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D.R. Nelson (Harvard)

A. Zee (UC Santa Barbara)

Q l ¶ £

N.H. and D.R. Nelson:

PRL 77, 570 (1996)

PRB 56, 8651 (1997)

PRB 58, 8384 (1998)

N.H.:

Physica A 254, 317 (1998)

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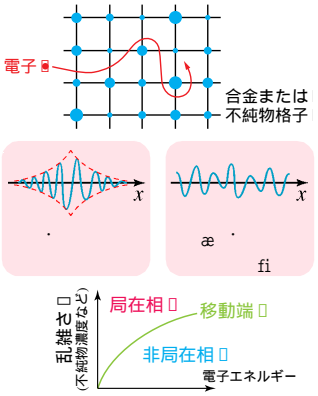

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$$H = \frac{(p+ig)^2}{2m} + V(x)$$

g: “ x N g | e

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$V(x)$: (X J [) _

@ @ @ | e V

g=0: (° G ~ [g¨)

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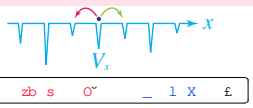
i q ″ ^

$$H = -\frac{t}{2}\sum_x \sum_{v=1}^{d} (e^{\bar{g}\cdot e_v}|x+e_v\rangle\langle x| + e^{-\bar{g}\cdot e_v}|x-e_v\rangle\langle x|) + \sum_x V_x|x\rangle\langle x|$$



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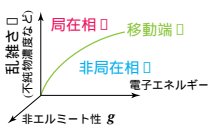
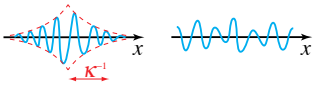


æ G ~ [g æ ·

g=0: · " ¶

$\psi \sim e^{-\kappa|x|}$ $\kappa = 0$



(i) $g \uparrow$: $g = g_c$ -
@ æ ·] • Ø

(ii) æ ·] ˘
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(iii) · • t : $\kappa = g_c$

æ ·]
¡ f Q W ˇ •

$$H_g = \frac{(p+ig)^2}{2m} + V(x)$$

$eA \leftrightarrow ig$

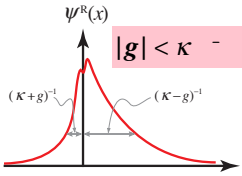
$g = 0$: $H_0\psi_0 = \varepsilon_0\psi_0$

$g \neq 0$: $H_g\psi_g = \varepsilon\psi_g$

Q [W ˇ : $\psi_g = \psi_0 e^{g\cdot x}$

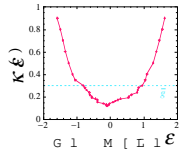
$\varepsilon = \varepsilon_0$: l -

$\psi_0 \sim e^{-\kappa|x|} \Rightarrow \psi_g^R \sim e^{-\kappa|x|+g\cdot x}$



$|g| < \kappa$ - ß

$|g| > \kappa$: $\psi^R \sim e^{ik\cdot x}$, $\varepsilon \sim \frac{(k+ig)^2}{2m}$



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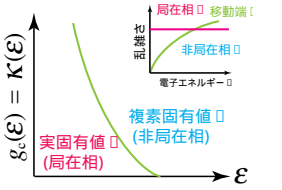
G ~ [g (g = 0): $\psi_0 \sim e^{-\kappa|x|}$

$g = g_c$ - ¡ f - L l
o » $\kappa = g_c$



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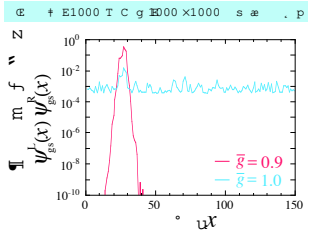
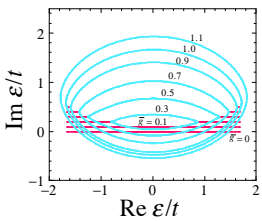


F - q ¶ ¡ $\neq |\psi(x)|^2$

$H|\psi^R\rangle = \varepsilon|\psi^R\rangle$

$\langle\psi^L|H = \varepsilon\langle\psi^L|$ $\rightarrow\langle\psi^L|$ $|\psi^R\rangle^\dagger$

¡ f - L l ˘ æ]
l v Z Æ



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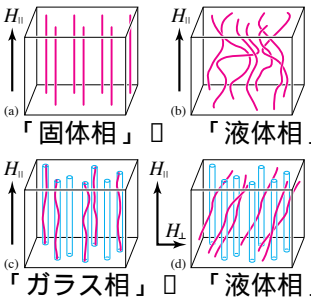

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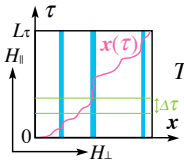
$$E_{cl}[x(\tau)] = \int_0^{L_\tau} d\tau \left[\frac{m}{2}\left(\frac{dx}{d\tau}\right)^2 - g \cdot \frac{dx}{d\tau} + V(x) \right]$$

$$g \equiv \Phi_0 H_\perp / (4\pi)$$

Nelson and Vinokur, PRB **48**, 13060 (1993)



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$$T(\Delta\tau) \approx \exp(-\Delta\tau H)$$

$$Z = \int Dx\ e^{-E_{cl}[x(\tau)]} = \langle \psi^f | e^{-L_\tau H} | \psi^i \rangle$$

$$H = \frac{(p+ig)^2}{} + V(r)$$

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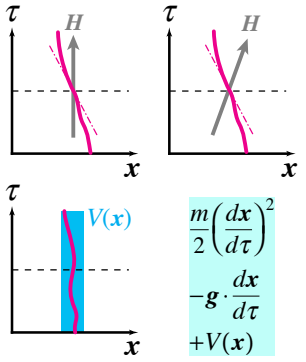

$$\frac{m}{2}\left(\frac{dx}{d\tau}\right)^2 - g \cdot \frac{dx}{d\tau} + V(x)$$

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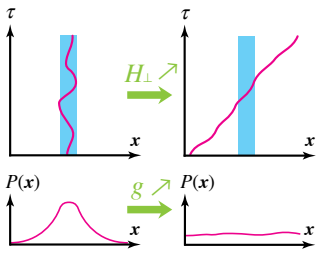

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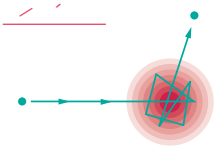


$$E_{res} = E_r - i\Gamma/2 \approx \frac{(k-i\gamma)^2}{2m}$$

Γ^{-1}: ⁄ ´ ı ‰

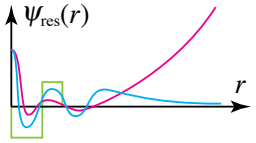
$$\psi_{res}(r) \sim e^{i(k-i\gamma)r} \quad \text{as} \quad r \to \infty$$

« E ‰ ‡ ¨ ¢

$$H = \frac{(p+ig)^2}{2m} + V(r)\ ;\ g = -g_0 \frac{x}{r}$$

⬇

$$\psi_{res}(r;g) = \psi_{res}(r;0)\ e^{-g_0 r} \sim e^{ikr-(g_0-\gamma)r}$$



Aguilar *et al*, Comm. Math. Phys. **22** (1971)

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¡ f X P [$\begin{cases} r \to re^{i\theta} \\ p \to pe^{-i\theta} \end{cases}$

» ... p E

- d § x g s ~ j
  Chen *et al.*, PRB **54**, 12798 (1996)
- t H b J Ł v N ß fi
  Nelson and Shnerb, PRE **58**, 1383 (1998)
- _ Ł [W Œ
  f B N b E t F ~ I
  Mudry *et al*. PRL **80**, 4257 (1998)
- *PT* « ¯ ł
  Bender and Boettcher, PRL **80**, 5243 (1998)
  ¡ f G l M [¯ L ↭ *PT* . « j
- p ‰ Ł
  Lehrer and Nelson, cond-mat/9806016
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