FI 193 – Teoria Quântica de Sistemas de Muitos Corpos

1º Semestre de 2025

10/04/2025

Aula 13

Aula passada

Função de Green de um corpo ordenada temporalmente a T=0:

$$iG_{\alpha\beta}(\mathbf{r}t;\mathbf{r}'t') = \frac{\langle\Psi_{0H}|\,T\left[\psi_{H\alpha}(\mathbf{r},t)\,\psi^{\dagger}_{H\beta}(\mathbf{r}',t')\right]|\Psi_{0H}\rangle}{\langle\Psi_{0H}|\Psi_{0H}\rangle}$$

$$= \theta(t-t')\,\frac{\langle\Psi_{0H}|\,\psi_{H\alpha}(\mathbf{r},t)\,\psi^{\dagger}_{H\beta}(\mathbf{r}',t')\,|\Psi_{0H}\rangle}{\langle\Psi_{0H}|\Psi_{0H}\rangle}$$

$$+\zeta\theta(t'-t)\,\frac{\langle\Psi_{0H}|\,\psi^{\dagger}_{H\beta}(\mathbf{r}',t')\,\psi_{H\alpha}(\mathbf{r},t)\,|\Psi_{0H}\rangle}{\langle\Psi_{0H}|\Psi_{0H}\rangle}$$

$$\boxed{\zeta = \begin{cases} +1, & \text{bósons} \\ -1, & \text{férmions} \end{cases}}$$

Aula passada

Propriedades:

(a) Sistema isolado:

$$G_{\alpha\beta}\left(\mathbf{r}t;\mathbf{r}'t'\right)=G_{\alpha\beta}\left(\mathbf{r},\mathbf{r}',t-t'\right)$$

(b) Sistema isolado e invariância translacional:

$$G_{\alpha\beta}\left(\mathbf{r}t;\mathbf{r}'t'\right)=G_{\alpha\beta}\left(\mathbf{r}-\mathbf{r}',t-t'\right)\equiv G_{\alpha\beta}\left(\mathbf{R},T\right)$$

(c) Sistema isolado, invariância translacional e simetria de reversão temporal (ausência de campo magnético ou de magnetização):

$$G_{\alpha\beta}\left(\mathbf{r}t;\mathbf{r}'t'\right)=\delta_{\alpha\beta}G\left(\mathbf{r}-\mathbf{r}',t-t'\right)\equiv\delta_{\alpha\beta}G\left(\mathbf{R},T\right)$$

Aula passada

Valores esperados no estado fundamental de operadores de um corpo:

$$\widehat{U} = \sum_{\alpha\beta} \int d^3 r \psi_\alpha^\dagger(\mathbf{r})\, U_{\alpha\beta}(\mathbf{r})\, \psi_\beta(\mathbf{r})$$

$$\boxed{\langle U \rangle = \zeta i \sum_{\alpha\beta} \int d^3 r \lim_{\eta \to 0^+} \lim_{\mathbf{r} \to \mathbf{r}'} \left[U_{\alpha\beta}(\mathbf{r})\, G_{\beta\alpha}(\mathbf{r}t; \mathbf{r}'t + \eta) \right]}$$

Aula passada

Função de Green não interagente (férmions):

$$\boxed{iG^{(0)}_{\alpha\beta}\left(\mathbf{r}t;\mathbf{r}'t'\right)=\frac{\delta_{\alpha\beta}}{V}\sum_{\mathbf{k}}e^{i\mathbf{k}\cdot\left(\mathbf{r}-\mathbf{r}'\right)}e^{-i\epsilon(\mathbf{k})(t-t')}\left[\theta\left(t-t'\right)\theta\left(k-k_F\right)-\theta\left(t'-t\right)\theta\left(k_F-k\right)\right]}$$

$$\begin{aligned}G_{\alpha\beta}\left(\mathbf{k},\omega\right) &= \int d^3RdTe^{-i\mathbf{k}\cdot\mathbf{R}}e^{i\omega T}G_{\alpha\beta}\left(\mathbf{R},T\right)\\ G_{\alpha\beta}\left(\mathbf{R},T\right) &= \int\frac{d^3kd\omega}{\left(2\pi\right)^4}e^{i\mathbf{k}\cdot\mathbf{R}}e^{-i\omega T}G_{\alpha\beta}\left(\mathbf{k},\omega\right)\end{aligned}$$

$$G^{(0)}_{\alpha\beta}\left(\mathbf{k},\omega\right)=\delta_{\alpha\beta}G^{(0)}\left(\mathbf{k},\omega\right)$$

$$\boxed{G^{(0)}\left(\mathbf{k},\omega\right) = \frac{1}{\omega-\epsilon\left(\mathbf{k}\right)+i\eta\mathrm{sgn}\left(k-k_F\right)},\quad \eta\rightarrow 0^+}$$

Valor esperado de um operador de dois corpos a partir da função de Green

Sistema homogêneo com interação de pares:

$$H=\sum_{\alpha}\int d^3r\psi_{\alpha}^{\dagger}(\mathbf{r})\left(-\frac{\hbar^2\nabla^2}{2m}\right)\psi_{\alpha}(\mathbf{r})+\frac{1}{2}\sum_{\alpha\beta}\int d^3rd^3r'\psi_{\alpha}^{\dagger}(\mathbf{r})\,\psi_{\beta}^{\dagger}(\mathbf{r}')\,U(\mathbf{r}-\mathbf{r}')\,\psi_{\beta}(\mathbf{r}')\,\psi_{\alpha}(\mathbf{r})$$

$$\boxed{\langle U\rangle=\frac{i\zeta}{2}\sum_{\alpha}\int d^3r\lim_{t'\to t^+}\lim_{\mathbf{r}\to\mathbf{r}'}\left[\left(i\partial_t+\frac{\hbar^2\nabla^2}{2m}\right)G_{\alpha\alpha}(\mathbf{r}t;\mathbf{r}'t')\right]}$$

$$\boxed{\langle H\rangle=\frac{i\zeta}{2}\sum_{\alpha}\int d^3r\lim_{t'\to t^+}\lim_{\mathbf{r}\to\mathbf{r}'}\left[\left(i\partial_t-\frac{\hbar^2\nabla^2}{2m}\right)G_{\alpha\alpha}(\mathbf{r}t;\mathbf{r}'t')\right]}$$

Transformadas de Fourier

$$G_{\alpha\beta}\left(\mathbf{k},\omega\right) \;=\; \int d^3R\,dT\,e^{-i\mathbf{k}\cdot\mathbf{R}}e^{i\omega T}G_{\alpha\beta}\left(\mathbf{R},T\right)$$

$$G_{\alpha\beta}\left(\mathbf{R},T\right) \;=\; \int \frac{d^3k\,d\omega}{\left(2\pi\right)^4}e^{i\mathbf{k}\cdot\mathbf{R}}e^{-i\omega T}G_{\alpha\beta}\left(\mathbf{k},\omega\right)$$

$$e^{-i\omega(t-t')} = e^{-i\omega(t-t-\eta)} = e^{i\omega\eta}$$

$$\eta \to 0^+$$

Operadores de um corpo

Valores esperados no estado fundamental de operadores de um corpo: exemplos.

$\eta \to 0^+$

ENERGIA CINÉTICA

$$\langle H_0 \rangle = \zeta i V \sum_{\alpha} \int \frac{d^3k d\omega}{(2\pi)^4} e^{i\omega\eta} \left(\frac{k^2}{2m} \right) G_{\alpha\alpha}(\mathbf{k}, \omega)$$

$$\langle N \rangle = \zeta i V \sum_{\alpha} \int \frac{d^3k d\omega}{(2\pi)^4} e^{i\omega\eta} G_{\alpha\alpha}(\mathbf{k}, \omega)$$

$$\langle \mathbf{S} \rangle = \zeta i V \sum_{\alpha\beta} \int \frac{d^3k d\omega}{(2\pi)^4} e^{i\omega\eta} \left(\frac{\boldsymbol{\sigma}_{\alpha\beta}}{2} \right) G_{\beta\alpha}(\mathbf{k}, \omega)$$

Operadores de dois corpos

Valores esperados de operadores de dois corpos: sistema homogêneo com interação de pares.

$$H = \sum_{\alpha} \int d^3 r \psi_{\alpha}^{\dagger}(\mathbf{r}) \left(-\frac{\hbar^2 \nabla^2}{2m} \right) \psi_{\alpha}(\mathbf{r}) + \frac{1}{2} \sum_{\alpha\beta} \int d^3 r d^3 r' \psi_{\alpha}^{\dagger}(\mathbf{r}) \psi_{\beta}^{\dagger}(\mathbf{r}') V(\mathbf{r} - \mathbf{r}') \psi_{\beta}(\mathbf{r}') \psi_{\alpha}(\mathbf{r})$$

$$\boxed{\begin{aligned} \langle V \rangle &= \frac{i\zeta V}{2} \sum_{\alpha} \int \frac{d^3 k d\omega}{(2\pi)^4} e^{i\omega\eta} \left(\omega - \frac{k^2}{2m} \right) G_{\alpha\alpha}(\mathbf{k}, \omega) \\ \langle H \rangle &= \frac{i\zeta V}{2} \sum_{\alpha} \int \frac{d^3 k d\omega}{(2\pi)^4} e^{i\omega\eta} \left(\omega + \frac{k^2}{2m} \right) G_{\alpha\alpha}(\mathbf{k}, \omega) \end{aligned}}$$

A representação espectral de Lehmann

- FÓRMULA EXATA PARA $G_{\alpha\beta}(\vec{k},\omega)$
- POUCO ÚTIL PARA CÁLCULOS DE $G_{\alpha\beta}(\vec{k},\omega)$
- MUITO ÚTIL PARA ANALISARMOS PROPRIEDADES DE $G_{\alpha\beta}(\vec{k},\omega)$
- GENERALIZÁVEL PARA AS OUTRAS FUNÇÕES DE GREEN.

$\langle \Psi_{0H} | \Psi_{0H} \rangle = 1$

$$\psi_{\alpha H}(x) = e^{iHt}\,\psi_\alpha(\vec{x})\,e^{-iHt}$$

$$\psi^\dagger_{\beta H}(x') = e^{iHt'}\,\psi^\dagger_\beta(\vec{x}')\,e^{-iHt'}$$

$$i\,G_{\alpha\beta}(x,x') = \theta(t-t')\langle \Psi_0 | \psi_{\alpha H}(x)\,\psi^\dagger_{\beta H}(x') | \Psi_0 \rangle$$
$$-\,\theta(t'-t)\langle \Psi_0 | \psi^\dagger_{\beta H}(x')\,\psi_{\alpha H}(x) | \Psi_0 \rangle$$

1) INSERÇÃO DO FECHAMENTO: $\sum_n |\Psi_n\rangle\langle\Psi_n| = \mathbb{1}$ AUTO-ESTADOS DE H

$$i\,G_{\alpha\beta}(x,x') = \sum_n \Big[\theta(t-t')\langle \Psi_0 | \psi_{\alpha H}(x) | \Psi_n\rangle\langle\Psi_n | \psi^\dagger_{\beta H}(x') | \Psi_0 \rangle -$$
$$-\,\theta(t'-t)\langle \Psi_0 | \psi^\dagger_{\beta H}(x') | \Psi_n\rangle\langle\Psi_n | \psi_{\alpha H}(x) | \Psi_0 \rangle \Big]$$

$$i G_{\alpha\beta}(x,x') = \sum_n \Big[\theta(t-t') \langle \Phi_0 | \psi_{\alpha H}(x) | \psi_n \rangle \langle \psi_n | \psi^{\dagger}_{\beta H}(x') | \Phi_0 \rangle -$$

$$- \theta(t'-t) \langle \Phi_0 | \psi^{\dagger}_{\beta H}(x') | \Phi_n \rangle \langle \psi_n | \psi_{\alpha H}(x) | \psi_0 \rangle \Big]$$

$$= \sum_n \Big[\theta(t-t') e^{-i(E_n - E_0)(t-t')} \langle \Phi_0 | \psi_\alpha(\vec{r}) | \Phi_n \rangle \langle \Phi_n | \psi^{\dagger}_\beta(\vec{r}\,') | \Phi_0 \rangle$$

$$- \theta(t'-t) e^{i(E_n - E_0)(t-t')} \langle \Phi_0 | \psi^{\dagger}_\beta(\vec{r}\,') | \Phi_n \rangle \langle \Phi_n | \psi_\alpha(\vec{r}) | \Phi_0 \rangle \Big]$$

ISSO PROVA QUE SE O SISTEMA É ISOLADO, $G_{\alpha\beta}(x,x') =$

$= G_{\alpha\beta}(\vec{r}, \vec{r}\,', t-t')$

2) TOMAR T. FOURIER NO TEMPO: $\tau = t - t'$

$$G_{\alpha\beta}(\vec{r}, \vec{r}\,', \omega) = \int_{-\infty}^{+\infty} d\tau \, e^{i\omega\tau} G_{\alpha\beta}(\vec{r}, \vec{r}\,'; \tau)$$

DE MANEIRA GERAL:

$$\int_{-\infty}^{+\infty} d\tau \, e^{i\omega\tau} (\pm) \theta(\pm\tau) e^{\mp i(E_n - E_0)\tau} = \pm \int_{0}^{\infty} d\tau \, e^{i[\omega \mp (E_n - E_0)]\tau} =$$

$$= \frac{(\pm 1) e^{i[\omega \mp (E_n - E_0)]\tau}}{i[\omega \mp (E_n - E_0)]} \Bigg|_{0, -\infty}^{\infty, 0} \rightarrow \frac{\mp i (\mp 1)^{0, -\infty}}{\omega \mp (E_n - E_0) \pm i\eta} = \frac{i}{\omega \mp (E_n - E_0) \pm i\eta}$$

$$G_{\alpha\beta}(\vec{r},\vec{r}\,',\omega) = \sum_n \left[\frac{\langle \Psi_0 | \psi_\alpha(\vec{r}) | \Psi_n \rangle \langle \Psi_n | \psi^\dagger_\beta(\vec{r}\,') | \Psi_0 \rangle}{\omega - (E_n - E_0) + i\eta} + \frac{\langle \Psi_0 | \psi^\dagger_\beta(\vec{r}\,') | \Psi_n \rangle \langle \Psi_n | \psi_\alpha(\vec{r}) | \Psi_0 \rangle}{\omega + (E_n - E_0) - i\eta} \right]$$

NO 1º (2º) TERMO, $|\Psi_n\rangle$ TEM $N+1$ ($N-1$) PARTÍCULAS SE $|\Psi_0\rangle$ TEM $\underline{N}$ PARTÍCULAS.

$$E_n - E_0 = E_n(N \pm 1) - E_0(N) = \underbrace{E_n(N\pm1) - E_0(N\pm1)}_{\epsilon_n(N\pm1) \geq 0} -$$

$$- \big[\underbrace{E_0(N) - E_0(N\pm1)}_{\sim (\mp)\frac{\partial E_0}{\partial N} = \mp\mu} \big] =$$

$$= \epsilon_n(N\pm1) \pm \mu$$

$$G_{\alpha\beta}(\vec{r},\vec{r}\,',\omega) = \sum_n \left[\frac{\langle \Phi_0 | \psi_\alpha(\vec{r}) | \Phi_n \rangle \langle \Phi_n | \psi_\beta^\dagger(\vec{r}\,') | \Phi_0 \rangle}{\omega - \epsilon_n(N+1) - \mu + i\eta} + \frac{\langle \Phi_0 | \psi_\beta^\dagger(\vec{r}\,') | \Phi_n \rangle \langle \Phi_n | \psi_\alpha(\vec{r}) | \Phi_0 \rangle}{\omega + \epsilon_n(N-1) - \mu - i\eta} \right]$$

3) SE HÁ INVARIÂNCIA TRANSLACIONAL:

O MOMENTO LINEAR TOTAL É CONSERVADO:

$$\vec{P} = \int d^3r \sum_\alpha \psi_\alpha^\dagger(\vec{r}) \left[\frac{\vec{\nabla}}{i} \right] \psi_\alpha(\vec{r}) = \sum_{\vec{k}\sigma} \vec{k}\, c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma}$$

$$\Rightarrow [\vec{P}, H] = 0$$

$$\psi_\beta^\dagger(\vec{r}\,') = e^{-i\vec{P}\cdot\vec{r}\,'} \psi_\beta^\dagger(0) e^{i\vec{P}\cdot\vec{r}\,'}$$

PODE-SE PROVAR: $\psi_\alpha(\vec{r}) = e^{-i\vec{P}\cdot\vec{r}} \psi_\alpha(\vec{0}) e^{i\vec{P}\cdot\vec{r}}$ (NOTAS)

LEVANDO NA EXPRESSÃO PARA $G_{\alpha\beta}(\vec{r},\vec{r}\,',\omega)$ E

SUPONDO QUE $\vec{P}|\Phi_0\rangle = 0$ (MOMENTO LINEAR TOTAL DO EST. FUND. É ZERO)

$$G_{\alpha\beta}(\vec{r},\vec{r}\,',\omega) = \sum_n \left[\frac{e^{i\vec{p}_n\cdot(\vec{r}-\vec{r}\,')}\langle\Psi_0|\psi_\alpha(0)|\psi_n\rangle\langle\Psi_n|\psi^\dagger_\beta(0)|\psi_0\rangle}{\omega - E_n(N+1) - \mu + i\eta} + \frac{e^{-i\vec{p}_n\cdot(\vec{r}-\vec{r}\,')}\langle\Psi_0|\psi^\dagger_\beta(0)|\psi_n\rangle\langle\psi_n|\psi_\alpha(0)|\psi_0\rangle}{\omega + E_n(N-1) - \mu - i\eta} \right]$$

O QUE PROVA QUE $G_{\alpha\beta}(\vec{r},\vec{r}\,',\omega) = G_{\alpha\beta}(\vec{r}-\vec{r}\,',\omega)$

T. FOURIER NO ESPAÇO: $\vec{R} = \vec{r} - \vec{r}\,'$

$$G_{\alpha\beta}(\vec{k},\omega) = \int d^3R\, e^{-i\vec{k}\cdot\vec{R}}\, G_{\alpha\beta}(\vec{R},\omega)$$

$$\int d^3R\, e^{-i\vec{k}\cdot\vec{R}}\, e^{\pm i\vec{p}_n\cdot\vec{R}} = V\delta_{\vec{k},\pm\vec{p}_n}$$

$$G_{\alpha\beta}(\vec{k},\omega) = \sum_n \left[\frac{\langle\Psi_0|\psi_\alpha(0)|n,\vec{k}\rangle\langle n,\vec{k}|\psi^\dagger_\beta(0)|\Psi_0\rangle}{\omega - E_{n,\vec{k}}(N+1) - \mu + i\eta} + \frac{\langle\Psi_0|\psi^\dagger_\beta(0)|n,-\vec{k}\rangle\langle n,-\vec{k}|\psi^\dagger_\beta(0)|\Psi_0\rangle}{\omega + E_{n,-\vec{k}}(N-1) - \mu - i\eta} \right]$$

SE HÁ SIMETRIA DE REVERSÃO TEMPORAL, $\alpha=\beta$:

$$G(\vec{k},\omega) = V \sum_m \left[\frac{A_{m,\vec{k}}}{\omega-\mu-\epsilon_{m,\vec{k}}(N+1)+i\eta} + \frac{B_{m,\vec{k}}}{\omega-\mu+\epsilon_{m,-\vec{k}}(N-1)-i\eta} \right]$$

ONDE:

$$A_{m,\vec{k}} = |\langle m,\vec{k}|\psi_\alpha^\dagger(0)|\Phi_0\rangle|^2 \geq 0$$

$$B_{m,\vec{k}} = |\langle m,-\vec{k}|\psi_\alpha(0)|\Phi_0\rangle|^2 \geq 0$$

ESSA É A REPRESENTAÇÃO DE LEHMANN.

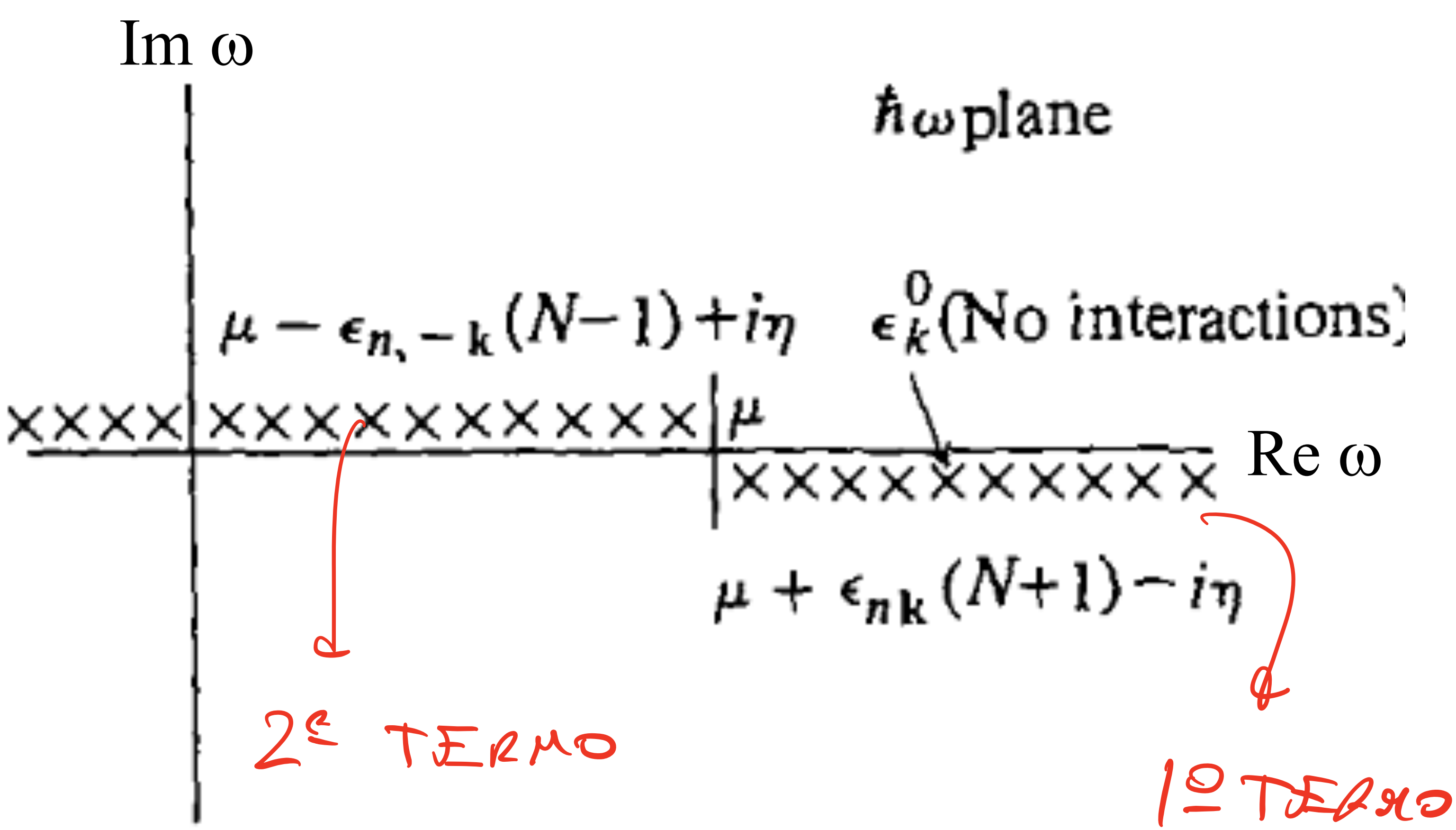
POLOS SIMPLES: 1º TERMO: $\epsilon_{m\vec{k}}(N+1)+\mu-i\eta \Rightarrow \begin{cases} \text{Re}: >\mu \\ \text{Im}: <0 \end{cases}$

2º TERMO: $-\epsilon_{m,k}(N-1)+\mu+i\eta \Rightarrow \begin{cases} \text{Re}: <\mu \\ \text{Im}: >0 \end{cases}$

RESÍDUOS DOS POLOS: $A_{m,\vec{k}}$ (1º TERMO)

$B_{m,\vec{k}}$ (2º TERMO)

Estrutura analítica da função de Green no plano ω complexo



UTILIZANDO: $\dfrac{1}{x \pm i\delta} = P\dfrac{1}{x} \mp i\pi\,\delta(x) \quad (\delta \to 0)$

NA REP. DE LEHMANN:

$$\mathrm{Im}\,G(\vec{k},\omega) = \pi V \sum_{n} \Big[-A_{n,\vec{k}}\,\delta\big[\omega - \mu - \epsilon_{n,\vec{k}}(N+1)\big] +$$
$$+ B_{n,\vec{k}}\,\delta\big[\omega - \mu + \epsilon_{n,-\vec{k}}(N-1)\big] \Big]$$

$$\mathrm{Re}\,G(\vec{k},\omega) = V \sum_{n} \left[P\,\frac{A_{n,\vec{k}}}{\omega - \mu - \epsilon_{n,\vec{k}}(N+1)} + P\,\frac{B_{n,\vec{k}}}{\omega - \mu + \epsilon_{n,-\vec{k}}(N-1)} \right]$$

$$\mathrm{Im}\,G(\vec{k},\omega) = \begin{cases} <0 & \text{SE} \quad \omega > \mu \\ >0 & \text{SE} \quad \omega < \mu \end{cases}$$

$$\mathrm{sgn}\big[\mathrm{Im}\,G(\vec{k},\omega)\big] = \mathrm{sgn}(\mu - \omega)$$

NO LIMITE TERMODINÂMICO, O ESPECTRO É CONTÍNUO

$$V \sum_n A_{n,\vec{k}} \to A(\vec{k},\epsilon)\, d\epsilon \qquad \epsilon < \epsilon_{n,\vec{k}}(N+1) < \epsilon + d\epsilon$$

$$V \sum_n B_{n,\vec{k}} \longrightarrow B(\vec{k},\epsilon)\, d\epsilon \qquad \epsilon < \epsilon_{n,-\vec{k}}(N-1) < \epsilon + d\epsilon$$

$$G(\vec{k},\omega) = \int_0^\infty d\epsilon \left[\frac{A(\vec{k},\epsilon)}{\omega-\mu-\epsilon+i\eta} + \frac{B(\vec{k},\epsilon)}{\omega-\mu+\epsilon-i\eta} \right]$$

$$\mathrm{Im}\, G(\vec{k},\omega) = \underbrace{-\pi A(\vec{k},\omega-\mu)}_{\omega>\mu} + \underbrace{\pi B(\vec{k},\mu-\omega)}_{\omega<\mu}$$

$$\mathrm{Re}\, G(\vec{k},\omega) = P \int_0^\infty d\epsilon \left[\frac{A(\vec{k},\epsilon)}{\omega-\mu-\epsilon} + \frac{B(\vec{k},\epsilon)}{\omega-\mu+\epsilon} \right]$$

SEGUE QUE:

$$\mathrm{Re}\, G(\vec{k},\omega) = P\int_{-\infty}^{+\infty} \frac{dx}{\pi} \frac{\mathrm{Im}\, G(\vec{k},x)\, \mathrm{sgn}(x-\mu)}{x-\omega}$$

DADA A PARTE IMAGINÁRIA DE $G(\vec{k},\omega)$, SUA PARTE REAL SEGUE DE MANEIRA ÚNICA.

NO LIMITE $|\omega| \to \infty$, SE $A(\vec{k},\epsilon)$ E $B(\vec{k},\epsilon)$ TÊM SUPORTE EM REGIÕES FINITAS DE $\underline{\epsilon}$:

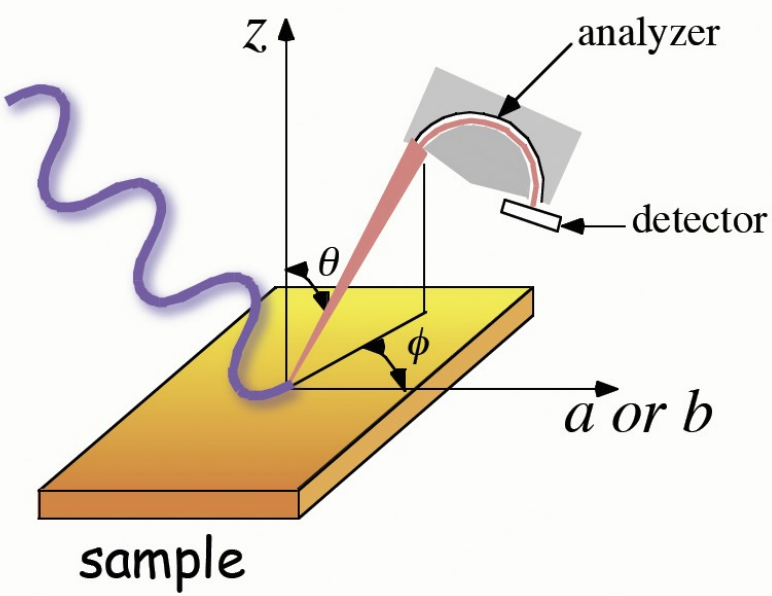
$$G(\vec{k},\omega) \xrightarrow[|\omega|\to\infty]{} \frac{1}{\omega}\left\{ \int_0^\infty \left[A(\vec{k},\epsilon)+B(\vec{k},\epsilon)\right] d\epsilon \right\}$$

PODE-SE PROVAR, A PARTIR DE $\{\psi_\alpha(\vec{r}), \psi_\beta^\dagger(\vec{r}\,')\} = \delta^{(3)}(\vec{r}-\vec{r}\,')\delta_{\alpha\beta}$ QUE O TERMO $\{\ \} = 1$

$$G(\vec{k},\omega) \xrightarrow[|\omega|\to\infty]{} \frac{1}{\omega}$$

Angle-resolved photoemission spectroscopy (ARPES)

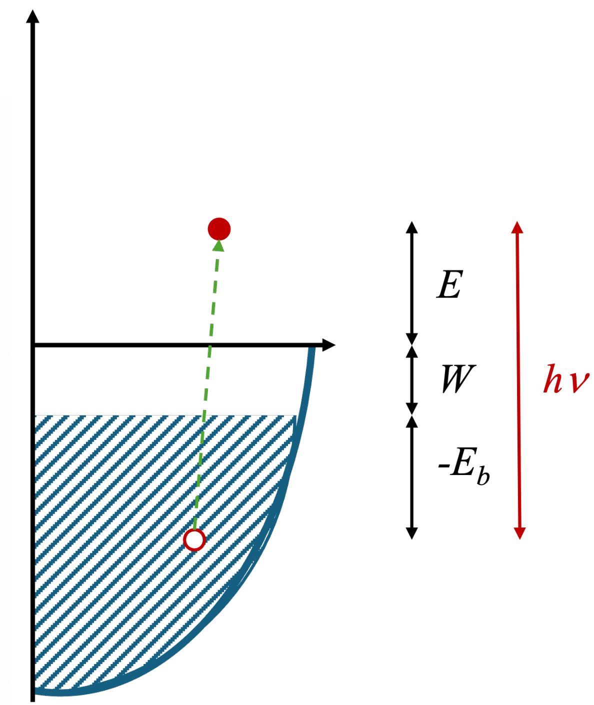
ARPES experiment



We need:

binding energy - E_b

initial momentum - k^i



$$E_b = E - h\nu + W$$

$$k^i_{\parallel} = k^f_{\parallel} = \sqrt{2mE/\hbar^2}\,\sin\theta$$

$$k^i_{\perp} = k^f_{\perp} - G = \sqrt{2mE/\hbar^2}\,\cos\theta - G$$

Função trabalho

Perda na superfície

Angle-resolved photoemission spectroscopy (ARPES)

$$H_I = -\int d^3x\, \vec{j}(x) \cdot \vec{A}(x)$$

$$\langle \zeta, \mathbf{k}+\mathbf{q}| -\vec{j}\cdot\vec{A}|\lambda, \mathbf{q}\rangle \sim \Lambda(\mathbf{q}, \hat{e}_\lambda)\langle\zeta|c_{\mathbf{k}\sigma}|\lambda\rangle$$

Aproximação súbita (“sudden”): Dependência de Λ com momento e energia pode ser ignorada.

Distrib. Fermi-Dirac

$$I_{ARPES}(\mathbf{k}, \omega) \propto f(-\omega)A(\mathbf{k}, -\omega)$$

Parte imaginária da função de Green $[B(\mathbf{k},\mu-\omega)]$

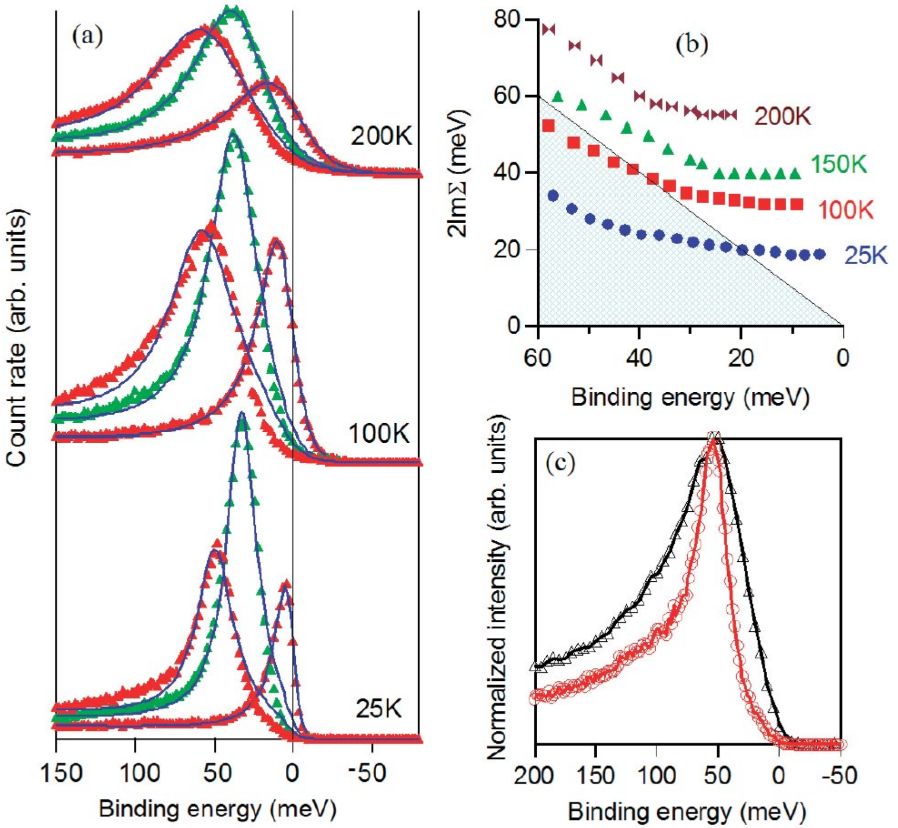


FIG. 3 (color). (a) EDCs (triangles) and Lorentzian fits (blue lines) at different temperatures (offset for clarity) for three emission angles each. (b) Summary of EDC fitting results showing full-width $2\,\mathrm{Im}\Sigma$ versus peak position. The shaded region indicates where peak full widths are sharper than their energy, which should be considered quasiparticle-like. (c) Raw EDCs from the laser (red circles) and 52 eV synchrotron source (black triangles) measured at the same **k** value.

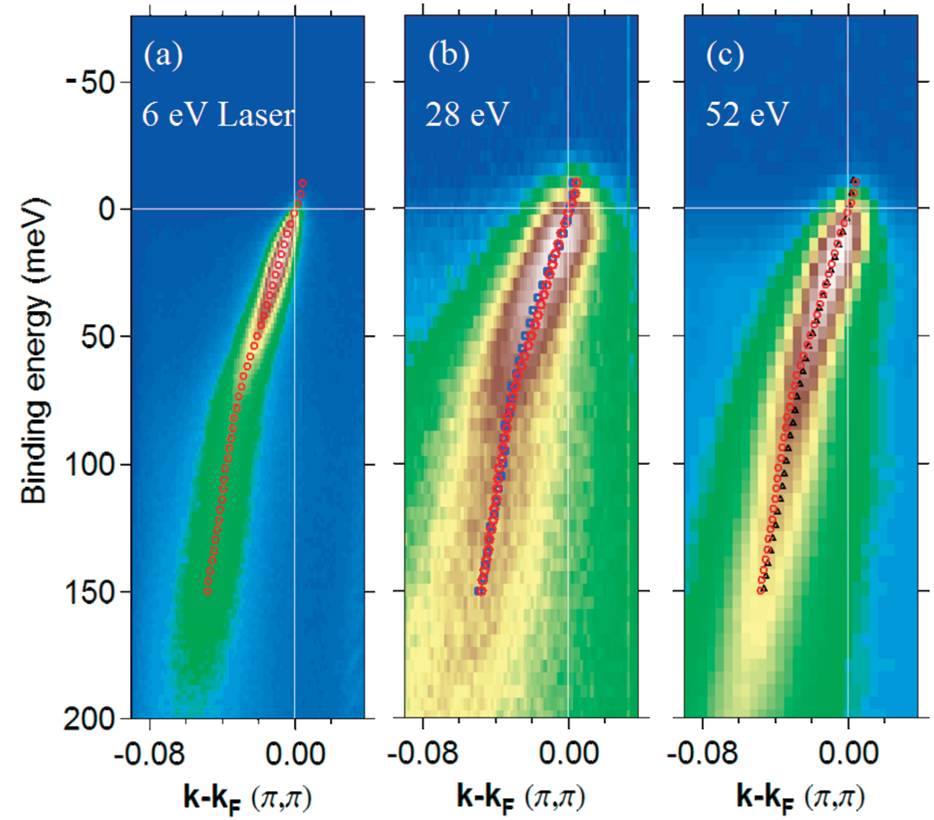


FIG. 1 (color). Comparison of ARPES along the node in near-optimally doped Bi2212 using (a) 6 eV laser photons at $T = 25$ K, (b) 28 eV photons at $T = 26$ K, and (c) 52 eV photons at $T = 16$ K. The images are scaled identically in E and **k**, and all three contain MDC derived dispersion for the laser data (red circles). Additionally, the dispersions for the data of panels (b) and (c) are shown as blue squares and black triangles, respectively.

Laser Based Angle-Resolved Photoemission, the Sudden Approximation, and Quasiparticle-Like Spectral Peaks in Bi2Sr2CaCu2O8, J. D. Koralek *et al.*, PRL **96,** 017005 (2006)

Cones de Dirac no grafeno

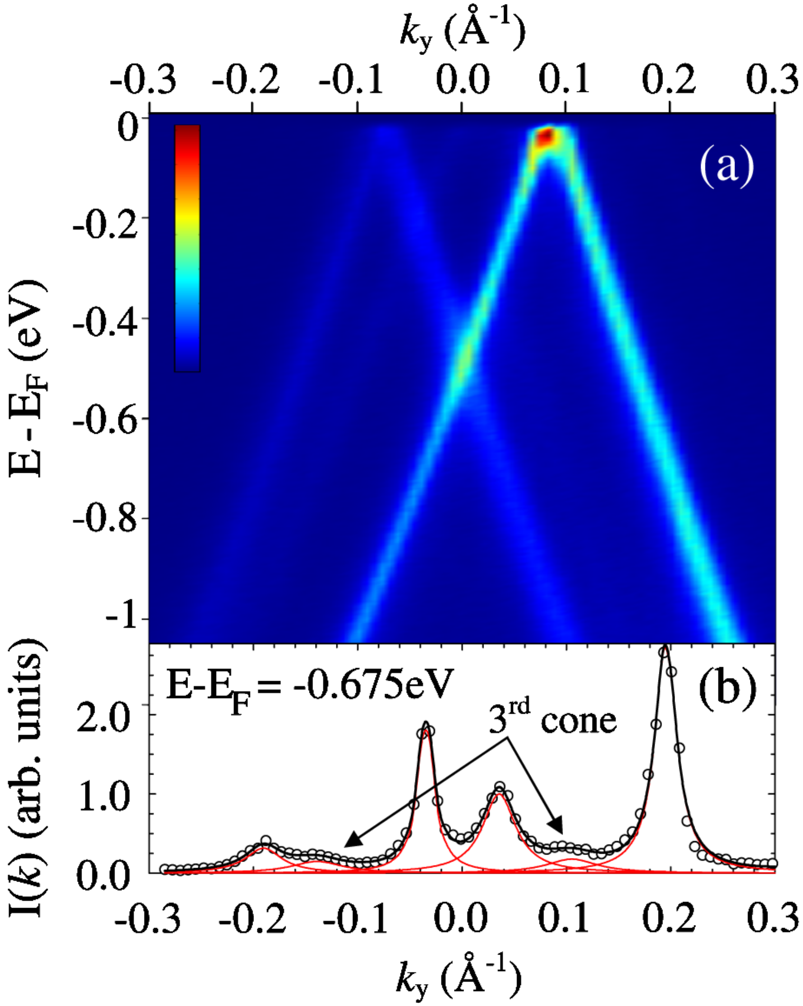
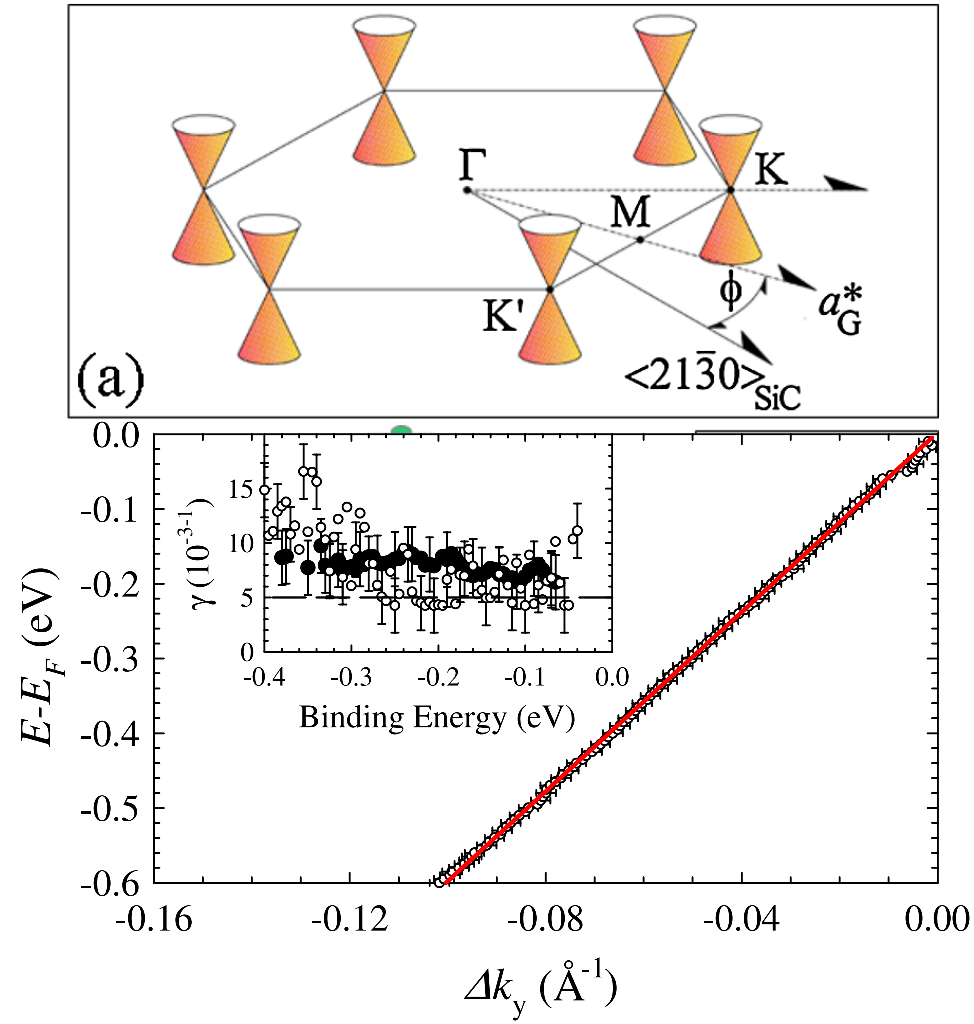


FIG. 2 (color online). (a) ARPES measured band structure of an 11-layer C-face graphene film grown on the 6*H* SiC. The ARPES resolution was set at 7 meV at $\hbar\omega = 30$ eV. The sample temperature is 6 K. The scan in k_y is perpendicular to the SiC $\langle 10\bar{1}0\rangle_{SiC}$ direction at the K point (see Fig. 1). Two linear Dirac cones are visible. (b) A MDC at $BE = E_F - 0.675$ eV shows a third faint cone. Heavy solid line is a fit to the sum of six Lorentzians (thin solid lines).



M. Sprinkle *et al*., Phys. Rev. Lett. **103**, 226803 (2009)