共鳴物理の完全WKB法による非摂動解析

Non-perturbative analysis of resonance physics by exact WKB method

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- OM and S. Ogawa, [PTEP [arXiv:2503.18741 [hep-th]]].
- OM and S. Ogawa, [arXiv:2505.02301 [hep-th]].
- OM and S. Ogawa, [arXiv:2508.09211 [quant-ph]].

(Collaboration with nuclear physicist)

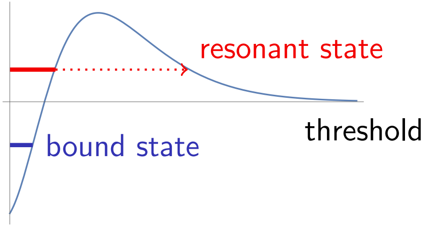
Quantum mechanics from phys or math

- Quantum mechanics (QM) is a well-established framework
  1. Physicist:
     From Schrödinger equation (diff eq), compute physical phenomena.
  2. Mathematician:
     Construct infinite-dim Hilbert space with unbounded operators.
- Works well for harmonic oscillator, ... (stable potentials)
- Also interesting in quasi-stationary potentials with developments of non-perturbative approaches
- Related to
  - scattering theory (how about hep?),
  - nuclear physics,
  - open system,
  - non-Hermitian QM,

  large gap between phys and math

Introduction to “Resonance”

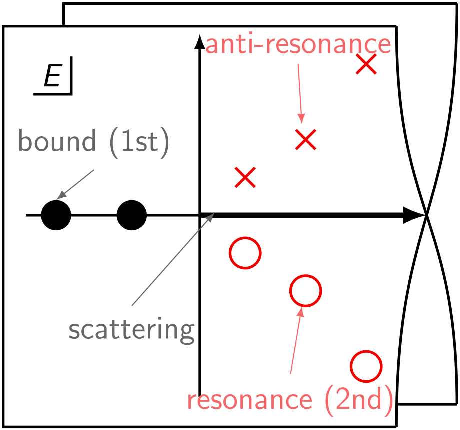
- (Usual) Quasi-stationary state in quantum system
  - There are some local minima (vacua); one decays to an other.
  - After decaying, finally stable ground state.
  - Eventually bound state beyond perturbation theory.
- Unstable state after decay: Resonant state



  - Simply say, plane wave in asymptotic region
    - ⋆ But, discrete and complex: $k = k_R - ik_I \in \mathbb{C}$.

Distribution of each state

- Riemann surface of complex E-plane



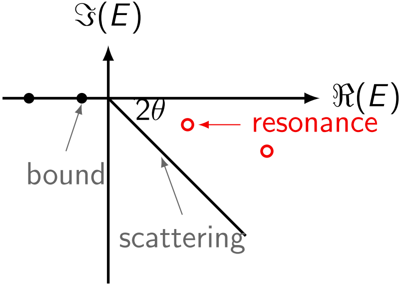
- Complex energy $E = E_r - i\frac{\Gamma}{2}$ in the 4th quadrant (Resonant energy E_r, decay width Γ)

Subtleties of resonance physics

- Resonance appears quite universally!
  - Traditional viewpoint: pole of S-matrix
- Some puzzling points:
  - Non-normalizable (divergence of norm)
    - ⋆ $e^{ikr} = e^{ik_R r + k_I r} \to \infty$
  - Completeness?
    - ⋆ Spectral theory $\overset{?}{\to} \sum_{\text{bound}} |\psi_B\rangle\langle\psi_B| + \int_{\text{scattering}} |\psi_S\rangle\langle\psi_S| = 1$
  - What is the wave function itself?
    - ⋆ Complex probability; what is expectation value?
    - ⋆ Transition cross-section?
- Some regularization schemes in phenomenological senses
  - Zel'dovich regularization, complex scaling method, rigged Hilbert space, etc.
  - No transparent relation has been found.

Prescription of complex scaling

- Complex scaling method
  Radial direction $r \to re^{i\theta}$



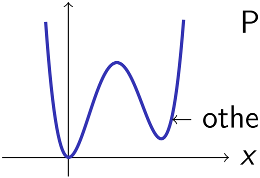
- Extended Hilbert space with resonance and θ
- Normalizable resonant wave function $\psi_R \sim$ "bound"
- $\sum_B |\psi_B\rangle\langle\psi_B| + \sum_{R_\theta} |\psi_{R_\theta}\rangle\langle\tilde{\psi}_{R_\theta}| + \int_{S_\theta} |\psi_{S_\theta}\rangle\langle\tilde{\psi}_{S_\theta}| = 1$

[See Myo–Kikuchi–Masui–Katō '14]

- Works well owing to sophisticated mathematical background [Aguilar—Balslev—Combes (ABC) theorem AC '71, BC '71]
- Physical meaning??? What is observed???

Resurgence approach to quasi-stationary states

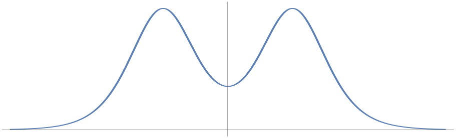
- E.g., for double well potential, perturbation theory suffers from



Perturbative vac decays w/ decay rate Γ
$\rightarrow$Resurgent asymptotic series

$\leftarrow$ other (false) vacuum

- Complex energy of resonance: $E = E_r - i\frac{\Gamma}{2}$
  (Resonant energy E_r, decay width Γ)



E.g., $V(x) = \frac{U_0}{\cosh^2 \beta(x-a)} + \frac{U_0}{\cosh^2 \beta(x+a)}$

- Can resurgence theory overcome difficulties as non-perturbative formulation of QM?
- If so, *essence in "$\forall$QM" = analyticity in resurgence*
  - Quite transparent and precise!!!

More issue: inverted Rosen–Morse potential

- Potential giving resonance

$$V(x) = \frac{U_0}{\cosh^2 \beta(x-a)} + \frac{U_0}{\cosh^2 \beta(x+a)}$$

$$\downarrow$$

$$V(x) = U_0/\cosh^2 \beta x$$

- Exact solution of Schrödinger equation is given by

$$\psi(x) = (1-\xi^2)^{-\frac{ik}{2\beta}} F\left(-\frac{ik}{\beta} - s, -\frac{ik}{\beta} + s + 1, -\frac{ik}{\beta} + 1, \frac{1-\xi}{2}\right)$$

F: Gauss hypergeometric function, $\xi = \tanh \beta x$, $k = \sqrt{2mE}/\hbar$,

$s = \frac{1}{2}(-1 + \sqrt{1 - 8mU_0/\beta^2\hbar^2})$

- Resonant energy

$$E_n^R = \frac{\hbar^2\beta^2}{8m}\left[\sqrt{\frac{8mU_0}{\beta^2\hbar^2} - 1} - i(2n+1)\right]^2$$

- Barrier resonance: localized state at potential bump (?)
  - Not intuitively clear why this is happening.

WKB ansatz

- Consider a Schrödinger equation

$$\left(-\frac{d^2}{dx^2} + \hbar^{-2} Q(x)\right)\psi = 0, \qquad Q(x) = 2[V(x) - E]$$

- Introduce WKB ansatz as a formal power series

$$\psi(x,\hbar) = e^{\int^x S(x',\hbar)dx'}, S(x,\hbar) = \frac{1}{\hbar} S_{-1}(x) + S_0(x) + \hbar S_1(x) + \dots,$$

  and substitute this into the equation; we have a recursive equation of S_i

- We have two solutions because of the leading-order equation

$$S_{-1}^2 = Q \qquad \Rightarrow \qquad S_{-1} = S_{-1}^{\pm} \equiv \pm\sqrt{Q}.$$

  Solutions are $\psi^{\pm} = e^{\int S^{\pm}} \sim e^{\pm \frac{1}{\hbar}\int \sqrt{Q}}$.

Borel resummation

- Borel resummation: summing divergent asymptotic series

$$f(\lambda) \sim \sum_{k=0}^{\infty} f_k \lambda^{k+1} \qquad \text{with } f_k \sim a^k k! \text{ as } k \to \infty$$

$\Downarrow$ Borel transform

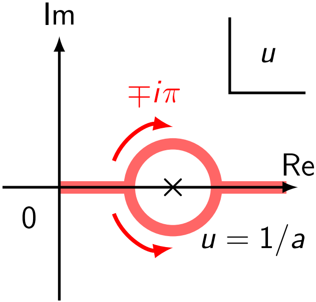
$$B(u) \equiv \sum_{k=0}^{\infty} \frac{f_k}{k!} u^k = \frac{1}{1-au} \qquad \text{(Pole singularity at } u = 1/a\text{)}.$$

- The Borel sum is given by

$$f(\lambda) \equiv \int_0^{\infty} du\, B(u) e^{-u/\lambda}.$$

- $a < 0$ (alternating series) $\to$ convergent
- $a > 0 \to$ ill-defined due to the pole

  $\Rightarrow$ Imaginary ambiguity $\sim \pm e^{-1/(a\lambda)}$

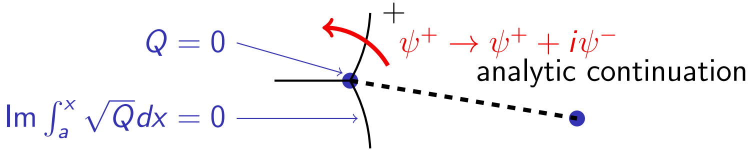


Stokes phenomena, Stokes geometry

- WKB ansatz is also asymptotic series; where is it Borel summable?
- Integral contour includes $\mp \int^x dx' \sqrt{Q}$ for $\psi^\pm$

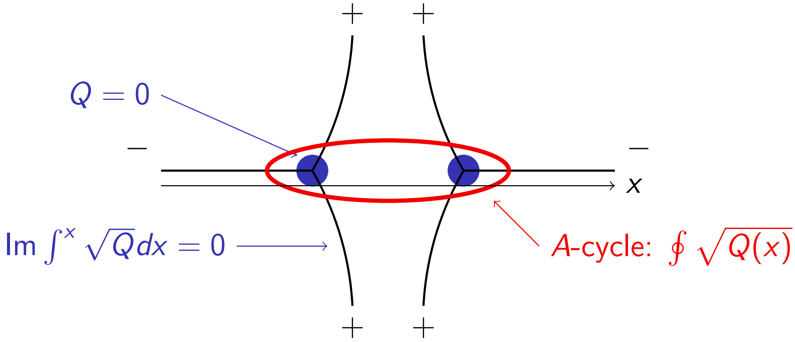
$$\text{Stokes curve}: \left\{ x \middle| \mathrm{Im} \int_a^x dx' \sqrt{Q} = 0, \text{where } Q(x=a) = 0 \right\}$$

  - a: turning point.
  - Not on Stokes curve, Borel summable (analytically continuable).
  - Across a Stokes curve, solution suddenly changes.
  - $\psi^\pm$ is dominant with $\mathrm{Re} \int_a^x dx' \sqrt{Q} \gtrless 0$.



Quantization condition from normalizability

- (Usual) QM: normalizable from $x \to -\infty$ to $x \to \infty$
  - E.g., Harmonic oscillator

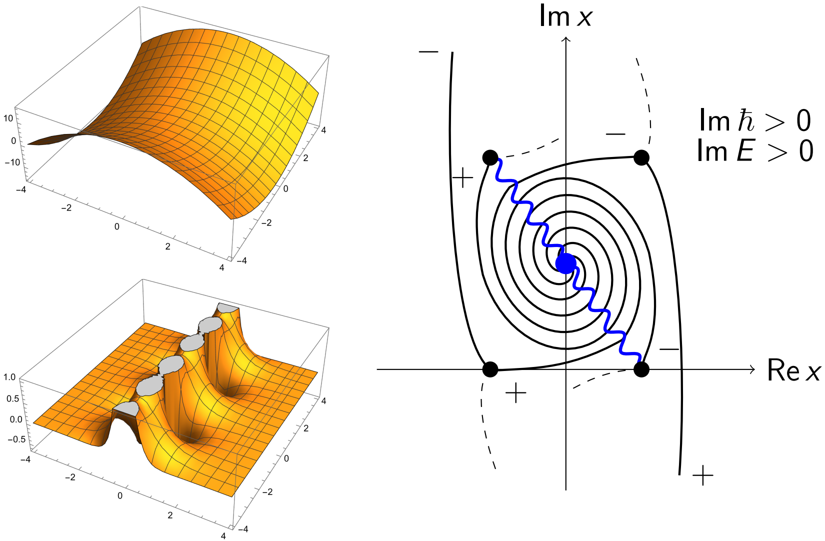


  - $\psi_{\text{final}} = (\text{analytic continuation, Stokes pheno}) \times \psi_{\text{initial}}$
  - Non-normalizable solution vanishes: $\psi^{-}_{\text{initial}} \not\to \psi^{+}_{\text{finial}}$

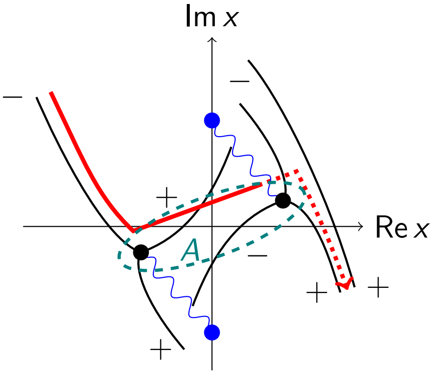
$$1 + A = 1 + e^{\hbar^{-1} \oint \sqrt{Q}} = 0 \qquad \Rightarrow \qquad E = \hbar \left(n + \frac{1}{2} \right)$$

How to see resonant state from exact WKB

- Resonant state: quasi-stable in complex region
  - $V = -x^2$ vs $V = 1/\cosh^2 x$



Quantization path and leading order estimate



- Normalizable path:
- Barrier resonant energy from exact WKB analysis (leading)
  - A-cycle

$$\int_{-\cosh^{-1}\sqrt{\frac{1}{E}}}^{\cosh^{-1}\sqrt{\frac{1}{E}}} \sqrt{2\left(\frac{1}{\cosh^2 x} - E\right)} = \sqrt{2}\pi(1+\sqrt{E})$$

quantization condition: $1 - A = 0$ $\qquad E = \left(1 - \frac{in}{\sqrt{2}}\right)^2$

Backup: Rigorous estimate = exact solution

- $A = 1$:

$$\left[\frac{F\left(-\frac{ik}{\beta} - s, -\frac{ik}{\beta} + s + 1, -\frac{ik}{\beta} + 1, \frac{1-|\xi|}{2}\right)}{F\left(-\frac{ik}{\beta} - s, -\frac{ik}{\beta} + s + 1, -\frac{ik}{\beta} + 1, \frac{1+|\xi|}{2}\right)} \right]^2 = 1,$$

where $|\xi| = \tanh(\beta \cosh^{-1} \sqrt{U_0/E})$.

- Here, we use the formula of the hypergeometric function as

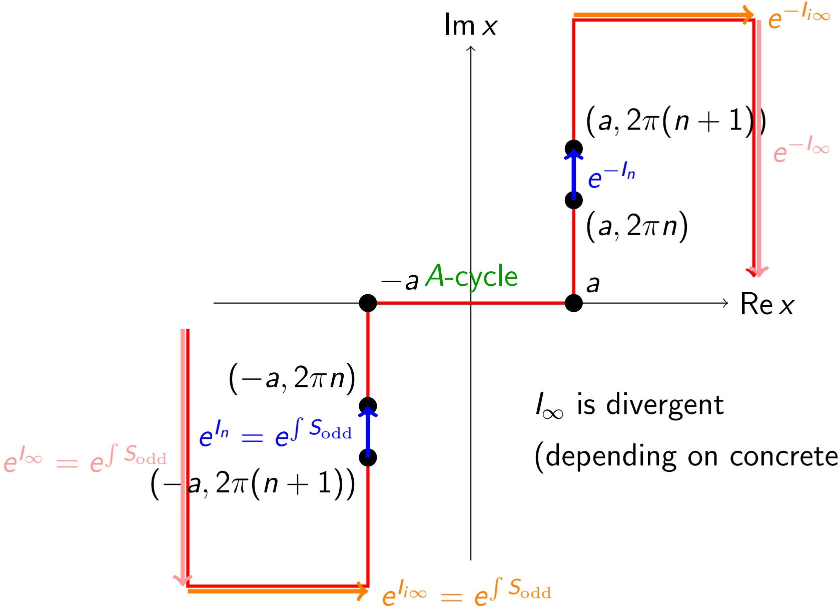
$$F\left(-\frac{ik}{\beta} - s, -\frac{ik}{\beta} + s + 1, -\frac{ik}{\beta} + 1, \frac{1 \pm |\xi|}{2}\right)$$
$$= \mathfrak{A} F\left(-\frac{ik}{2\beta} - \frac{s}{2}, -\frac{ik}{2\beta} + \frac{s+1}{2}, \frac{1}{2}, |\xi|^2\right) \mp \mathfrak{B} F\left(-\frac{ik}{2\beta} - \frac{s-1}{2}, -\frac{ik}{2\beta} + \frac{s}{2} + 1, \frac{3}{2}, |\xi|^2\right),$$

where

$$\mathfrak{A} = \frac{\Gamma\left(-\frac{ik}{\beta} + 1\right)\Gamma\left(\frac{1}{2}\right)}{\Gamma\left(-\frac{ik}{2\beta} - \frac{s-1}{2}\right)\Gamma\left(-\frac{ik}{2\beta} + \frac{s}{2} + 1\right)}, \quad \mathfrak{B} = \frac{\Gamma\left(-\frac{ik}{\beta} + 1\right)\Gamma\left(-\frac{1}{2}\right)}{\Gamma\left(-\frac{ik}{2\beta} - \frac{s}{2}\right)\Gamma\left(-\frac{ik}{2\beta} + \frac{s+1}{2}\right)}.$$

- $\mathfrak{A} = 0$, $\mathfrak{B} = 0$: odd/even number of nodes

What is problematic in naive path?



I_∞ is divergent

(depending on concrete path)

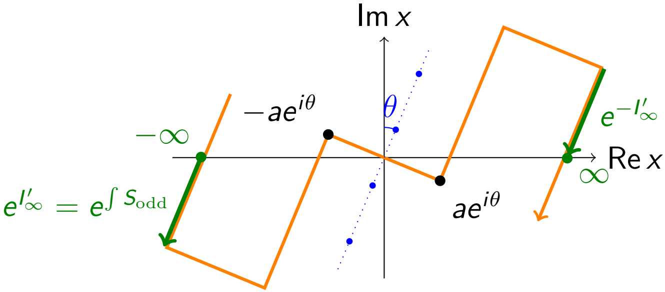
Regularization schemes

- Zel'dovich transformation: $S = e^{-\epsilon x^2}$ ['61, Berggren '68]

$$H\psi = E\psi \to H_S\psi_S = E\psi_S, \qquad \psi_S \equiv S\psi,\ H_S \equiv SHS^{-1}.$$

  - We find $H_S = H - \frac{\hbar^2\epsilon}{m}\left(\frac{d}{dx}x + x\frac{d}{dx}\right)$
  - Now, $e^{I_\infty} \to e^{\int(S_{\mathrm{odd}} - 2\epsilon x)}$ becomes finite.

- Complex scaling by θ rotates the Stokes graph as



  - Now, $e^{I_\infty} \to e^{I'_\infty}$ becomes finite.

Backup: Rigged Hilbert space

- We introduce

$$\mathcal{D}_\varepsilon^{\mathrm{R}} = \{x \in \mathbb{C} | \varepsilon > 0, \lim_{r\to\pm\infty} |x - r| < \varepsilon\}$$

  - $\mathcal{D}_\varepsilon^{\mathrm{R}}$ is the most crucial singular region.
- if $x \in \mathbb{C} \setminus \mathcal{D}_\varepsilon^{\mathrm{R}}$, the Hilbert space is well-defined, $\mathcal{H}_\varepsilon$
  - Def. of norm and inner product is quite different!
  - Resonance is included as "bound" state.
- (Operator algebra) Set of operators $\{A_i\}$ where A_i is defined on $D(A_i) \subset \mathcal{H}_\varepsilon$; then let us introduce the dense subspace

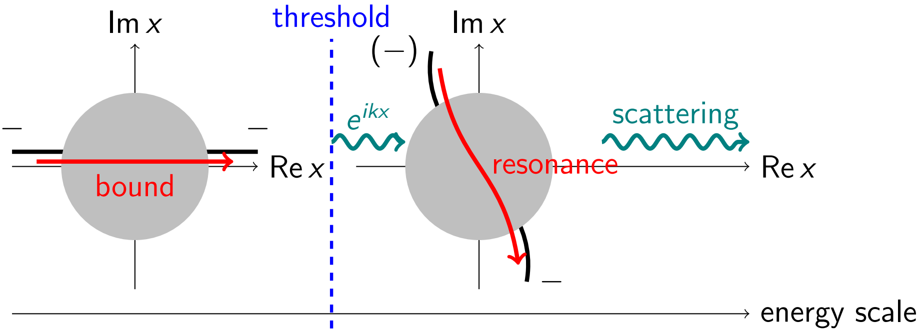
$$\Phi \equiv \cap_i D(A_i) \subseteq \mathcal{H}_\varepsilon.$$

- The range is defined by the limit as $\varepsilon \to 0$, say, $\Phi^\times$
- We find the Gelfand multiplet

$$\Phi \subseteq \mathcal{H}_\varepsilon \subset \Phi^\times,$$

and $(\mathcal{H}_\varepsilon, \Phi)$ is the rigged （艤装） Hilbert space.

Backup: Scattering theory



- Below threshold: Bound states
- Above threshold: Resonance & continuum spectrum
  - Read transmission/reflection coefficient from monodromy&analytic continuation

Summary

- We develop a unified framework for analyzing quantum mechanical resonances using exact WKB method
  - Serving as a non-perturbative formulation of QM.
  - Incorporating the Zel'dovich regularization, the complex scaling method, and the rigged Hilbert space.
  - Demonstrated by examining the inverted Rosen–Morse potential.

- Future works:
  - Realistic potential (E.g., $1/\cosh^2(x-a) + 1/\cosh^2(x+a)$)
  - Numerical approach (Quantization cond $\to$ Estimate cycles)
  - Higher dim???

Backup: Resonant state and S-matrix

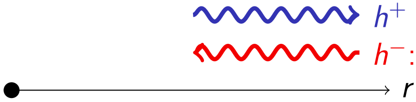
- Let φ_l be regular solution of radial Schrödinger equation
  - φ_l is subject to

$$\varphi_l(k,r) \overset{r\to 0}{\to} j_l(kr) \qquad j_l\text{: Spherical Bessel function}$$

with angular momentum l.

- At $r \to \infty$, linear combination of Hankel functions h_l:

$$\varphi_l(k,r) \to \mathcal{F}_l(k) h_l^-(kr) - \mathcal{F}_l^*(k) h_l^+(kr) \quad \mathcal{F}_l\text{: Jost function}$$



- S-matrix is written in terms of Jost function

$$S_l(k) = \frac{\mathcal{F}_l^*(k)}{\mathcal{F}_l(k)} \to \infty \qquad \text{pole singularity}$$

- Some kind of scattering of multiple particles

Backup: What is problematic in naive path?

- Total quantization condition is given by

$$
\begin{aligned}
0 &= e^{\int_{a+i\infty}^{a+\infty} dx S_{\mathrm{odd}}} \left[\prod_{n=0}^{\infty} e^{\int_{a+2\pi i n/\beta}^{a+2\pi i(n+1)/\beta} dx S_{\mathrm{odd}}} \right] (1-A) \\
&\quad \times \left[\prod_{n=0}^{\infty} e^{\int_{-a-2\pi i(n+1)/\beta}^{-a-2\pi i n/\beta} dx S_{\mathrm{odd}}} \right] e^{\int_{-a-\infty}^{-a-i\infty} dx S_{\mathrm{odd}}} \\
&\overset{?}{=} e^{\int_{a}^{-a} dx S_{\mathrm{odd}}} (1-A),
\end{aligned}
$$

  - $S_{\mathrm{odd}} = \frac{1}{\hbar} S_{-1} + \hbar S_1 + \dots$

- Naively, any factor at infinity appears to cancel against each other.