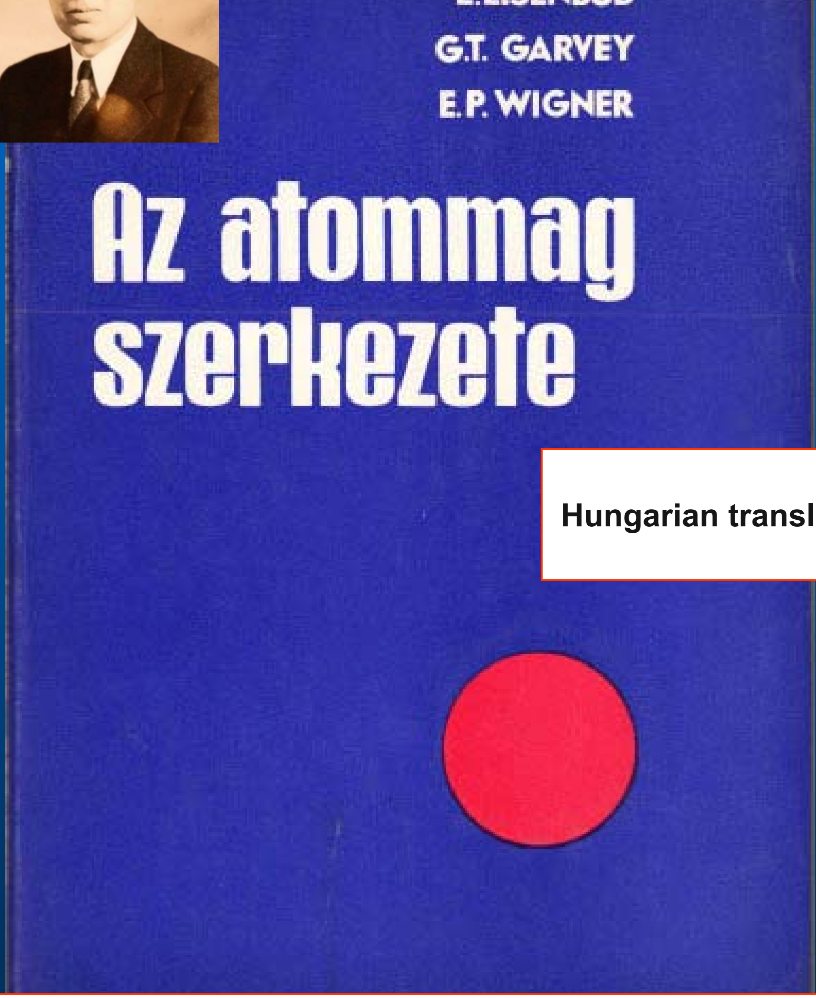
Wigner Jenő, *Csoportelméleti Módszer a Kvantummechanikában*. Fordította Györgyi Géza és Sebestyén Ákos (Akadémia Kiadó, Budapest, 1979)

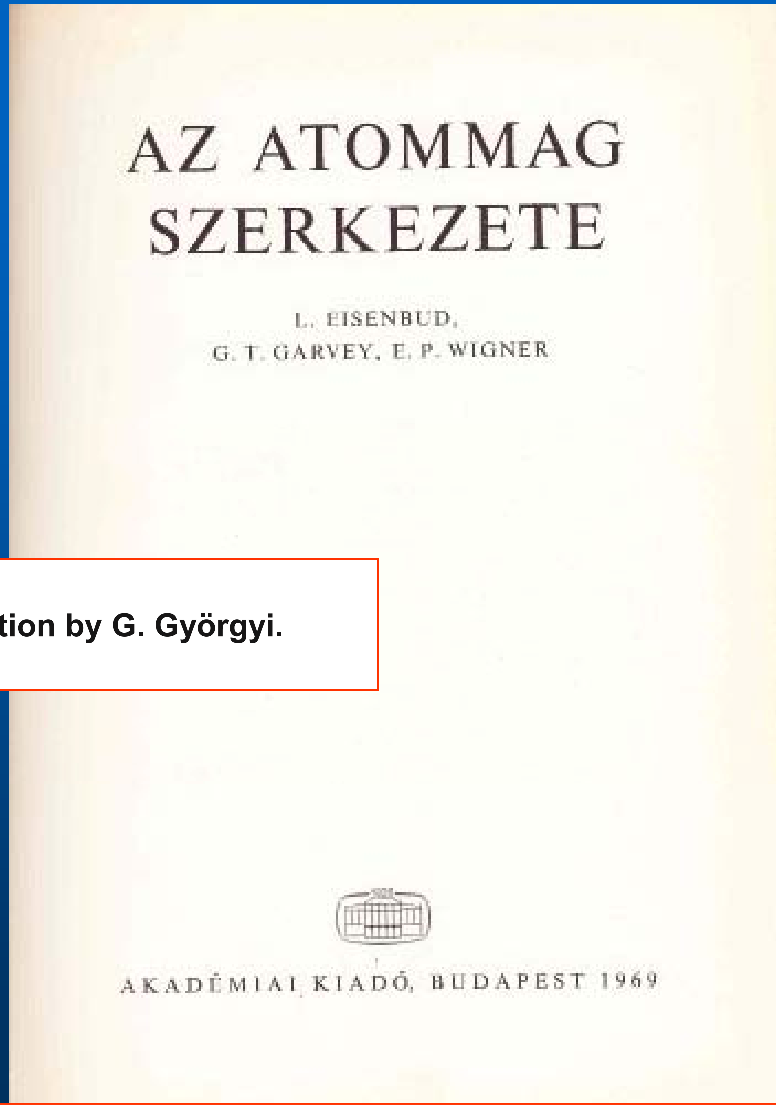
E. P. Wigner, *Symmetries and Reflections*. Scientific Essays of Eugene P. Wigner. (Indiana University Press, Bloomington London, 1967)

Wigner Jenő, *Szimmetriák és Reflexiók. Tudományos Esszék*. Fordította Györgyi Géza (Gondolat Kiadó, Budapest, 1972)

L. Eisenbud, G. T. Garvey and E. P. Wigner, *General Principles of Nuclear Structure*, in HANDBOOK OF PHYSICS, Eds. E. U. Condon and H. Odishaw, second edition (Mc Graw-Hill Book Co., New York, 1967)

L. Eisenbud, G. T. Garvey and E. P. Wigner, *Az Atommag Szerkezete*. Fordította Györgyi Géza (Akadémia Kiadó, Budapest, 1969)





AZ ATOMMAG SZERKEZETE

L. EISENBUD,
G. T. GARVEY, E. P. WIGNER

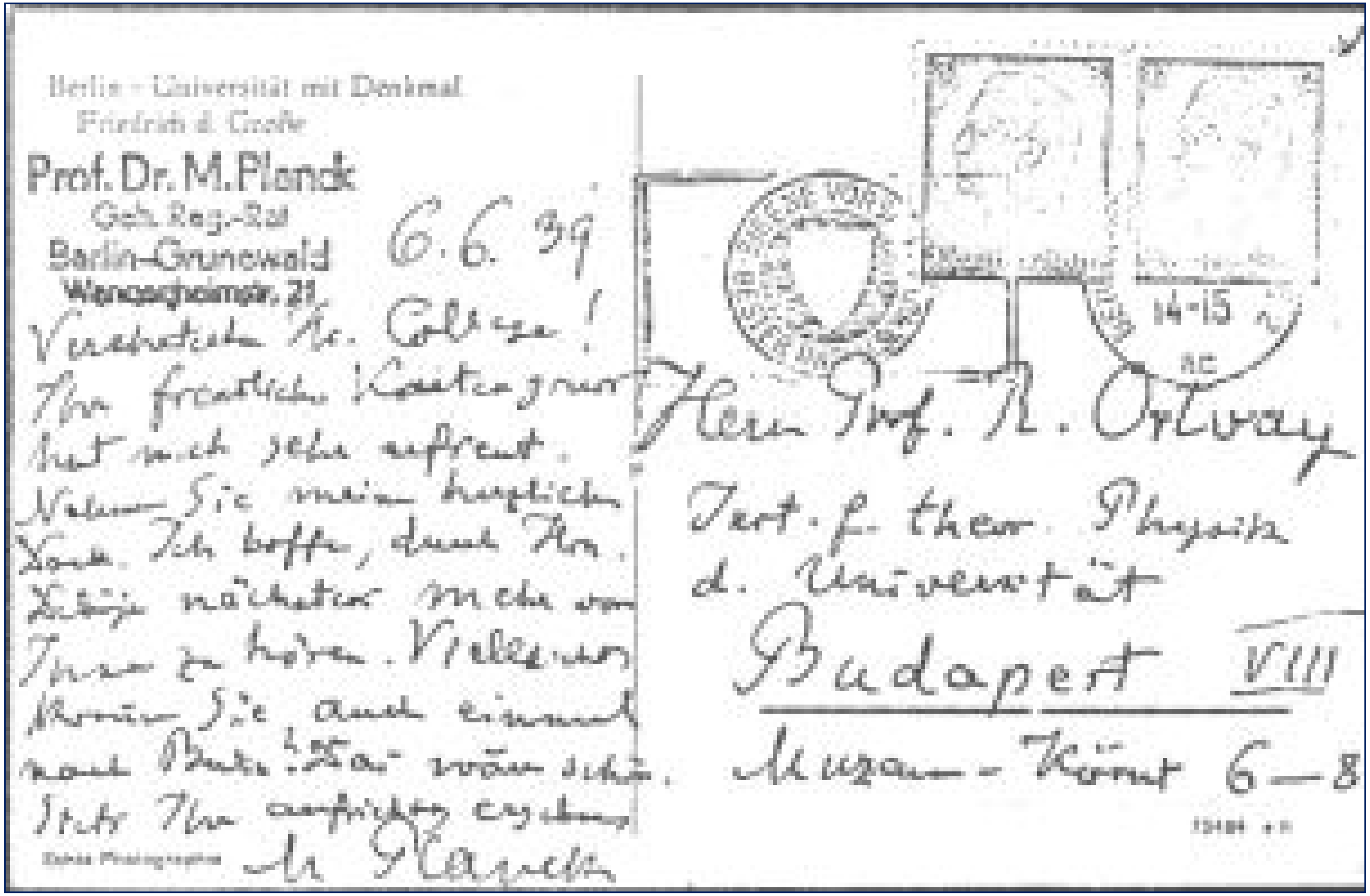
AKADÉMIAI KIADÓ, BUDAPEST 1969

Hungarian translation by G. Györgyi.

Note: The very first book on theoretical nuclear physics in Hungary:

Györgyi G, Elméleti magfizika. (Műszaki Kiadó, Budapest, 1961).

G. Györgyi's activity in history of science. Correspondence of R. ORTVAY with Sommerfeld, Neumann, Teller, Tisza, Wigner.... E.g.:Planck in Hungary [1939].


Berlin – Universität mit Denkmal
Friedrich d. Große

Prof. Dr. M. Planck
Geh. Reg.-Rat
Berlin-Grunewald
Wangenheimstr. 21

6. 6. 39

Verehrter Hr. Collega!
Ihr freundlicher Kartengruss
hat mich sehr erfreut.
Nehmen Sie meinen herzlichen
Dank. Ich hoffe, durch Ihre
Schüler nächstens mehr von
Ihnen zu hören. Vielleicht
kommen Sie auch einmal
nach Berlin. Das wäre schön.
Stets Ihr aufrichtig ergebener
M. Planck

Herrn Prof. R. Ortvay
Inst. f. theor. Physik
d. Universität
Budapest VIII
Muzeum-Körut 6–8

Planck's postcard to his host, Rudolf Ortvay.
copied from: Györgyi G, Max Planck Magyarországon. Fizikai Szemle 1972/10. 307.o..

Györgyi search for Ortvay's correspondenceEötvös Loránd Mathematikai és Physikai Társulat. A modern fizika érkezése". Ortvay Rudolf. Kollokviumok.

Ortvay Rudolf "A de Broglie és Schrödinger-féle hullámmechanika" (1927). "A vegyérték problémája a quantummechanikában" (1928)

Arnold Sommerfeld *"A fémek elektronelméletéről és az elektron természetéről"*(1930)

Tisza László „A rádióaktív bomlás kvantummechanikai tárgyalása"

Neumann János „Dirac-egyenlet és elektronspin"

Ortvay „A Heisenberg-féle reláció"

Schay Géza „A kétféle hidrogén"

Neumann János „A Dirac-féle fényelmélet"

Bródy Imre „Fémek elektron-elmélete"

Lánczos Kornél „Stark-effektus erős mágneses térben"

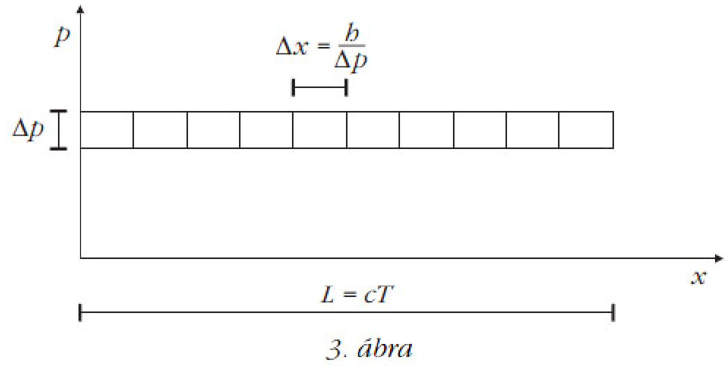
Neugebauer Tibor „Perturbációelmélet Schrödinger szerint"

Teller Ede „Kétatomos molekulák felépítése"

Wigner Jenő „A kémiai kötés kvantumelmélete.

Photo copied from: Füstöss László, A modern fizika érkezése (1919-1945). Fizikai Szemle 1991/11. 381.o. „The arrival of modern physics."

Györgyi G, Fluctuations and correlations of bundles of rays, on the basis of the particle picture. Fizikai Szemle,1962. (12. évf.) 5. sz. 146–152. (in Hungarian).

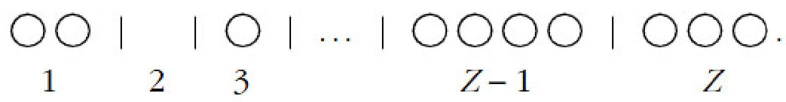


3. ábra

$$Z = 2L\Delta\nu / c$$

Planck-Bose.

$$\frac{\binom{N+Z-n-2}{N-n}}{\binom{N+Z-1}{N}} \to \frac{1}{1+\bar{n}}\left(\frac{\bar{n}}{1+\bar{n}}\right)^n = p_n$$



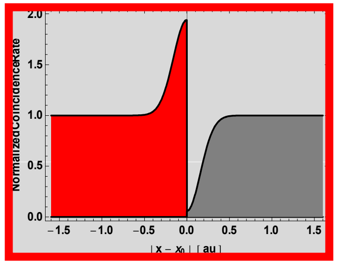
Convolution → Negative Binomial:

$$\overline{(\Delta n_1)^2} = \bar{n}_1[1+\bar{n}_1(\tau_c / 2t)]$$

$$q_n(z) = \binom{n+z-1}{z-1}\left(\frac{1}{1+\bar{n}}\right)^z\left(\frac{\bar{n}}{1+\bar{n}}\right)^n$$

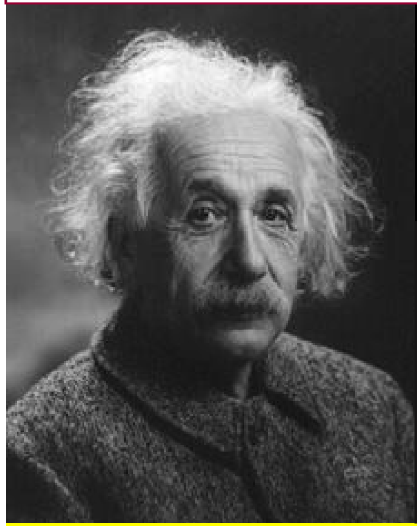
The expectation value of the number of coincidences during T:

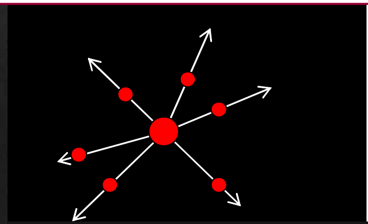
$$k = \frac{T}{2\tau_D}\left(\bar{n}_1\bar{n}_2 + \overline{\Delta n_1 \Delta n_2}\right) = \frac{T}{2\tau_D}\bar{n}_1\bar{n}_2\left(1+\frac{\tau_c}{\tau_D}\right)$$



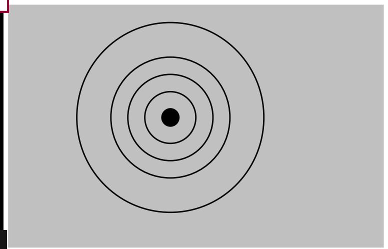
6. Über einen
die Erzeugung und Verwandlung des Lichtes
betreffenden heuristischen Gesichtspunkt;
von A. Einstein.

What would PLANCK and EINSTEIN say on the logo of the 'International Year of Light 2015?

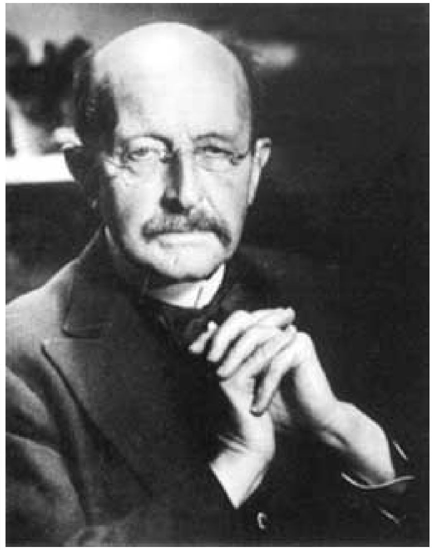




What



International
Year of Light
2015



"...by spreading from a point in the outgoing light rays the energy is not distributed continuously to larger and larger spatial regions, but these rays consist of a finite number of energy quanta localized in spatial points ..." [Einstein A, On a heuristic viewpoint concerning the production and transformation of light. *Annalen der Physik* (4) **17**, 132-148 (1905)]

„The wavefront is not spotty." ["Die Wellenfront ist nicht fleckig."] [Planck M, Das Wesen des Lichts. *Natur-wissenschaften* **7**, 903-909 (1919)]

Györgyi Géza

1930 - 1973

Acknowledgements.

Long ago the late prof. Gy. Farkas (coworker of L. Jánossy) drew my attention to Györgyi's 'HBT-paper' (1962). I thank the late prof. H. Rauch for many discussions on the neutron antibunching experiment.
I thank T. Csörgő and S. Hegyi for the idea and encouragement for giving the present talk. I also thank them for supplying me with some illustration materials (e.g. the electronic copy of the book by L. Kovács on G. Györgyi).

Varró S, Correlations of wave intensities and particle numbers. Thoughts on the 50th anniversary of Géza Györgyi's death. [Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] File:"Varro_S_Talk_A_ISMD_2023_GyorgyiG_v_1.ppt"

Barátok, kollégák, iskolatársak, tisztelők (Kármán Tamás felvétele)

Pictures copied from the book:
KOVÁCS László, GYÖRGYI GÉZA. Egy kivételes elméleti fizikusi életpálya 1930 – 1973. **(Magyar Tudománytörténeti és Egészségtudományi Intézet, Budapest 2016) An exceptional life of a theoretical physicist.**

Appendix.

Varró S, Correlations of wave intensities and particle numbers. Thoughts on the 50th anniversary of Géza Györgyi's death. [Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] File:"Varro_S_Talk_A_ISMD_2023_GyorgyiG_v_1.ppt"

‚HBT Renaissance.’

‘Hanbury Brown – Twiss Anticorrelations’ for free electrons(2002).

Observation of Hanbury Brown–Twiss anticorrelations for free electrons

Harald Kiesel, Andreas Renz & Franz Hasselbach

Institut für Angewandte Physik der Universität Tübingen, Auf der Morgenstelle 10, D-72076 Tübingen, Germany

Fluctuations in the counting rate of photons originating from uncorrelated point sources become, within the coherently illuminated area, slightly enhanced compared to a random sequence of classical particles. This phenomenon, known in astronomy as the Hanbury Brown–Twiss effect[1–5], is a consequence of quantum interference between two indistinguishable photons and Bose–Einstein statistics[6]. The latter require that the composite bosonic wavefunction is a symmetric superposition of the two possible paths. For fermions, the corresponding two-particle wavefunction is antisymmetric: this excludes overlapping wave trains, which are forbidden by the Pauli exclusion principle. Here we use an electron field emitter to coherently illuminate two detectors, and find anticorrelations in the arrival times of the free electrons. The particle beam has low degeneracy (about 10^{-4} electrons per cell in phase space); as such, our experiment represents the fermionic twin of the Hanbury Brown–Twiss effect for photons.

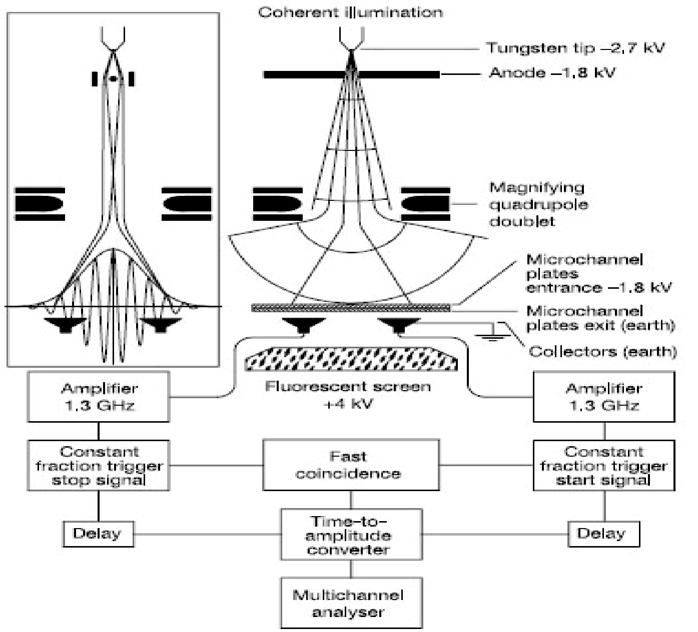


Figure 1 Electron optical set-up (top) and fast coincidence electronics (bottom) to measure electron anticorrelations. The quadrupoles produce an elliptically shaped beam of coherent electrons (schematically shown in the pictograms of Fig. 3). For geometrical reasons, fewer coherent electrons miss the collectors than for isotropic magnification. This greatly reduces the measuring time T_M. The parts of the spherical cones emerging from the cathode represent single coherence volumina. Between the electron source and the quadrupole a biprism (inset) is inserted temporarily to check the coherence of illumination of the collectors. The very short electron avalanches (rise time and width of about 0.5 ns) leaving the channel plates are transferred coaxially from the collectors via microwave amplifiers (bandwidth 1.3 GHz) to modified constant fraction trigger modules that extract timing signals with low variance of transit time resulting in a very good time resolution. A fast coincidence circuit preselects events within a time window of ±3 ns and opens the gate of a time-to-amplitude converter. The time spectra with a resolution of 26 ps are accumulated by a multichannel analyser. Capacitive crosstalk between the collectors was well below 1% and did not cause spurious coincidences.

Intensity interferometry with x-rays from undulator.

INTENSITY INTERFEROMETRY FOR THE STUDY OF . . . PHYSICAL REVIEW A **69**, 023813 (2004)

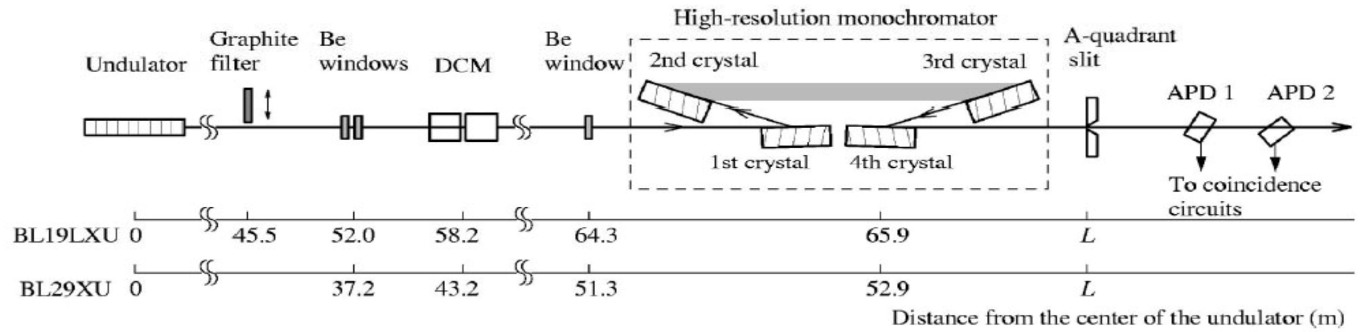


FIG. 1. Top view of the experimental setup. Undulator radiation ($\Delta E/E \gtrsim 10^{-3}$) is monochromatized with the double-crystal monochromator (DCM) using cryogenically cooled Si (111) [40] in $\Delta E/E \sim 10^{-4}$, and with the high-resolution monochromator (HRM) in $\Delta E/E \sim 10^{-8}$. The slit placed after the HRM adjusts beam size to the two avalanche photodiodes (APDs). The distances from the center of the undulator to the components for two beam lines are indicated below the figure, while those to the slit (L) appear in the text.

Yabashi, M.; Tamasaku, K.; Ishikawa, T.: Measurement of x-ray pulse widths by intensity interferometry. *Phys. Rev. A* **2004**, *69*, 023813. Ikonen, E.; Yabashi, M.; Ishikawa, T.: Excess coincidence of reflected and refracted x-rays from a synchrotron-radiation beamline. *Phys. Rev. A* **2006**, *74*, 013816.

The mathematical structure of the joint count probabilities. [Illustration for thermal beams.]

$$P_{AB} = \frac{\eta_A \eta_B}{(\hbar\omega)^2} \int\iiint F_S(\boldsymbol{x}_1) F_T(t_1) F_S(\boldsymbol{x}_2) F_T(t_2) \Gamma_{12}^{(2)}(\boldsymbol{x}_1, t_1; \boldsymbol{x}_2, t_2) d\boldsymbol{x}_1 dt_1 d\boldsymbol{x}_2 dt_2$$

$$P_{AB} = P_A P_B \left[1 \pm \frac{1}{M_x M_y M_t} \right] = \overline{\xi \cdot \eta} = \overline{\xi} \cdot \overline{\eta} \left[1 \pm \frac{1}{M_x M_y M_t} \right]$$

Number of longitudinal and transverse modes

$$M = \left[\frac{1}{x} - \frac{1}{2} \left(\frac{1}{x} \right)^2 (1 - e^{-2x}) \right]^{-1}$$

$$M_x = \left\{ \frac{\pi^{1/2} \sigma_x}{w_x} erf\left(\frac{w_x}{\sigma_x} \right) - \frac{\sigma_x^2}{w_x^2} \left[1 - \exp\left(-\frac{w_x^2}{\sigma_x^2} \right) \right] \right\}^{-1}$$

Varró S; The role of self-coherence in correlations of bosons and fermions in linear counting experiments. Notes on the wave-particle duality; *Fortschritte der Physik – Progr. Phys.*; 59, No. 3–4, 296-324 (2011).

Boson correlations [He^4].
Fermion correlations [He^3].

$$\frac{\overline{\xi \cdot \eta}}{\overline{\xi} \cdot \overline{\eta}} = 1 \pm \frac{1}{M} = 1 \pm \frac{1}{M_x M_y M_{l\ or\ t}}$$

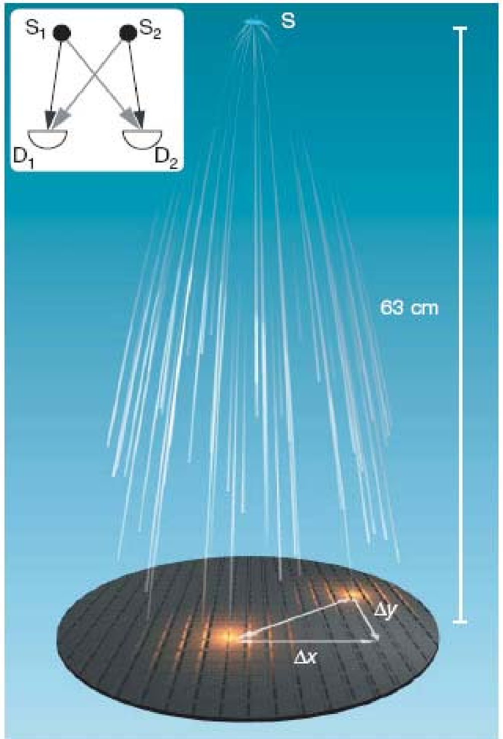


Figure 1 | The experimental set-up. A cold cloud of metastable helium atoms is released at the switch-off of a magnetic trap. The cloud expands and falls under the effect of gravity onto a time-resolved and position-sensitive detector (microchannel plate and delay-line anode) that detects single atoms. The horizontal components of the pair separation Δr are denoted Δx and Δy. The inset shows conceptually the two 2-particle amplitudes (in black or grey) that interfere to give bunching or antibunching: S_1 and S_2 refer to the initial positions of two identical atoms jointly detected at D_1 and D_2.

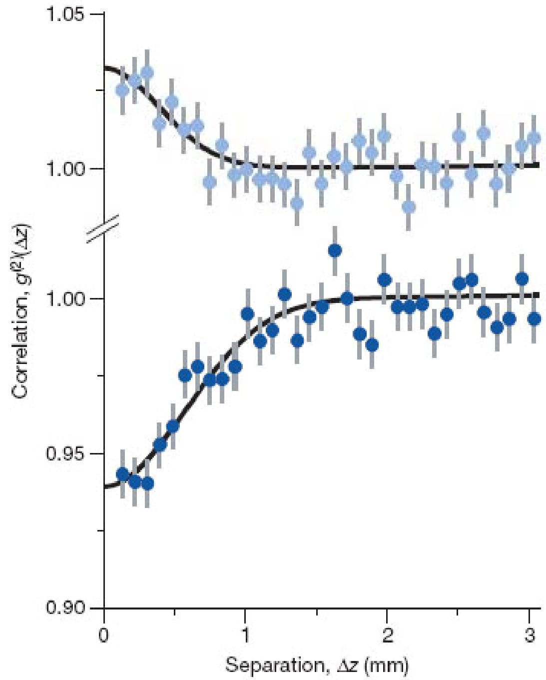


Figure 2 | Normalized correlation functions for $^4He^*$ (bosons) in the upper plot, and $^3He^*$ (fermions) in the lower plot. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters. Error bars correspond to the square root of the number of pairs in each bin. The line is a fit to a gaussian function. The bosons show a bunching effect, and the fermions show antibunching. The correlation length for $^3He^*$ is expected to be 33% larger than that for $^4He^*$ owing to the smaller mass. We find 1/e values for the correlation lengths of 0.75 ± 0.07 mm and 0.56 ± 0.08 mm for fermions and bosons, respectively.

Jeltes, T.; McNamara, J. M.; Hogervorst, W.; Vassen, W.; Krachmalnikoff, V.; Schellekens, M.; Perrin, A.; Chang, H.; Boiron, D.; Aspect, A.; Westbrook, C. I.: Comparison of the Hanbury Brown – Twiss effect for bosons and fermions, *Nature* 2007, *445*, 402-405.

Neutron anti-bunching.

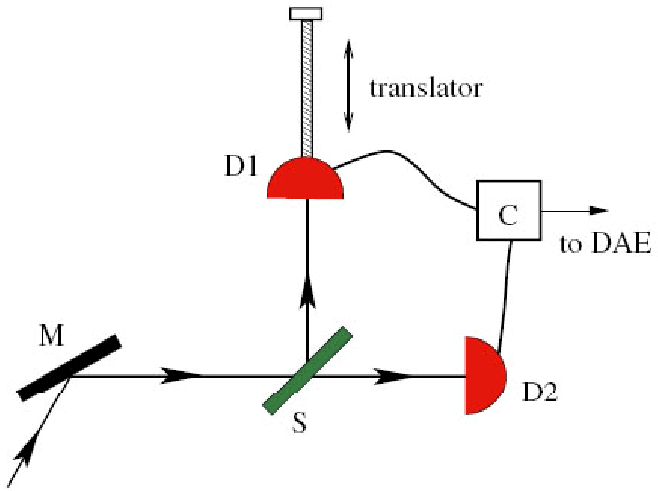
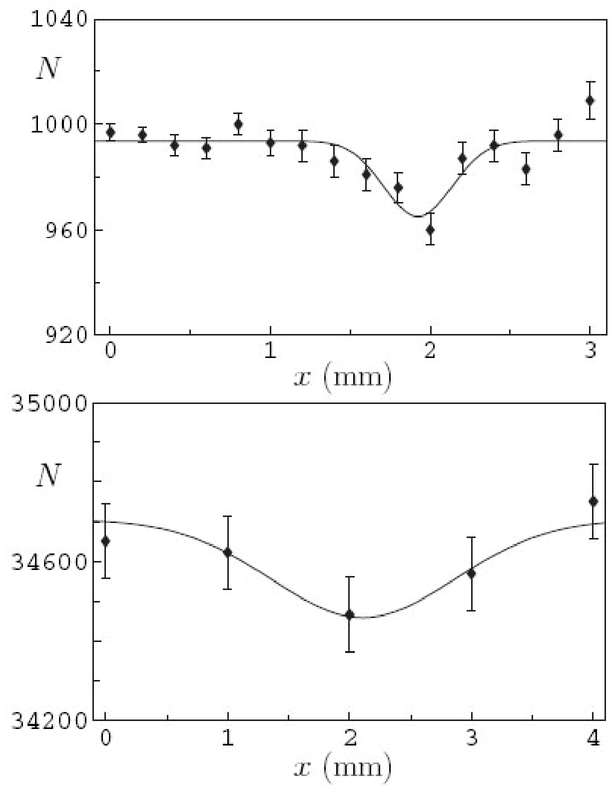


FIG. 1 (color online). Schematic drawing of the experimental setup: M, monochromator; S, beam splitter; D1 and D2, detectors; C, coincidence counter; DAE, Data Acquisition Electronics. The two detectors can be positioned at the same distance from S, and one of them can be moved across this distance. The collimators are not shown.



M. Iannuzzi, A. Orecchini, F. Sacchetti, P. Facchi and S. Pascazio: Direct experimental observation of free-fermion antibunching. ***Phys. Rev. Lett*****. 96, 080402 (2006). See also:** Varró S; The role of self-coherence in correlations of bosons and fermions in linear counting experiments. Notes on the wave-particle duality; *Fortschritte der Physik – Progr. Phys.*; **59**, No. 3–4, 296-324 (2011).

For the most intense neutron beams (ILL) the degeneracy parameter is extremely small; $\delta \sim 10^{-14}$

" Dear Professor Varró,

....

The neutron intensity is indeed rather low. When we consider the phase space density (degeneracy parameter) it is 10E-14 and that means that there is on the average always only one neutron in the apparatus, the next one is still in the Uranium nucleus of the reactor fuel.

Best regards,
Helmut Rauch "

"All the performed experiments belong to the regime of self-interference because the phase-space density of any neutron beam is extremely low (10^{-14}) and nearly every case when a neutron passes through the interferometer the next neutron is still in a uranium nucleus of the reactor fuel."

[H. Rauch, J. Sumhammer, M. Zawisky and E. Jericha: Low-contrast and low-counting-rate measurements in neutron interferometry.

***Phys. Rev. A* 42, 3726-3732 (1990)]**

NOTE: Fluctuations of boson and fermion fields. [The neutrino theory of light. By P. Jordan (1935).]

Pascual Jordan [1902-1980]

Zum Mehrkörperproblem der Quantentheorie.

Von **P. Jordan** [1] und **O. Klein** in Kopenhagen.

(Eingegangen am 4. Oktober 1927.)

Über das Paulische Äquivalenzverbot.

Von **P. Jordan** und **E. Wigner** in Göttingen.

(Eingegangen am 26. Januar 1928.)

$$\overline{\Delta^2} = const \times \overline{N} \cdot \overline{(1 \pm N)}$$

... kularer Gasatome und für die Gültigkeit des Paulischen Äquivalenzverbots verantwortlich sind. Die Einzelheiten der Theorie besitzen enge Analogien zu der entsprechenden Theorie für ...

M. Born, W. Heisenberg und P. Jordan, **Zur Quantenmechanik II**. *Zeitschrift für Physik* **35**, 557 (1926) . **"Dreimännerarbeit"**

P.Jordan und O. Klein, **Zum Mehrkörperproblem in der Quantentheory**. *Zeitschrift für Physik* **45**, 75 (1927).

P.Jordan und E. Wigner, **Über das Paulische Aequivalenzverbot**. *Zeitschrift für Physik* **47**, 631(1928).

P. Jordan und W. Pauli, **Zur Quantenelekrodynamik ladungfreier Felder**. *Zeitschrift für Physik* **47**, 151 (1928).

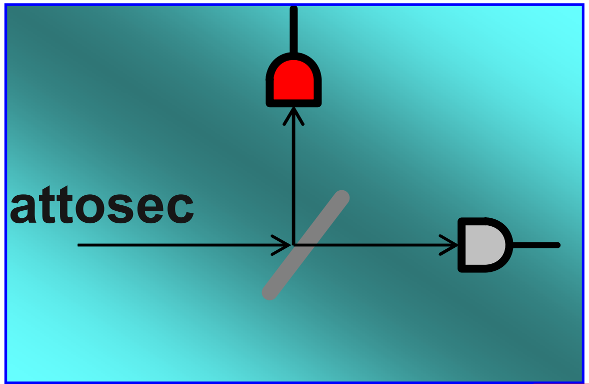
P. Jordan, J. Neumann and E. Wigner, On an algebraic generalization of the quantummechanical formalism. *Ann. Math.* **35**, 29-64 (1934)

P. Jordan, **Die Neutrinotheorie des Lichts**. *Zeitschrift für Physik* **93**, 464 (1935).

P. Jordan, **Beiträge zur Neutrinotheorie des Lichts.** *Zeitschrift für Physik* **114,** 229 (1937).

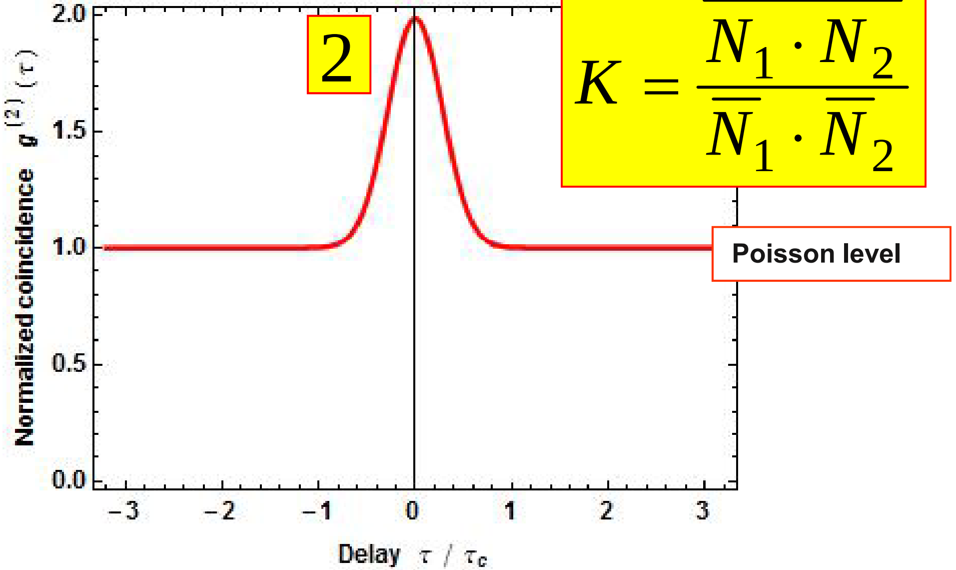
B. Schroer, Pascual Jordan's legacy and the ongoing research in quantum field theory. *Europian Physical Journal H* **35,** 377 (2011).

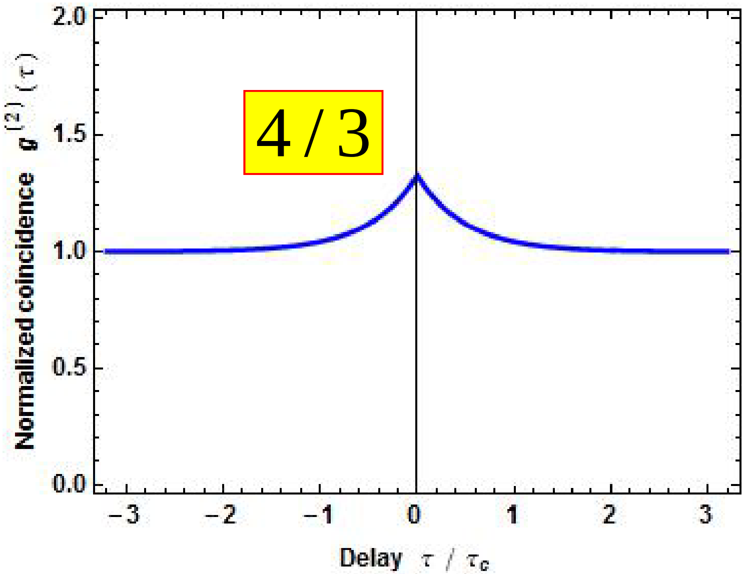
Hanbury Brown – Twiss correlation with an attosec pulse?



The left figure below is shown just for comparison (thermal states; usual 'photon bunching'). The right figure refers to a multimode phase eigenstate (as a quantum model of an attosecond pulse). [The width of the curve is expected to be of order of fs.]

$$K = \frac{\overline{N_1 \cdot N_2}}{\overline{N_1} \cdot \overline{N_2}}$$





Varró S, The role of self-coherence in correlations of bosons and fermions in linear counting experiments. Notes on the wave-particle duality; *Fortschritte der Physik – Progr. Phys.*; 59, No. 3–4, 296-324 (2011).