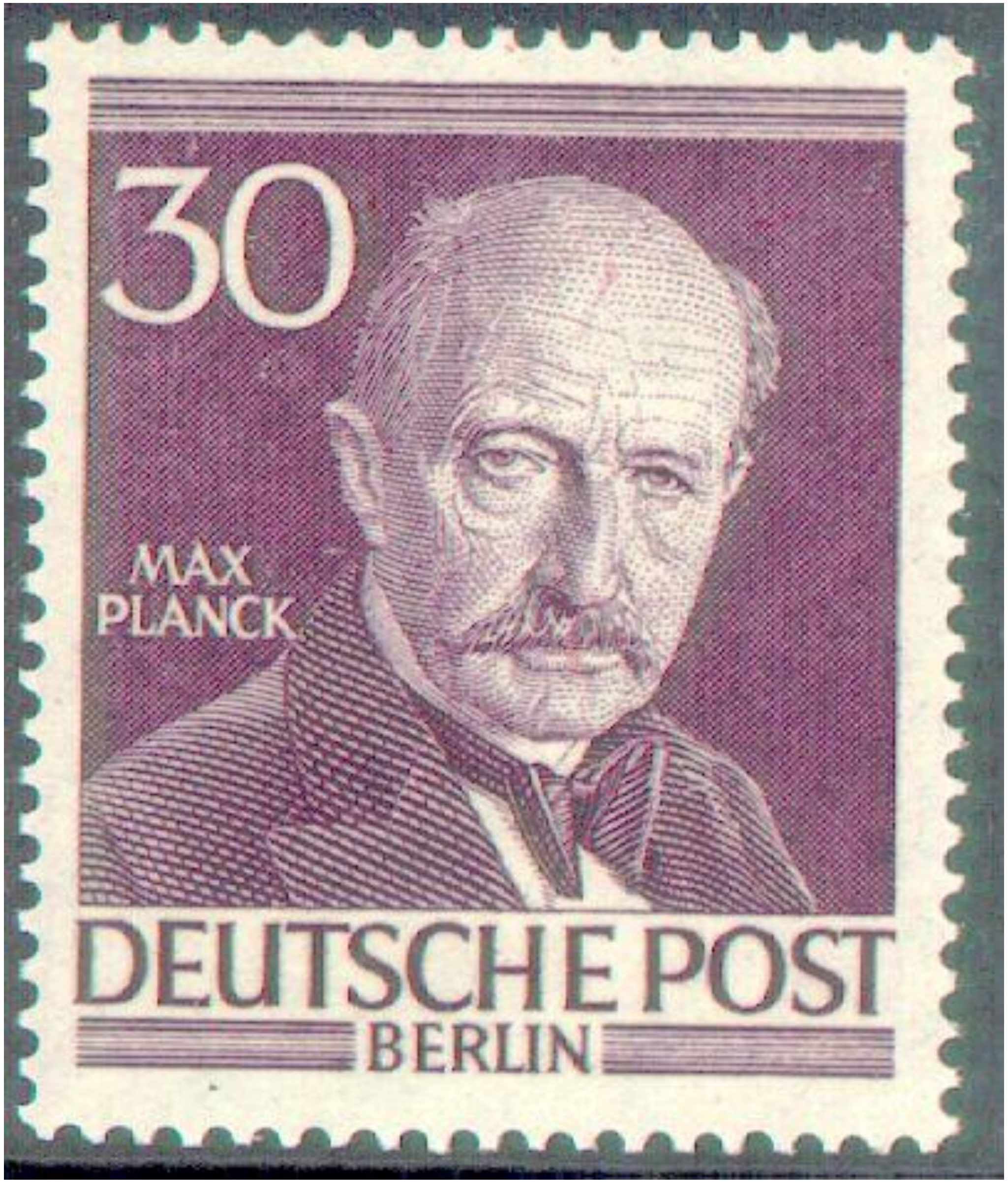
How Did We Find Out About Quantum Mechanics?

Dan Styer
Department of Physics and Astronomy
Oberlin College

Max Planck (age 42 in 1900)


30
MAX
PLANCK
DEUTSCHE POST
BERLIN

Albert Einstein (age 26 in 1905)

Einstein’s four 1905 papers:

Quantum mechanics of light (heuristic photoelectric effect)

Brownian motion (atoms exist!)

On the Electrodynamics of Moving Bodies

Does the Inertia of a Body Depend on its Energy Content?
($E = mc^2$)

Einstein’s four 1905 papers:

Quantum mechanics of light (heuristic photoelectric effect)

“is very revolutionary”

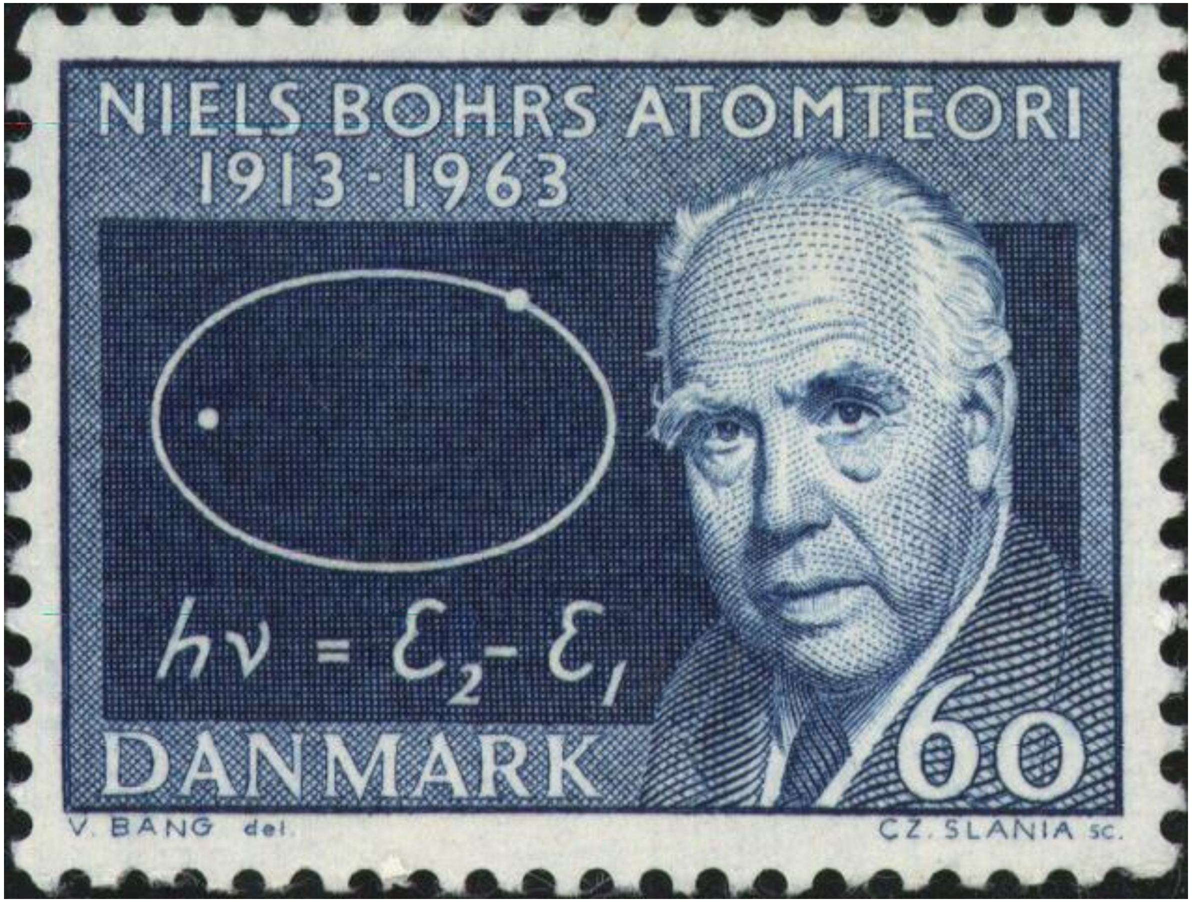
Brownian motion (atoms exist!)

On the Electrodynamics of Moving Bodies

“a modification of the theory of space and time”

Does the Inertia of a Body Depend on its Energy Content?
($E = mc^2$)

Niels Bohr (age 28 in 1913)

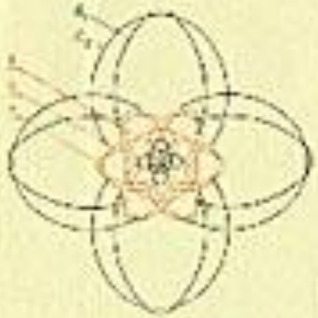

NIELS BOHRS ATOMTEORI
1913 - 1963
$h\nu = \mathcal{E}_2 - \mathcal{E}_1$
DANMARK
60
V. BANG del.
CZ. SLANIA sc.


172600A
A0972A
500
500
FEM HUNDREDE
KRONER
NIELS BOHR
DANMARKS NATIONALBANK

MAIN LINES OF THE ATOMIC STRUCTURE OF SOME ELEMENTS

HYDROGEN (1)

ARGON (18)

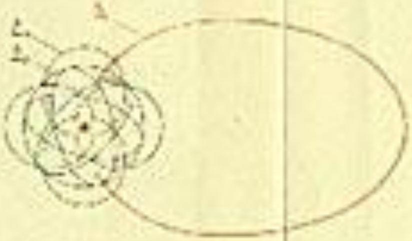


KRYPTON (36)

HELIUM (2)

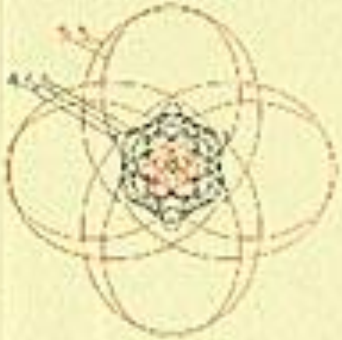
LITHIUM (3)

NEON (10)

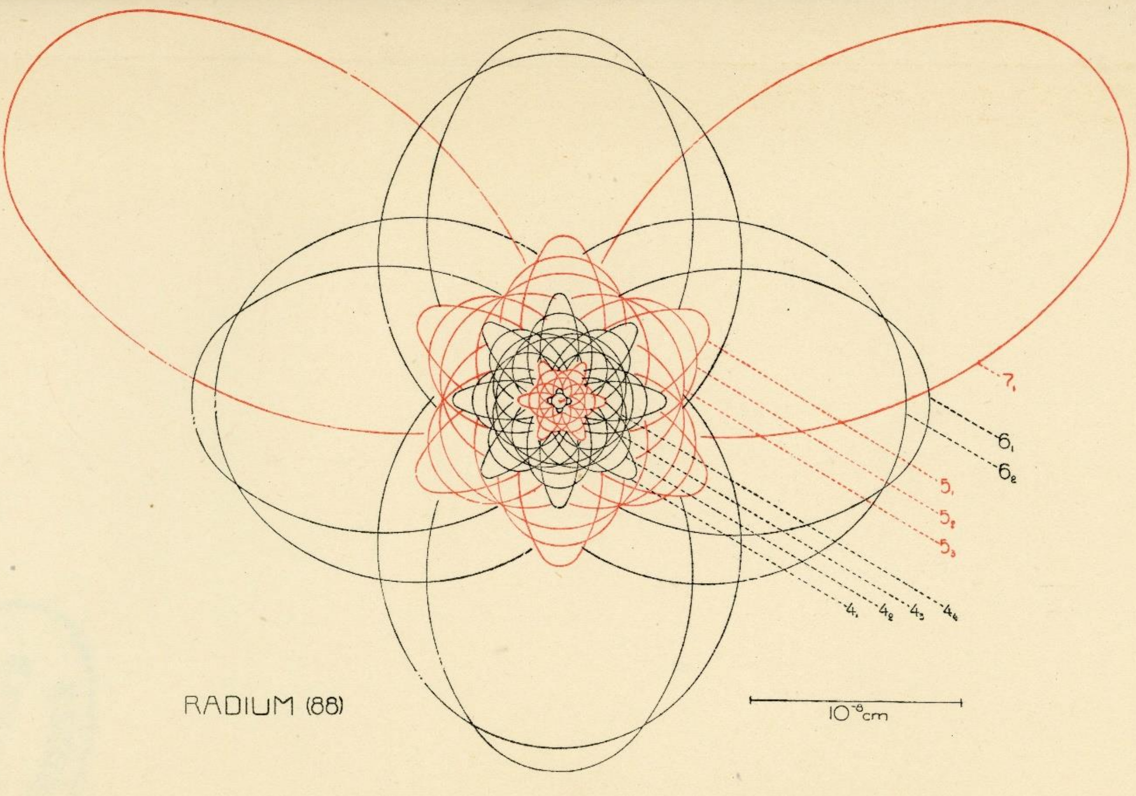


SODIUM (11)

COPPER (29)



XENON (54)

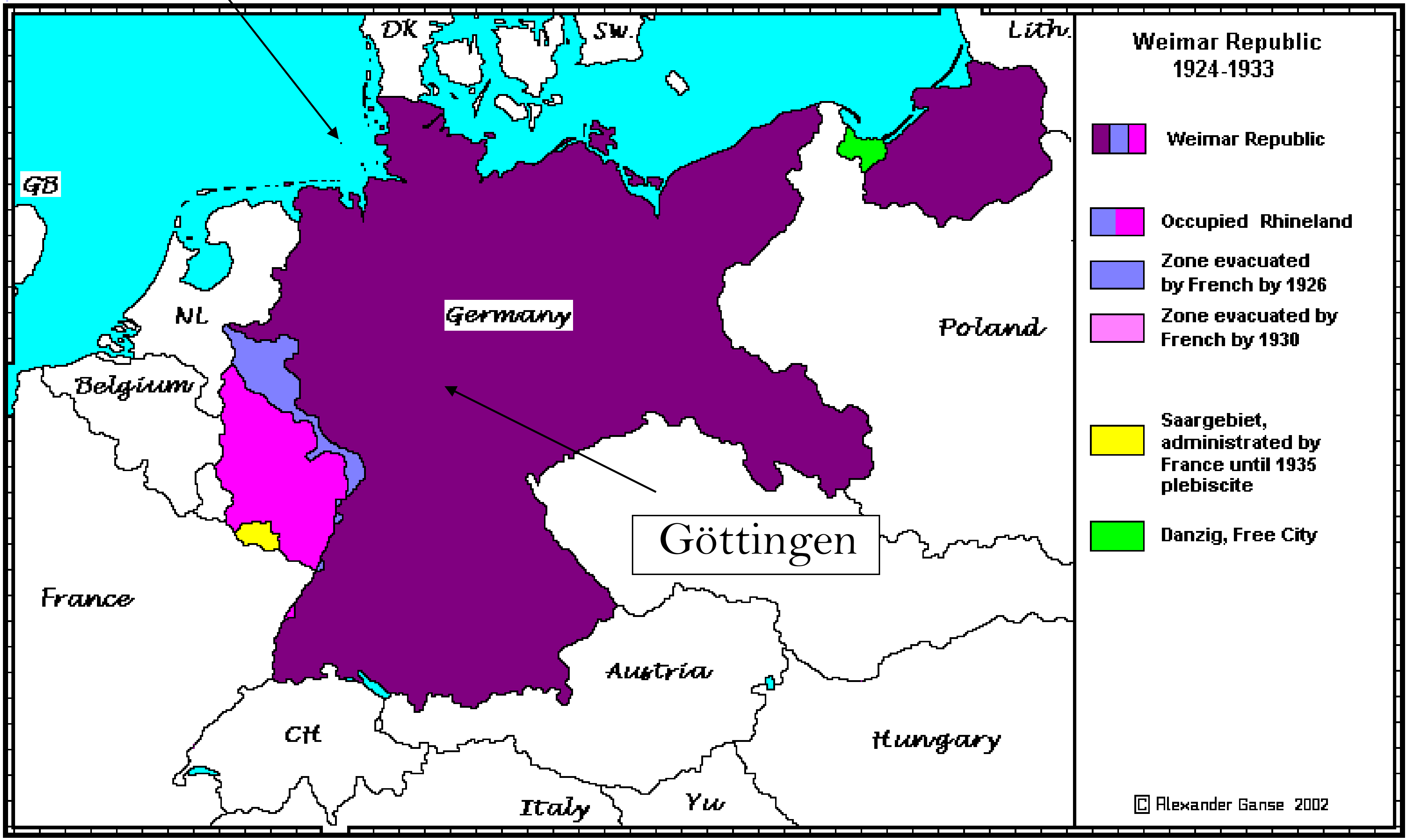


STRUCTURE OF THE RADIUM ATOM

Werner Heisenberg (age 24 in 1925)

Werner Heisenberg (age 24 in 1925)

Helgoland



Göttingen

Wolfgang Pauli (age 25 in 1925)

Louise de Broglie (age 31 in 1923)

Louise de Broglie


REPUBLIQUE
FRANCAISE
POSTES
1970
ΔW=hν
MAURICE
DE BROGLIE
1875-1960
0,40+0,10
SERVEAU
J. COMBET

Erwin Schrödinger (age 38 in 1925)

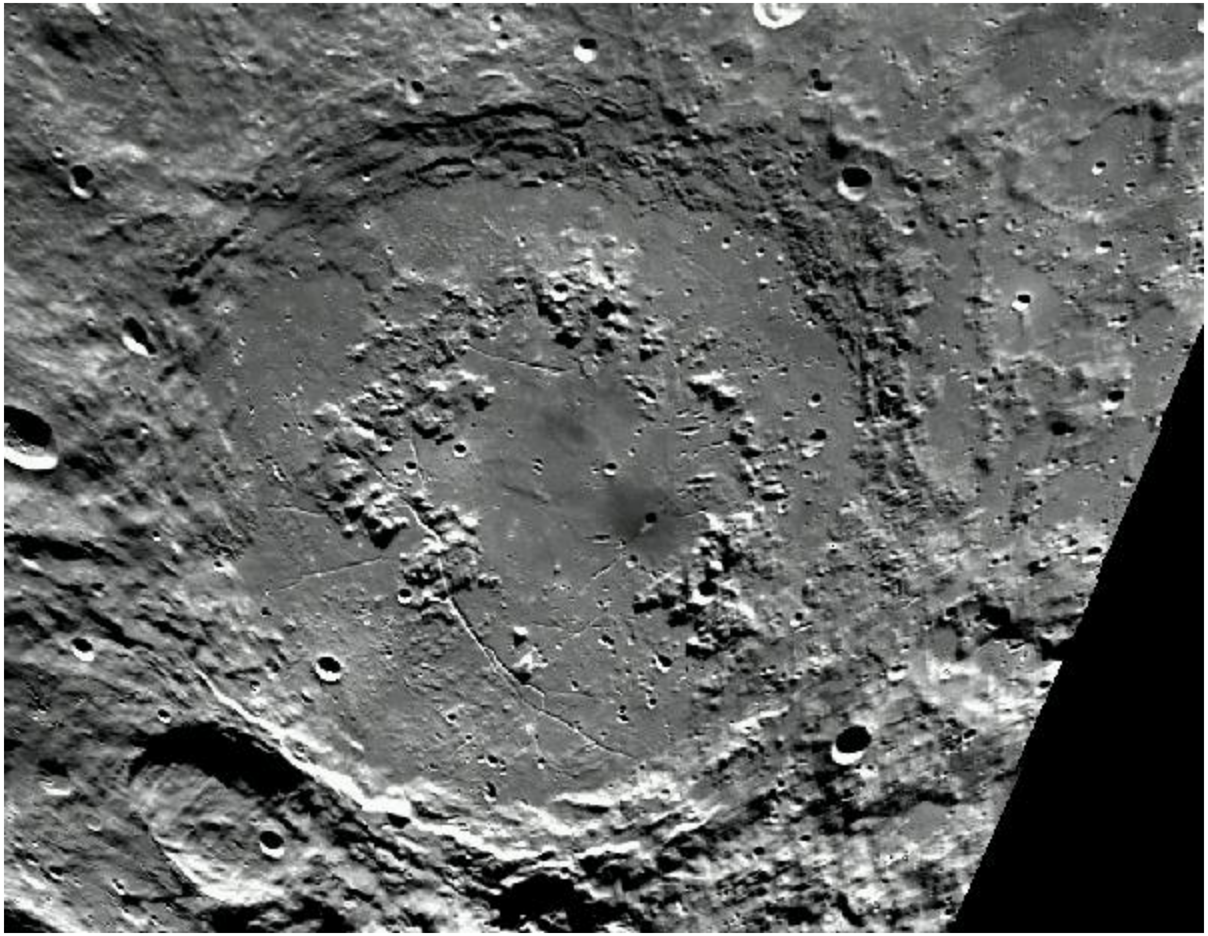
Arosa, Switzerland

Arosa, Switzerland

Arosa, Switzerland

Erwin Schrödinger (age 38 in 1925)

Erwin Schrödinger



Crater Schrödinger

Matrix Mechanics (Heisenberg, Born)

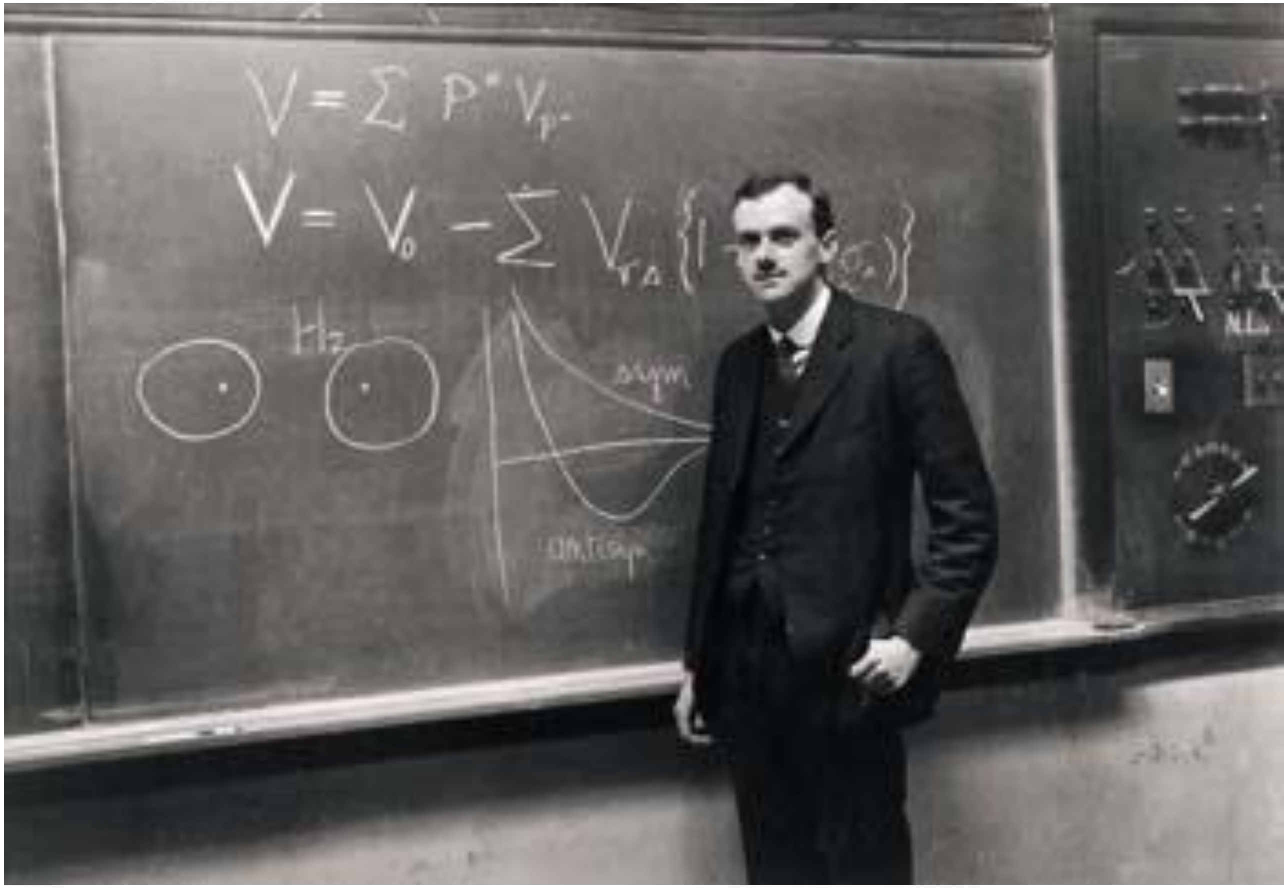
versus

Wave Mechanics (Schrödinger)

Matrix and Wave Mechanics proven equivalent in 1926 by Schrödinger, Pauli, and Carl Eckert (age 24)

Carl Eckert (photo 1948)

Paul A. M. Dirac (age 24 in 1926)



Paul A. M. Dirac

Westminster Abbey

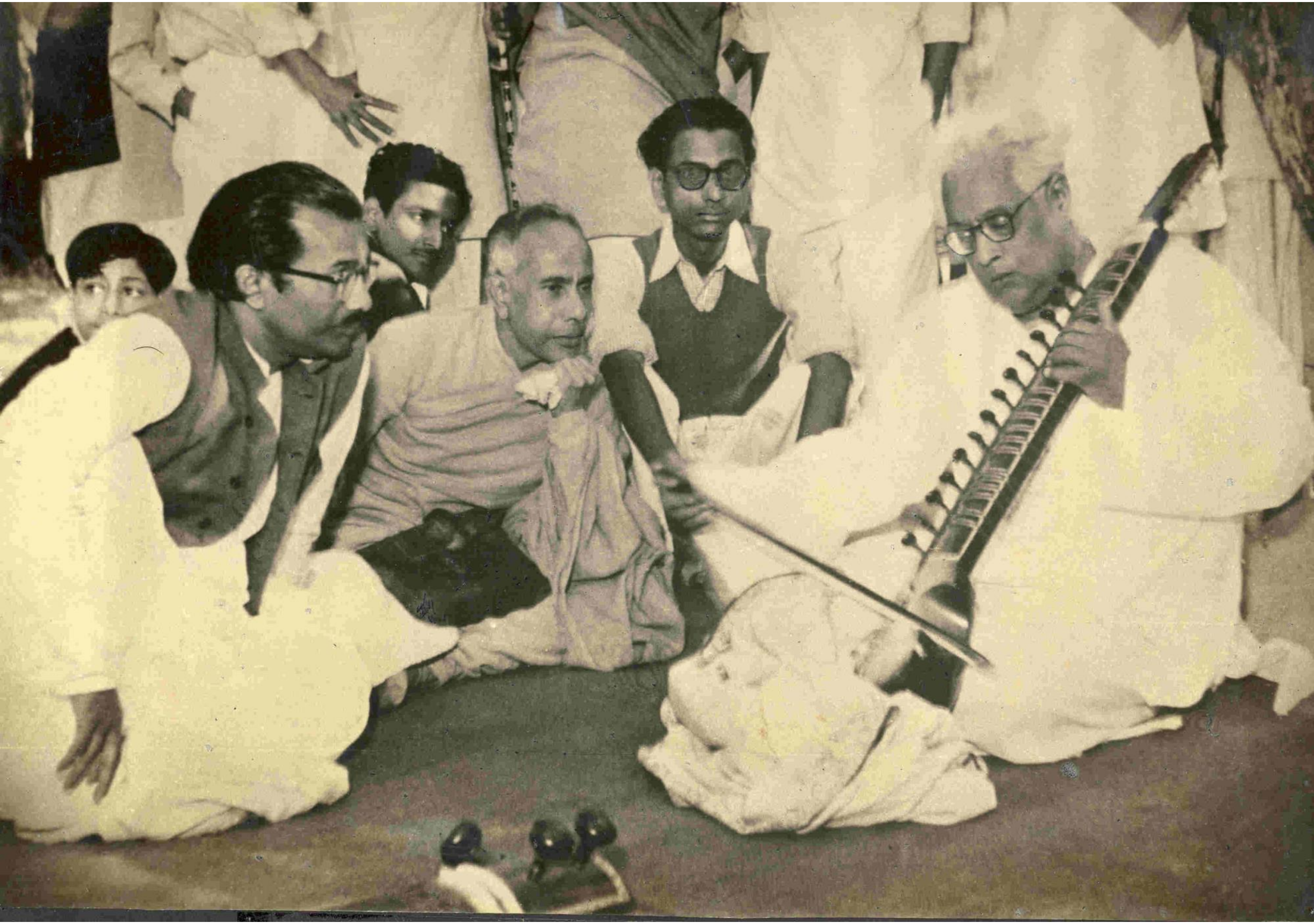
Satyendra Bose

1924-25: quantum mechanics applied to large number of particles (with A. Einstein)

(age 31 in 1925)

Satyendra Bose

1925: predicted a new phase of matter – solid, liquid, gas, and "Bose condensate"

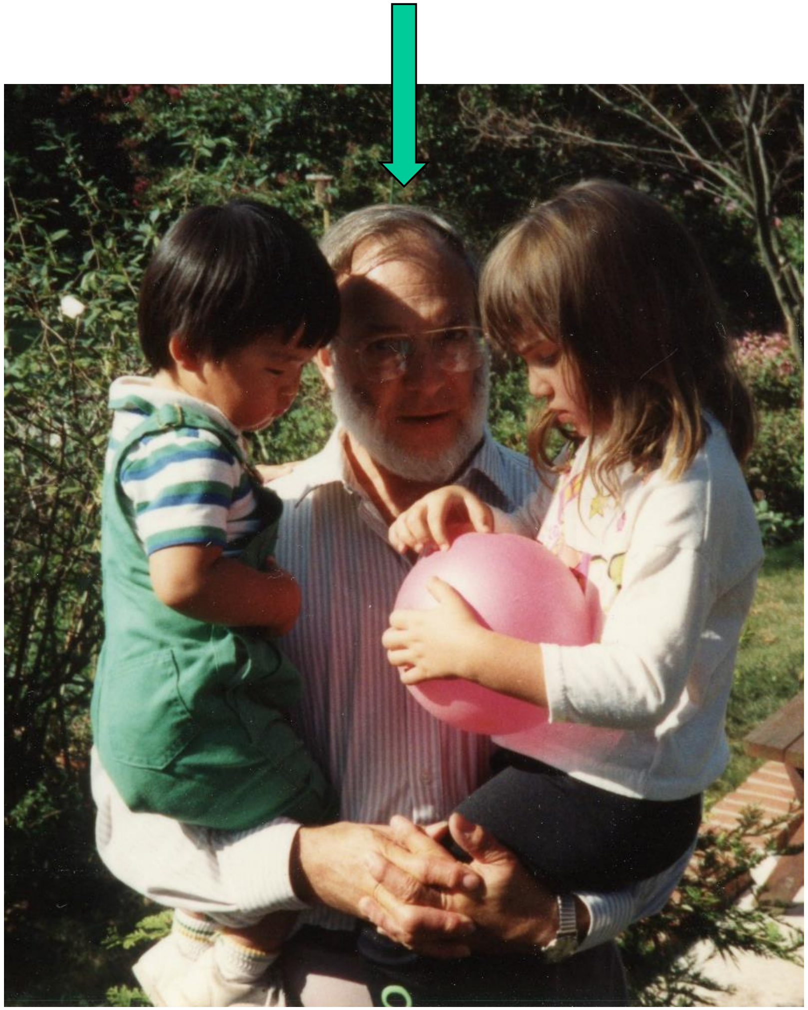



SATYENDRA NATH BOSE
सत्येन्द्र नाथ बोस
100
भारत INDIA
1994

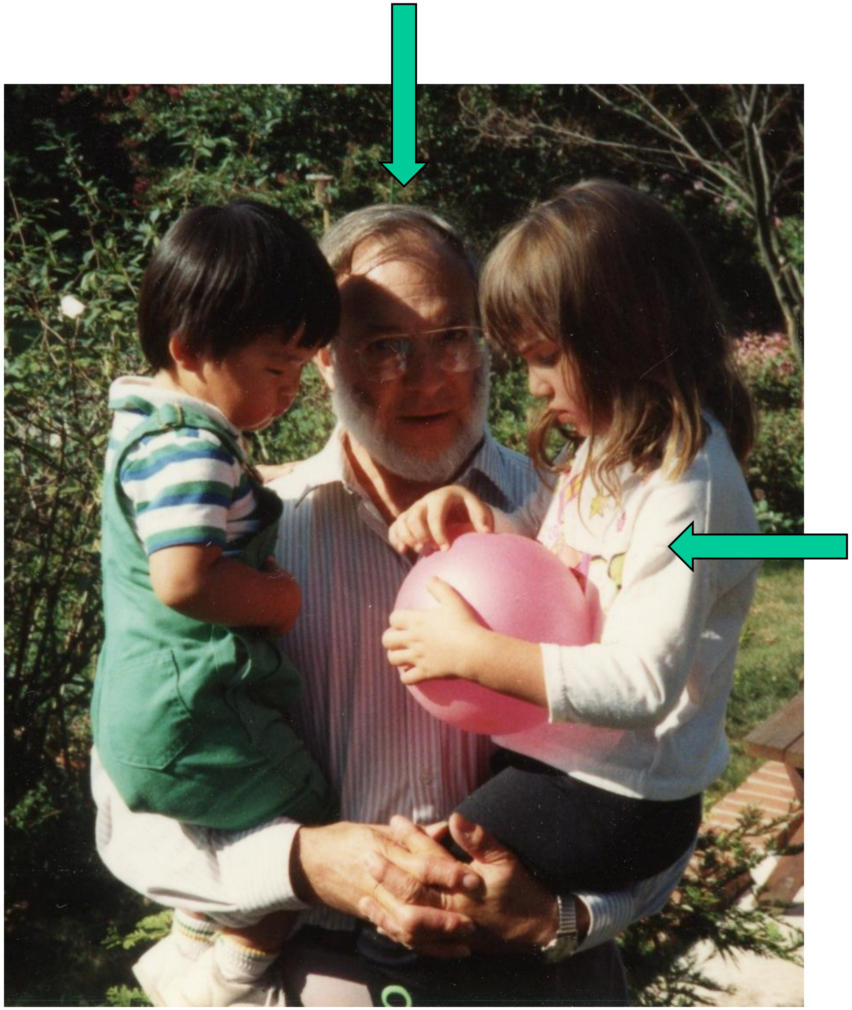
Michael Fisher

1970s: extended this work

Michael Fisher

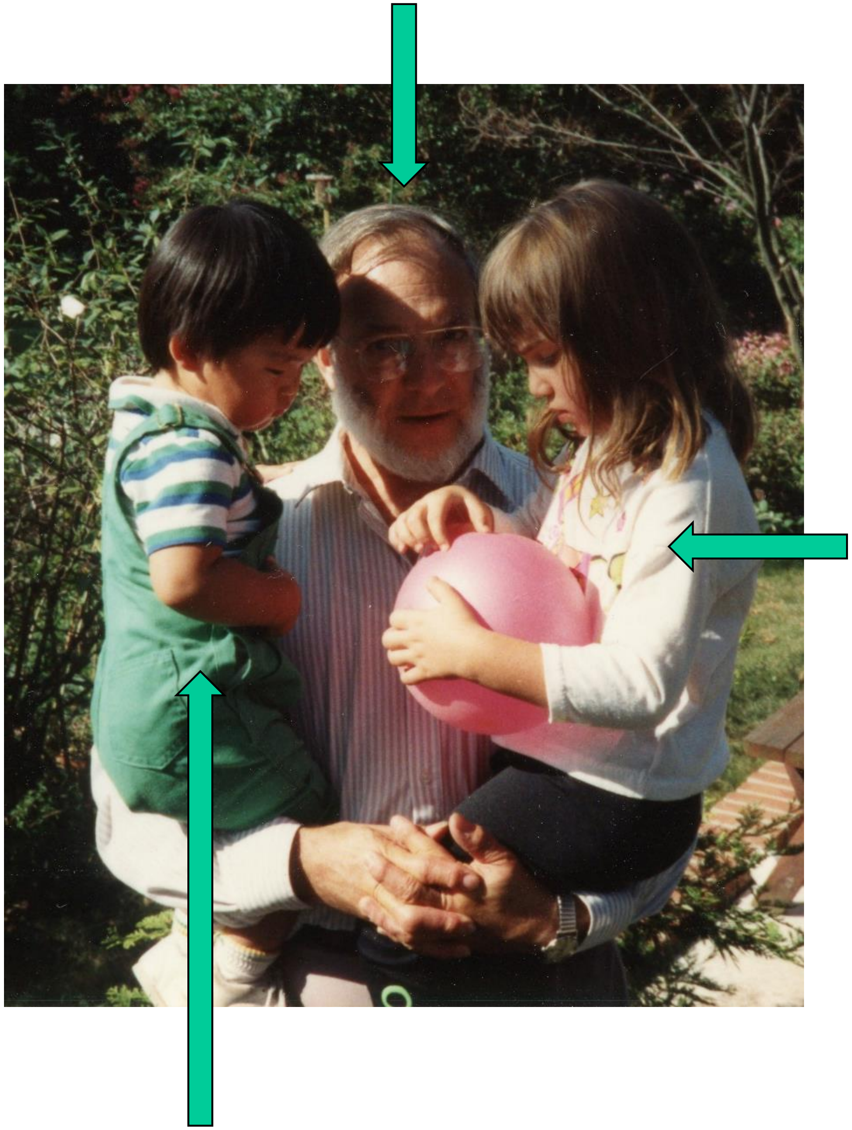


Michael Fisher



Michael Fisher's
granddaughter

Michael Fisher



Michael Fisher's granddaughter

My son,
Gregory Michael Styer

2 Groups of Physicists Produce Matter That Einstein Postulated

By MALCOLM W. BROWNE

By chilling a cloud of atoms to a temperature barely above absolute zero, scientists at a Colorado laboratory have at last created a bizarre type of matter that had eluded experimenters ever since its potential existence was postulated by Albert Einstein 70 years ago.

The creation of this Bose-Einstein condensate — named for Einstein and the Indian theorist Satyendra Nath Bose — was hailed yesterday as the basis of a new field of research expected to explain some fundamental mysteries of atomic physics.

A Texas group later produced similar results. The achievement should allow physicists to peer directly into the realm of the ultrasmall.

In a comment being published today by the journal Science, Dr. Keith Burnett, a physicist at Oxford University in England, said, "The term Holy Grail seems quite appropriate, given the singular importance of this discovery."

Details of the achievement were disclosed in a technical paper published by Science and at a news conference yesterday in Boulder, Colo.

Separately, a research team led

that it had independently created a Bose-Einstein condensate made of atoms different from those used in the Colorado laboratory and using a somewhat different method.

A Bose-Einstein condensate is a gas of atoms that have been so chilled that their normal motion is virtually halted. In this almost stationary condition, the wavelengths of individual atoms — the dimensions that define the regions in which they may be found — grow to relatively enormous size, overlapping each other and merging into a kind of super atom. This merged atom, despite growing to a range of sizes typical of those of bacteria, obeys the rules of quantum mechanics, the physics of the ultrasmall.

The creation of this unique state of matter by the Colorado group occurred on June 5, when a microscopic blob of Bose-Einstein condensate abruptly appeared in the glass vessel containing super-cold rubidium atoms. The condensate was de-

Continued on Page A14, Column 4

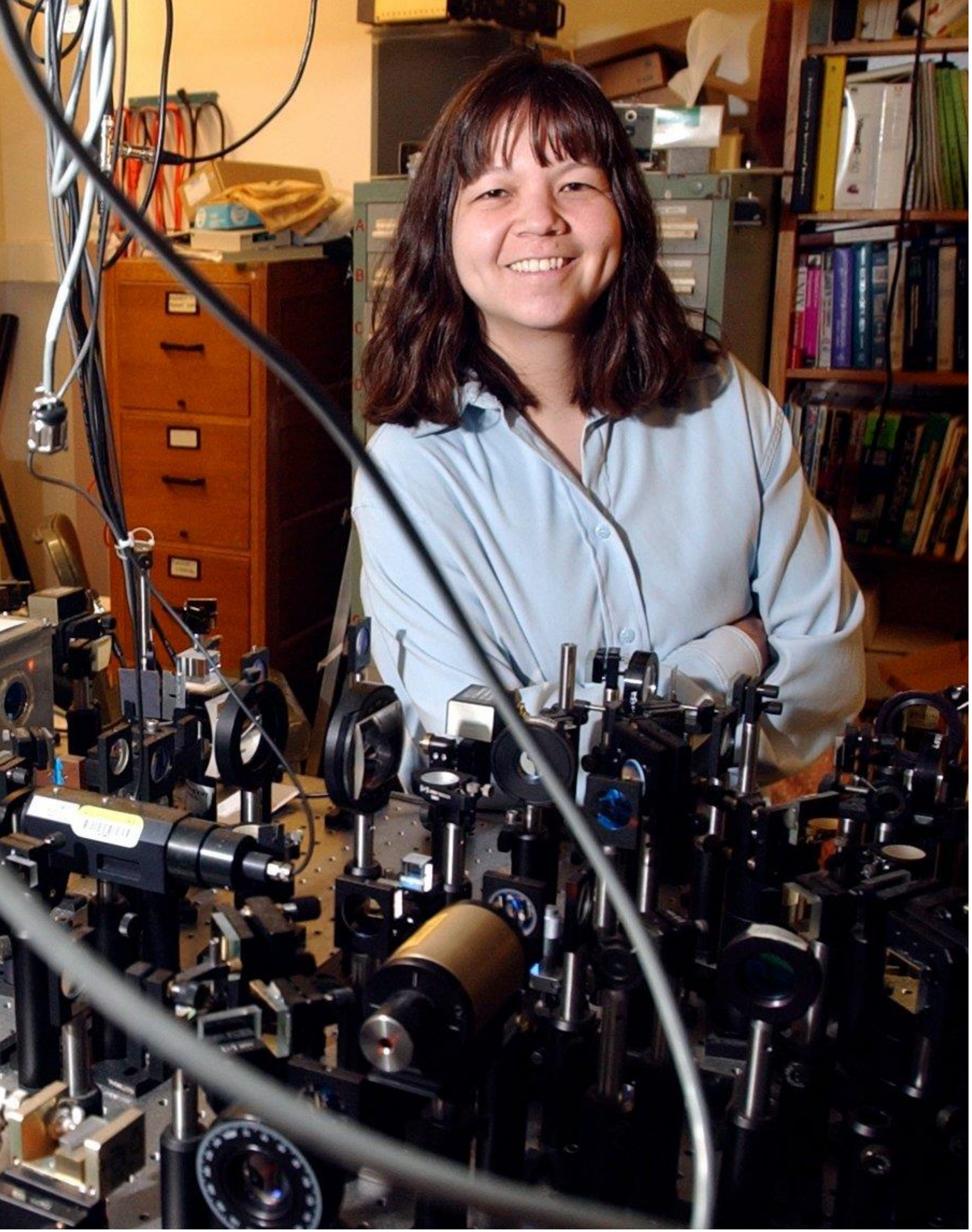
Experimental verification!

1995

Experimental verification!

1995

by Carl Wieman
and Eric Cornell



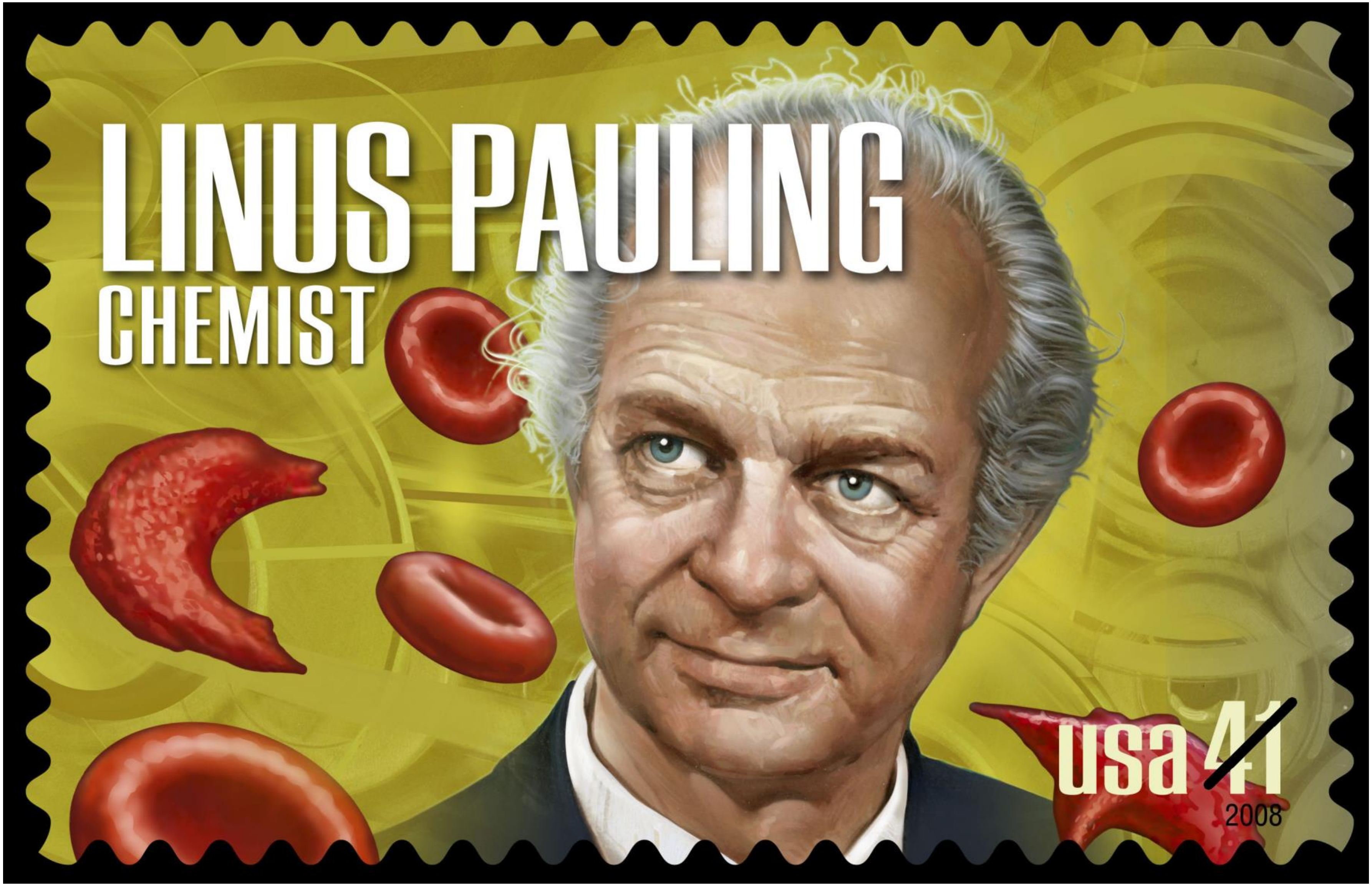
Experimental verification!

extended to “fermionic condensate” by Deborah Jin in 2003

Linus Pauling (age 30 in 1931)

Linus Pauling and family

Linus Pauling


LINUS PAULING
CHEMIST
usa 41
2008

Linus Pauling
gave his name to
Linus Torvalds
who gave his name to
Linux

Maria Goeppert Mayer
nuclear shell theory, 1950


2011
~~FOREVER~~
USA
SCANDIUM
CALCIUM
TITANIUM
VANADIUM
CHROMIUM
MANGANESE
IRON
COBALT
GALLIUM
20
21
22
23
24
25
31
Maria Goeppert Mayer
3 ħω
odd
2p
1f
2p½
1f5/2
2p3/2
Physicist
MARIA GOEPPERT MAYER

Crater Goeppert Mayer
on Venus

Maria Goeppert Mayer

1950: nuclear shell theory

1960: appointed professor
at U. Calif. San Diego

1963: Nobel Prize

Maria Goeppert Mayer

1950: nuclear shell theory

1960: appointed professor
at U. Calif. San Diego

1963: Nobel Prize

Headline in San Diego newspaper:

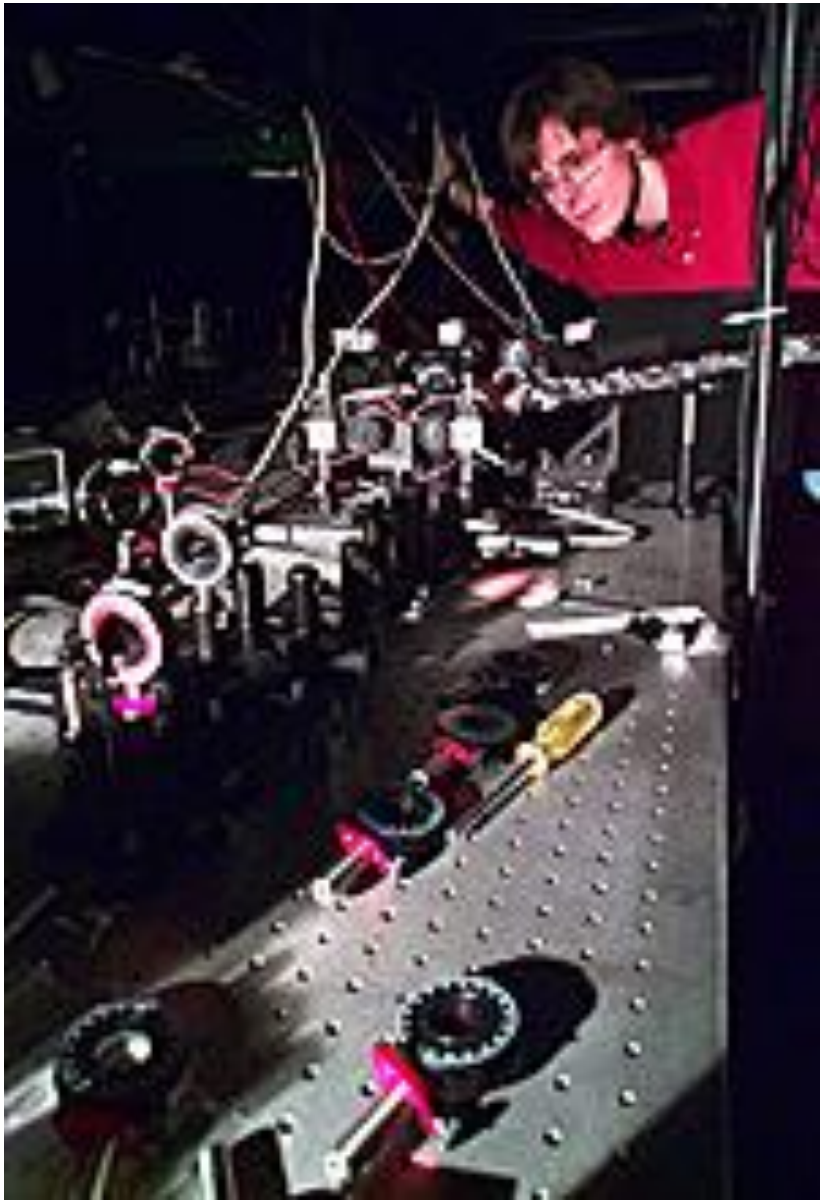
“S.D. Mother Wins Nobel Prize”

Einstein
and
Bohr
in 1930

Einstein
and
Bohr
in 1930

John Bell (age 36 in 1964)

Lucien Hardy



Paul Kwiat

Paul Kwiat

PHYSICAL REVIEW LETTERS **128,** 010402 (2022)

Exceptional Bound States and Negative Entanglement Entropy

Ching Hua Lee*
Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Received 9 December 2020; accepted 29 November 2021; published 7 January 2022)

This Letter introduces a new class of robust states known as exceptional bound (EB) states, which are distinct from the well-known topological and non-Hermitian skin boundary states. EB states occur in the presence of exceptional points, which are non-Hermitian critical points where eigenstates coalesce and fail to span the Hilbert space. This eigenspace defectiveness not only limits the accessibility of state information but also interplays with long-range order to give rise to singular propagators only possible in non-Hermitian settings. Their resultant EB eigenstates are characterized by robust anomalously large or negative occupation probabilities, unlike ordinary Fermi sea states whose probabilities lie between 0 and 1. EB states remain robust after a variety of quantum quenches and give rise to enigmatic negative entanglement entropy contributions. Through suitable perturbations, the coefficient of the logarithmic

PHYSICAL REVIEW LETTERS **128,** 010402 (2022)

Exceptional Bound States and Negative Entanglement Entropy

Ching Hua Lee[*]
Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Received 9 December 2020; accepted 29 November 2021; published 7 January 2022)

This Letter introduces a new class of robust states known as exceptional bound (EB) states, which are distinct from the well-known topological and non-Hermitian skin boundary states. EB states occur in the presence of exceptional points, which are non-Hermitian critical points where eigenstates coalesce and fail to span the Hilbert space. This eigenspace defectiveness not only limits the accessibility of state information but also interplays with long-range order to give rise to singular propagators only possible in non-Hermitian settings. Their resultant EB eigenstates are characterized by robust anomalously large or negative occupation probabilities, unlike ordinary Fermi sea states whose probabilities lie between 0 and 1. EB states remain robust after a variety of quantum quenches and give rise to enigmatic negative entanglement entropy contributions. Through suitable perturbations, the coefficient of the logarithmic

PHYSICAL REVIEW LETTERS **128,** 010402 (2022)

Exceptional Bound States and Negative Entanglement Entropy

Ching Hua Lee[*]
Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Received 9 December 2020; accepted 29 November 2021; published 7 January 2022)

This Letter introduces a new class of robust states known as exceptional bound (EB) states, which are distinct from the well-known topological and non-Hermitian skin boundary states. EB states occur in the presence of exceptional points, which are non-Hermitian critical points where eigenstates coalesce and fail to span the Hilbert space. This eigenspace defectiveness not only limits the accessibility of state information but also interplays with long-range order to give rise to singular propagators only possible in non-Hermitian settings. Their resultant EB eigenstates are characterized by robust anomalously large or negative occupation probabilities, unlike ordinary Fermi sea states whose probabilities lie between 0 and 1. EB states remain robust after a variety of quantum quenches and give rise to enigmatic negative entanglement entropy contributions. Through suitable perturbations, the coefficient of the logarithmic

PHYSICAL REVIEW LETTERS **128,** 010402 (2022)

Exceptional Bound States and Negative Entanglement Entropy

Ching Hua Lee*

Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Received 9 December 2020; accepted 29 November 2021; published 7 January 2022)

This Letter introduces a new class of robust states known as exceptional bound (EB) states, which are distinct from the well-known topological and non-Hermitian skin boundary states. EB states occur in the presence of exceptional points, which are non-Hermitian critical points where eigenst to span the Hilbert space. This eigenspace defectiveness not only limits the information but also interplays with long-range order to give rise to singular propaga non-Hermitian settings. Their resultant EB eigenstates are characterized by robust negative occupation probabilities, unlike ordinary Fermi sea states whose probabilitie EB states remain robust after a variety of quantum quenches and give rise t entanglement entropy contributions. Through suitable perturbations, the coefficien

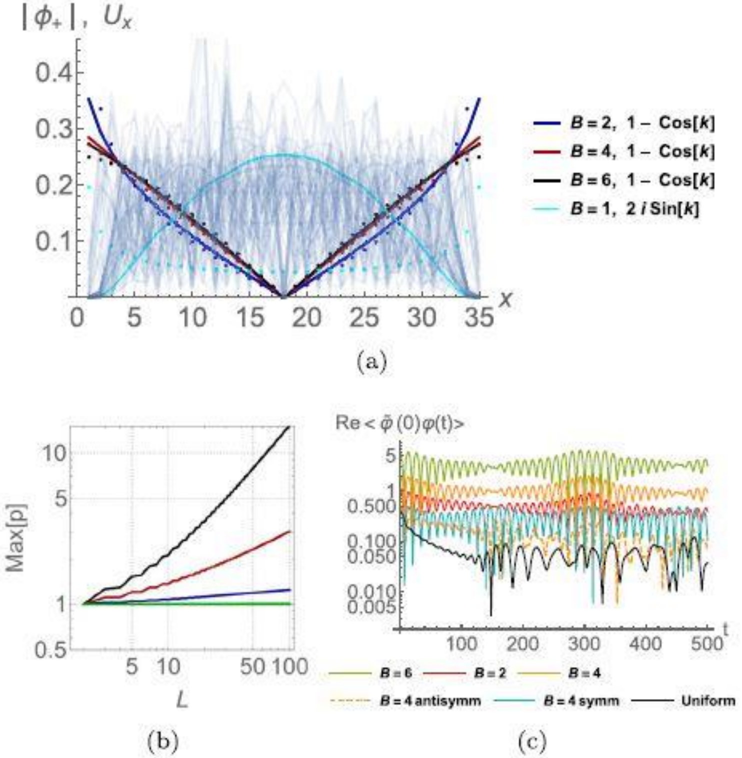


FIG. 2. (a) Numerical spatial lattice profiles of EB states ϕ_+ (solid) vs the 2-site propagator $U_x = \langle c^\dagger_{x,+} c_{0,-} \rangle$. Close agreement is observed for sufficiently singular EPs with $b(k)$ of $B = 2$, 4 and 6th order, but not the $B = 1$ case given by $b(k) = 2i \sin k$. Other non-EB states are superimposed as a gray background sea of states. (b) Anomalously large occupation probabilities $p =$

Exceptional Bound States and Negative Entanglement Entropy

Ching Hua Lee*

Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Received 9 December 2020; accepted 29 November 2021; published 7 January 2022)

This Letter introduces a new class of robust states known as exceptional bound (EB) states, which are
itian skin boundary states. EB states occur in the
critical points where eigenst
eness not only limits the
give rise to singular propaga
are characterized by robust
sea states whose probabilitie
quenches and give rise to
perturbations, the coefficier

We next examine how this asymmetrically singular $P(k)$ leads to EBs by studying the 2-site propagators obtained by Fourier transforming $U(k)$ and $D(k)$ to real space via $\langle c^\dagger_{x_1,+}c_{x_2,-}\rangle = -\frac{1}{2}\sum_k e^{ik(x_1-x_2)}U(k)$ and $\langle c^\dagger_{x_1,-}c_{x_2,+}\rangle = -\frac{1}{2}\sum_k e^{ik(x_1-x_2)}D(k)$. For concreteness, we introduce the ansatz

$$b(k) = b_0[2(1-\cos k)]^{B/2}, \tag{4a}$$

$$a(k) = b(-k) + a_0, \tag{4b}$$

which is realizable with lattice hoppings across at most $B/2$ sites (see [89] for odd B). Near the EP, $\langle c^\dagger_{x_1,-}c_{x_2,+}\rangle \sim \sqrt{(b_0/a_0)}2^{B/2}e^{-4(\Delta x)^2/B}$ is short-ranged, quadratically decaying with $\Delta x = x_1 - x_2$. However, due to the divergent denominator in $U(k) \sim \sqrt{a_0/b(k)}$, we have the following scaling behaviors with L (up to constant multiplicative factors, which play no role in the emergence of EB states), as numerically verified in [89]:

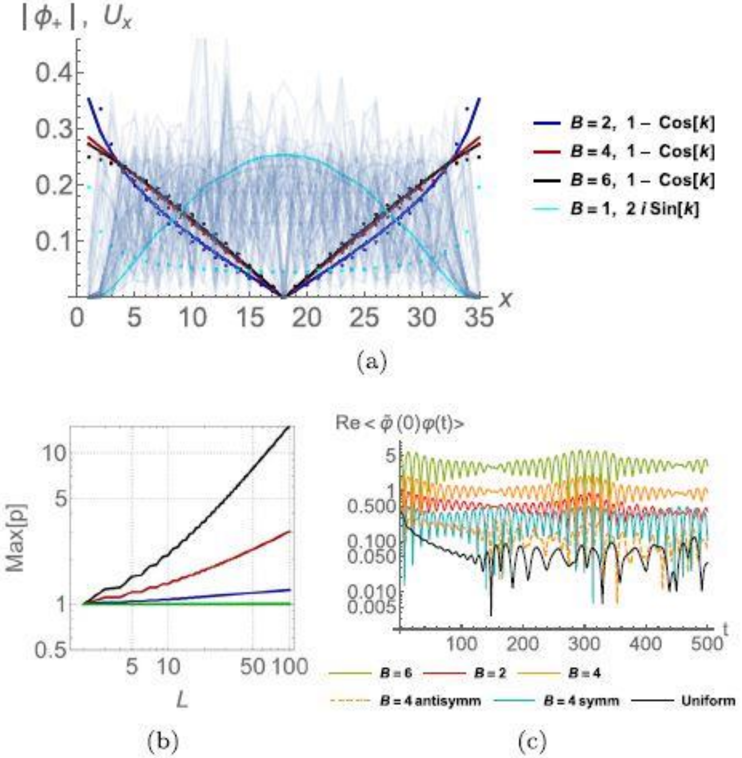
$$\langle c^\dagger_{x_1,+}c_{x_2,-}\rangle|_{B>4} \sim -\sqrt{\frac{a_0}{b_0}}\left(\frac{L}{\pi}\right)^{B/2-1} \times \left(2 - \frac{\pi^2\Delta x^2}{L^2}\right), \tag{5}$$

which is long-ranged in $\Delta x = x_1 — x_2$ and diverges as $L^{B/2-1}$. For the important cases of $B = 2$ and $B = 4$ [89],

$$\langle c^\dagger_{x_1,+}c_{x_2,-}\rangle|_{B=2} \sim -\sqrt{\frac{a_0}{b_0}}\left(\log\frac{L}{\pi\Delta x}\right), \tag{6}$$

$$\langle c^\dagger_{x_1,+}c_{x_2,-}\rangle|_{B=4} \sim -\sqrt{\frac{a_0}{b_0}}(L - 2\Delta x), \tag{7}$$

which diverges logarithmically and linearly with both L and x. Because of EP defectiveness, even a very small



(a)

(b)

(c)

FIG. 2. (a) Numerical spatial lattice profiles of EB states ϕ_+ (solid) vs the 2-site propagator $U_x = \langle c^\dagger_{x,+}c_{0,-}\rangle$. Close agreement is observed for sufficiently singular EPs with $b(k)$ of $B = 2$, 4 and 6th order, but not the $B = 1$ case given by $b(k) = 2i\sin k$. Other non-EB states are superimposed as a gray background sea of states. (b) Anomalously large occupation probabilities $p =$

Werner Heisenberg (age 24 in 1925)

On this frigid winter morning, I hope you'll spend a moment of appreciation for our universe that is both weird and wonderful.