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Introduction to PT-quantum mechanics, deformations of integrable models

Andreas Fring

La Parte y el Todo, 8/1/19 - 11/1/19, Afunalhue, Chile

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based on: A. Fring,
PT-Symmetric Deformations of Nonlinear Integrable Systems,
ch. 9 in "PT Symmetry: In Quantum and Classical Physics",
World Scientific Publishing Co., Singapore, 2018

Outline

1. Introduction to PT-quantum mechanics
2. PT-deformed quantum spin chains
3. PT-deformed Calogero-Moser-Sutherland models
4. PT-deformed KdV/Ito systems
5. Conclusions

Why is Hermiticity a good property to have?

- Hermiticity ensures real energies
  Schrödinger equation $H\psi = E\psi$

$$\left.\begin{array}{r}\langle\psi| H |\psi\rangle = E \langle\psi|\psi\rangle \\ \langle\psi| H^\dagger |\psi\rangle = E^* \langle\psi|\psi\rangle\end{array}\right\} \Rightarrow 0 = (E - E^*) \langle\psi|\psi\rangle$$

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- Hermiticity ensures conservation of probability densities

$$|\psi(t)\rangle = e^{-iHt} |\psi(0)\rangle$$

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- Thus when $H \neq H^\dagger$ one usually thinks of dissipation.
- However, these systems are usually open and do not possess a self-consistent description.

Hermiticity is not essential

- Operators $\mathcal{O}$ which are left invariant under an antilinear involution $\mathcal{I}$ and whose eigenfunctions Φ also respect this symmetry,

$$[\mathcal{O},\mathcal{I}]=0 \quad \wedge \quad \mathcal{I}\Phi=\Phi$$

  have a real eigenvalue spectrum.
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  [F. Scholtz, H. Geyer, F. Hahne, *Ann. Phys.* 213 (1992) 74,
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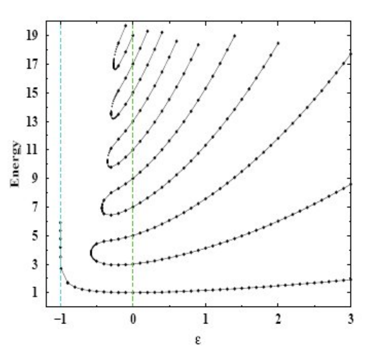
In particular this also holds for $\mathcal{O}$ being non-Hermitian.

"Recent" classical example

$$\mathcal{H} = \frac{1}{2}p^2 + x^2(ix)^\varepsilon \qquad \text{for } \varepsilon \geq 0$$



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A more classical example

- Lattice Reggeon field theory:

$$\mathcal{H} = \sum_{\vec{\imath}} \left[\Delta a^{\dagger}_{\vec{\imath}} a_{\vec{\imath}} + i g a^{\dagger}_{\vec{\imath}} (a_{\vec{\imath}} + a^{\dagger}_{\vec{\imath}}) a_{\vec{\imath}} + \tilde{g} \sum_{\vec{\jmath}} (a^{\dagger}_{\vec{\imath}+\vec{\jmath}} - a^{\dagger}_{\vec{\imath}})(a_{\vec{\imath}+\vec{\jmath}} - a_{\vec{\imath}}) \right]$$

- $a^{\dagger}_{\vec{\imath}}, a_{\vec{\imath}}$ are creation and annihilation operators, $\Delta, g, \tilde{g} \in \mathbb{R}$

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- for one site this is almost ix^3

$$\begin{aligned} \mathcal{H} &= \Delta a^{\dagger} a + iga^{\dagger} \left(a + a^{\dagger} \right) a \\ &= \frac{1}{2} \left(\hat{p}^2 + \hat{x}^2 - 1 \right) + i \frac{g}{\sqrt{2}} (\hat{x}^3 + \hat{p}^2 \hat{x} - 2\hat{x} + i\hat{p}) \end{aligned}$$

with $a = (\omega \hat{x} + i\hat{p})/\sqrt{2\omega}$, $a^{\dagger} = (\omega \hat{x} - i\hat{p})/\sqrt{2\omega}$
[P. Assis and A.F., J. Phys. A41 (2008) 244001]

- quantum spin chains: (c=-22/5 CFT)

$$\mathcal{H} = \frac{1}{2}\sum_{i=1}^{N} \sigma_i^x + \lambda\sigma_i^z\sigma_{i+1}^z + ih\sigma_i^z \qquad \lambda, h \in \mathbb{R}$$

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- Toda field theory:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{m^2}{\beta^2}\sum_{k=\mathbf{a}}^{\ell} n_k \exp(\beta\alpha_k \cdot \phi)$$

$a = 1 \equiv$ conformal field theory (Lie algebras)

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- strings on $AdS_5 \times S^5$-background
[A. Das, A. Melikyan, V. Rivelles, *JHEP* 09 (2007) 104]

- deformed space-time structure
  - deformed Heisenberg canonical commutation relations

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$$[X, P] = i\hbar q^{g(N)}(\alpha\delta + \beta\gamma) + \frac{i\hbar(q^2 - 1)}{\alpha\delta + \beta\gamma}\left(\delta\gamma X^2 + \alpha\beta\, P^2 + i\alpha\delta XP - i\beta\gamma PX\right)$$

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- limit: $\beta \to \alpha$, $\delta \to \gamma$, $g(N) \to 0$, $q \to e^{2\tau\gamma^2}$, $\gamma \to 0$

$$[X, P] = i\hbar\left(1 + \tau P^2\right)$$

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- representation: $X = (1 + \tau p_0^{2})x_0$, $P = p_0$, $[x_0, p_0] = i\hbar$

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- example harmonic oscillator:

$$\begin{aligned} H_{ho} &= \frac{P^2}{2m} + \frac{m\omega^2}{2} X^2, \\ &= \frac{p_0^2}{2m} + \frac{m\omega^2}{2}(1+\tau p_0^2)x_0(1+\tau p_0^2)x_0, \\ &= \frac{p_0^2}{2m} + \frac{m\omega^2}{2}\left[(1+\tau p_0^2)^2 x_0^2 + 2i\hbar\tau p_0(1+\tau p_0^2)x_0\right]. \end{aligned}$$

[B. Bagchi and A.F., Phys. Lett. A373 (2009) 4307]

- "dynamical" noncommutative space-time
  Replace

$$[x_0, y_0] = i\theta, \qquad [x_0, p_{x_0}] = i\hbar, \qquad [y_0, p_{y_0}] = i\hbar,$$
$$[p_{x_0}, p_{y_0}] = 0, \qquad [x_0, p_{y_0}] = 0, \qquad [y_0, p_{x_0}] = 0,$$

with $\theta \in \mathbb{R}$, by

$$[X, Y] = i\theta(1 + \tau Y^2) \qquad [X, P_x] = i\hbar(1 + \tau Y^2)$$
$$[Y, P_y] = i\hbar(1 + \tau Y^2) \qquad [X, P_y] = 2i\tau Y(\theta P_y + \hbar X)$$
$$[P_x, P_y] = 0 \qquad [Y, P_x] = 0$$

$\Rightarrow$ Non-Hermitian representation

$$X = (1 + \tau y_0^2)x_0 \quad Y = y_0 \quad P_x = p_{x_0} \quad P_y = (1 + \tau y_0^2)p_{y_0}$$

$$X^\dagger = X + 2i\tau\theta Y \quad Y^\dagger = Y \quad P_y^\dagger = P_y - 2i\tau\hbar Y \quad P_x^\dagger = P_x$$

[A.F., L. Gouba, F. Scholtz, J.Phys. A43 (2010) 345401]
[A.F., L. Gouba, B. Bagchi, J.Phys. A43 (2010) 425202]

How to explain the reality of the spectrum?

1. Pseudo/Quasi-Hermiticity
2. Supersymmetry (Darboux transformations)
3. $\mathcal{PT}$-symmetry

Pseudo/Quasi-Hermiticity

$$h = \eta H \eta^{-1} = h^\dagger = (\eta^{-1})^\dagger H^\dagger \eta^\dagger \quad \Leftrightarrow \quad H^\dagger \rho = \rho H \qquad \rho = \eta^\dagger \eta \quad (*)$$

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positivity of ρ	✓	✓	×
ρ Hermitian	✓	✓	✓
ρ invertible	✓	×	✓
terminology	(*)	quasi-Herm.	pseudo-Herm.
spectrum of H	real	could be real	real
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- pseudo-Hermiticity: [M. Froissart, Nuovo Cim. 14 (1959) 197] [A. Mostafazadeh, J. Math. Phys. 43 (2002) 2814]

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Decompose Hamiltonian $\mathcal{H}$ as:

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  $\Rightarrow$isospectral Hamiltonians

$$H_\pm^m = -\Delta + V_\pm^m + E_m \quad H_\pm^m \Phi_n^\pm = E_n \Phi_n^\pm \quad \text{for } n > m$$

Unbroken $\mathcal{PT}$-symmetry guarantees real eigenvalues (QM)

- $\mathcal{PT}$-symmetry: $\quad \mathcal{PT}: \quad x \to -x \quad p \to p \quad i \to -i$
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  $\varepsilon\Phi = \mathcal{H}\Phi = \mathcal{HPT}\Phi$

Unbroken $\mathcal{PT}$-symmetry guarantees real eigenvalues (QM)

- $\mathcal{PT}$-symmetry: $\mathcal{PT}: \quad x \to -x \quad p \to p \quad i \to -i$
  $(\mathcal{P}: x \to -x, p \to -p; \ \mathcal{T}: x \to x, p \to -p, i \to -i)$
- $\mathcal{PT}$ is an anti-linear operator:

$$\mathcal{PT}(\lambda\Phi + \mu\Psi) = \lambda^*\mathcal{PT}\Phi + \mu^*\mathcal{PT}\Psi \qquad \lambda, \mu \in \mathbb{C}$$

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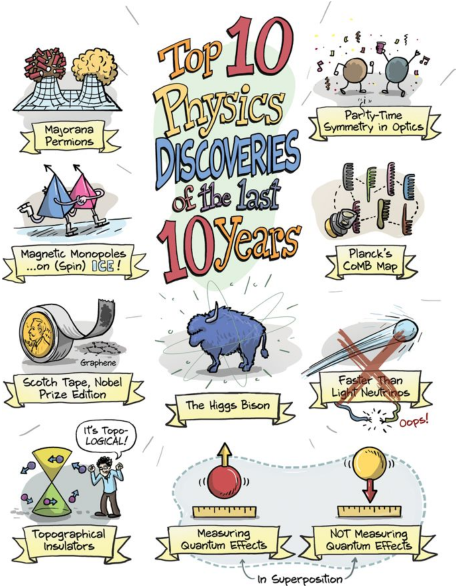
PT-symmetry is only an example of an antilinear involution

Nature Physics volume 11, page 799 (2015)



How to formulate a quantum mechanical framework?

1. orthogonality
2. observables
3. uniqueness
4. technicalities (new metric etc)

Orthogonality

- Take *h* to be a Hermitian and diagonalisable Hamiltonian:

$$\langle \phi_n | h\phi_m \rangle = \langle h\phi_n | \phi_m \rangle$$

$$\begin{aligned} |h\phi_m\rangle &= \varepsilon_m \quad |\phi_m\rangle \\ \langle h\phi_n| &= \varepsilon_n^* \langle \phi_n| \end{aligned}$$

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- Take H to be a non-Hermitian Hamiltonian:

$$H |\Phi_n\rangle = \varepsilon_n |\Phi_n\rangle$$

- reality and orthogonality no longer guaranteed. Define

$$\langle \Phi_n | \Phi_m \rangle_\eta := \langle \Phi_n | \eta^2 \Phi_m \rangle$$

- when $\langle \Phi_n | H\Phi_m \rangle_\eta = \langle H\Phi_n | \Phi_m \rangle_\eta \Rightarrow \langle \Phi_n | \Phi_m \rangle_\eta = \delta_{n,m}$

H is Hermitian with respect to new metric

- Assume pseudo-Hermiticity:

$$h = \eta H \eta^{-1} = h^\dagger = (\eta^{-1})^\dagger H^\dagger \eta^\dagger \quad \Leftrightarrow \quad H^\dagger \eta^\dagger \eta = \eta^\dagger \eta H$$

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$$= \langle H\Psi | \Phi \rangle_\eta$$

$\Rightarrow$ Eigenvalues of H are real, eigenstates are orthogonal

Observables

- Observables are Hermitian with respect to the new metric

$$\langle \Phi_n | \mathcal{O} \Phi_m \rangle_\eta = \langle \mathcal{O} \Phi_n | \Phi_m \rangle_\eta$$

$$\mathcal{O} = \eta^{-1} o \eta \qquad \Leftrightarrow \qquad \mathcal{O}^\dagger = \rho \mathcal{O} \rho^{-1}$$

- o is an observable in the Hermitian system
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- Ambiguities:
  Given H the metric is not uniquely defined for unknown h.
  $\Rightarrow$ Given only H the observables are not uniquely defined.
  This is different in the Hermitian case.
  - Fixing one more observable achieves uniqueness.
    [Scholtz, Geyer, Hahne, , *Ann. Phys.* 213 (1992) 74]

General technique:

- Given $H \begin{cases} \text{either} & \text{solve } \eta H \eta^{-1} = h \quad \text{for} \quad \eta \Rightarrow \rho = \eta^{\dagger}\eta \\ \text{or} & \text{solve } H^{\dagger} = \rho H \rho^{-1} \quad \text{for} \quad \rho \Rightarrow \eta = \sqrt{\rho} \end{cases}$

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Note:

- Thus, this is not re-inventing or disputing the validity of quantum mechanics.
- We only give up the restrictive requirement that Hamiltonians have to be Hermitian.

[A. Mostafazadeh, Int. J. Geom. Meth. Phys. 7 (2010) 1191]
[PT Symmetry: In Quantum and Classical Physics, World Scientific Publishing Co., Singapore, 2018]

Theoretical framework (key equations):

Is it possible to have a consistent description of time-dependent non-Hermitian Hamiltonian systems?

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Time-dependent Schrödinger eqn for $h(t) = h^\dagger(t)$, $H(t) \neq H^\dagger(t)$

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Time-dependent Dyson operator

$$\phi(t) = \eta(t)\Psi(t)$$

$\Rightarrow$ Time-dependent Dyson relation

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$$h(t) = \eta(t)H(t)\eta^{-1}(t) + i\hbar\partial_t\eta(t)\eta^{-1}(t)$$

$\Rightarrow$ Time-dependent quasi-Hermiticity relation

$$H^\dagger\rho(t) - \rho(t)H = i\hbar\partial_t\rho(t)$$

[from conjugating Dyson relation and $\rho(t) := \eta^\dagger(t)\eta(t)$)]

$H(t)$ governs unitary time-evolution:

Hermitian:

$$\phi(t) = u(t,t')\phi(t'), \qquad u(t,t') = T\exp\left[-i\int_{t'}^{t} ds h(s)\right]$$

with

$$h(t)u(t,t') = i\hbar\partial_t u(t,t'), \quad u(t,t')u(t',t'') = u(t,t''), \quad u(t,t) = \mathbb{I}$$

$$\left\langle u(t,t')\phi(t') \middle| u(t,t')\tilde{\phi}(t') \right\rangle = \left\langle \phi(t) \middle| \tilde{\phi}(t) \right\rangle$$

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Non-Hermitian:

$$\Psi(t) = U(t,t')\Psi(t'), \qquad U(t,t') = T\exp\left[-i\int_{t'}^{t} ds H(s)\right]$$

$$H(t)U(t,t') = i\hbar\partial_t U(t,t'),\ U(t,t')U(t',t'') = U(t,t''),\ U(t,t) = \mathbb{I}$$

$$\left\langle U(t,t')\Psi(t') \middle| U(t,t')\tilde{\Psi}(t') \right\rangle_\rho = \left\langle \Psi(t) \middle| \tilde{\Psi}(t) \right\rangle_\rho$$

Relation between $u(t,t')$ and $U(t,t')$:

$$U(t,t') = \eta^{-1}(t)u(t,t')\eta(t')$$

or the generalized Duhamel's formula

$$\begin{aligned} U(t,t') &= u(t,t') - \int_{t'}^{t} \frac{d}{ds}\left[U(t,s)u(s,t')\right] ds \\ &= u(t,t') - i\hbar \int_{t'}^{t} U(t,s)\left[H(s) - h(s)\right] u(s,t') ds \end{aligned}$$

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Relation between Green's functions:

$$G_h(t,t') := -iu(t,t')\theta(t-t') \quad G_H(t,t') := -iU(t,t')\theta(t-t')$$

$$G_U(t,t') = G_u(t,t') + i \int_{-\infty}^{\infty} G_U(t,s) \left[H(s) - h(s) \right] G_u(s,t') ds$$

$H(t)$ is nonobservable and not the energy operator

Observables $o(t)$ in the Hermitian system are self-adjoint.
Observables $\mathcal{O}(t)$ in the non-Hermitian $\mathcal{O}(t)$ are quasi Hermitian

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$$\langle \phi(t) \,| o(t)\phi(t) \rangle = \langle \Psi(t) \,| \rho(t)\mathcal{O}(t)\Psi(t) \rangle \ .$$

Since $H(t)$ is not quasi/pseudo Hermitian it is not an observable.
The observable energy operator is

$$\tilde{H}(t) = \eta^{-1}(t)h(t)\eta(t) = H(t) + i\hbar\eta^{-1}(t)\partial_t\eta(t).$$

Three scenarios:

1. $\partial_t \eta = 0$, $\partial_t H \neq 0$, $\partial_t h \neq 0$

   Technically reduces to time-independent case.

   [C. Figueira de Morisson Faria, A. Fring; J. of Phys. A 39 (2006) 9269]

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   - Solve full time-dependent Dyson equation $\eta(t)$
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Making sense of the broken $\mathcal{PT}$-regime:

Two-level system

$$H = -\frac{1}{2}\left[\omega\mathbb{I} + \lambda\sigma_z + i\kappa\sigma_x\right]$$

with eigensystem

$$E_\pm = -\frac{1}{2}\omega \pm \frac{1}{2}\sqrt{\lambda^2 - \kappa^2}, \qquad \varphi_\pm = \begin{pmatrix} i(-\lambda \pm \sqrt{\lambda^2 - \kappa^2}) \\ \kappa \end{pmatrix}$$

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Claim: This system has real energies for $|\lambda(t)| < |\kappa(t)|$!

Two-dimensional system with infinite dimensional Hilbert space

$$H_K = aK_1 + bK_2 + i\lambda K_3, \qquad a, b, \lambda \in \mathbb{R}$$

with Lie algebraic generators

$$K_1 = \frac{1}{2}\left(p_x^2 + x^2\right), \quad K_2 = \frac{1}{2}\left(p_y^2 + y^2\right), \quad K_3 = \frac{1}{2}(xy + p_x p_y)$$
$$K_4 = \frac{1}{2}(x p_y - y p_x)$$

$$[K_1, K_2] = 0, \qquad [K_1, K_3] = iK_4, \qquad [K_1, K_4] = -iK_3,$$
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$$\mathcal{PT}_\pm : x \to \pm x,\ y \to \mp y,\ p_x \to \mp p_x,\ p_y \to \pm p_y,\ i \to -i$$

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- H_K is quasi-Hermitian: $h_K = \eta H_K \eta^{-1}$

$$h_K = \frac{1}{2}(a+b)(K_1 + K_2) + \frac{1}{2}\sqrt{(a-b)^2 - \lambda^2}\,(K_1 - K_2)$$

with $\eta = e^{2\theta K_4}$, $\theta = \operatorname{arctanh}[\lambda/(b-a)]$

Spontaneously broken $\mathcal{PT}$-symmetry for $a = b$:

Eigenenergies:

$$E_{n,m} = E^*_{m,n} = a(1 + n + m) + i\frac{\lambda}{2}(n - m)$$

Eigenfunctions:

$$\varphi_{n,m}(x,y) = \frac{e^{-\frac{x^2}{2}-\frac{y^2}{2}}}{2^{n+m}\sqrt{n!m!\pi}}\left[\sum_{k=0}^{n}\binom{n}{k}H_k(x)H_{n-k}(y)\right] \times\left[\sum_{l=0}^{m}(-1)^l\binom{m}{l}H_l(y)H_{m-l}(x)\right]$$

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Claim: This system has real energies for $a(t), \lambda(t)$!

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$$\eta(t) = \prod_{i=1}^{4} e^{\gamma_i(t) K_i}, \qquad \gamma_i \in \mathbb{R}$$

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$$\gamma_1=\gamma_2=q_1,\quad \dot{\gamma}_3=-\lambda\cosh\gamma_4,\quad \dot{\gamma}_4=\lambda\tanh\gamma_3\sinh\gamma_4,$$

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Solution: $\gamma_4=\operatorname{arcsinh}\left(\kappa\operatorname{sech}\gamma_3\right),\;\chi(t):=\cosh\gamma_3,\;\kappa=const$
with dissipative Ermakov-Pinney equation

$$\ddot\chi-\frac{\dot\lambda}{\lambda}\dot\chi-\lambda^2\chi=\frac{\kappa^2\lambda^2}{\chi^3}$$

Lewis Riesenfeld invariants:

$$\frac{dI_{\mathcal{H}}(t)}{dt} = \partial_t I_{\mathcal{H}}(t) - i\hbar \left[I_{\mathcal{H}}(t), \mathcal{H}(t) \right] = 0, \quad \text{for} \;\; \mathcal{H} = h = h^\dagger, H \neq H^\dagger$$

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Solution to time-dependent Schrödinger equation:

$$\begin{aligned} I_{\mathcal{H}}(t) \left| \phi_{\mathcal{H}}(t) \right\rangle &= \Lambda \left| \phi_{\mathcal{H}}(t) \right\rangle, \qquad \left| \Psi_{\mathcal{H}}(t) \right\rangle = e^{i\hbar\alpha(t)} \left| \phi_{\mathcal{H}}(t) \right\rangle \\ \dot{\alpha} &= \left\langle \phi_{\mathcal{H}}(t) \right| i\hbar\partial_t - \mathcal{H}(t) \left| \phi_{\mathcal{H}}(t) \right\rangle, \qquad \dot{\Lambda} = 0 \end{aligned}$$

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Procedure:

1. Construct $I_h(t)$
2. Construct $I_H(t)$
3. Find $\eta(t)$ from similarity transformation

With Ansätze:

$$I_H(t) = \sum_{i=1}^{4} \alpha_i(t) K_i, \qquad I_h(t) = \sum_{i=1}^{4} \beta_i(t) K_i, \qquad h(t) = \sum_{i=1}^{4} b_i(t) K_i,$$

where $\alpha_i = \alpha_i^r + i\alpha_i^i \in \mathbb{C}$, $b_i, \beta_i, \alpha_i^r, \alpha_i^i \in \mathbb{R}$.

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$$\gamma_3 = \arctan\left[\frac{\tanh\left[q_2 - \int_0^t \lambda(s)ds\right]}{\sqrt{1 - q_3^2 \operatorname{sech}\left[q_2 - \int_0^t \lambda(s)ds\right]^2}}\right]$$

$$\gamma_4 = -\operatorname{arccot}\left[\frac{1}{q_3}\cosh\left[q_2 - \int_0^t \lambda(s)ds\right]\right]$$

$q_2, q_3 = const$

With γ_3 we obtain a solution to the Ermakov-Pinney equation

$$\chi(t) = \cosh \gamma_3 = \sqrt{\frac{\cosh^2 \left[q_2 - \int_0^t \lambda(s) ds \right] - q_3^2}{1 - q_3^2}}$$

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Explicit form of the Hermitian Hamiltonian:

$$h(t) = f_+(t) K_1 + f_-(t) K_2$$

with

$$f_\pm(t) = a(t) \pm \frac{q_3 \sqrt{1 - q_3^2} \lambda(t)}{1 + \cosh \left[2q_2 - 2 \int_0^t \lambda(s) ds \right] - 2q_3^2}$$

Solution for time-dependent Schrödinger equation

Solution for $\tilde{h}(t) = a(t)K_1, \quad a(t) \in \mathbb{R}$
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$$\alpha_n(t) = -\left(n + \frac{1}{2}\right)\int_0^t \frac{a(s)}{\varkappa^2(s)} ds$$

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$$\ddot{\varkappa} - \frac{\dot{a}}{a}\dot{\varkappa} + a^2\varkappa = \frac{a^2}{\varkappa^3}$$

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We compute

$$\begin{aligned}
\langle\tilde{\varphi}_n(x,t)| K_1 |\tilde{\varphi}_m(x,t)\rangle &= 2^{n-2} n!(2n+1)\sqrt{\pi}\frac{a^2(1+\varkappa^4)+\varkappa^2\dot{\varkappa}^2}{a^2\varkappa^2}\delta_{n,m} \\
\langle\tilde{\varphi}_n(x,t)|\tilde{\varphi}_n(x,t)\rangle &= 2^n n!\sqrt{\pi} := N
\end{aligned}$$

right hand side does not depend on t:

$$\frac{d}{dt}\left[\frac{a^2(1+\varkappa^4)+\varkappa^2\dot{\varkappa}^2}{a^2\varkappa^2}\right]=\frac{2\dot{\varkappa}}{a^2}\left(\ddot{\varkappa}-\frac{\dot{a}}{a}\dot{\varkappa}+a^2\varkappa-\frac{a^2}{\varkappa^3}\right)=0$$

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take previous solution

$$\varkappa(t)=\sqrt{\tilde{\kappa}\cos\left[2\int_0^t a(s)ds\right]+\sqrt{1+\tilde{\kappa}^2}}$$

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For $\hat{\varphi}_n(x,t)=\tilde{\varphi}_m(x,t)/\sqrt{N}$ we compute

$$\langle\hat{\varphi}_n(x,t)|\,K_1\,|\hat{\varphi}_m(x,t)\rangle=\left(n+\frac{1}{2}\right)\sqrt{1+\tilde{\kappa}^2}\delta_{n,m}$$

Solution for

$$h(t) = f_+(t)K_1 + f_-(t)K_2$$

$$f_\pm(t) = a(t) \pm \frac{q_3\sqrt{1-q_3^2}\lambda(t)}{1+\cosh\left[2q_2 - 2\int_0^t \lambda(s)ds\right] - 2q_3^2}$$

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$$\Psi_h^{n,m}(x,y,t) = \hat{\varphi}_n^{+}(x,t)\hat{\varphi}_m^{-}(y,t)$$

with $a \to f^{\pm}$, $\varkappa \to \varkappa_{\pm}$, $\tilde{\kappa} \to \tilde{\kappa}_{\pm}$, $\alpha_n \to \alpha_n^{\pm}$

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with $a \to f^\pm$, $\varkappa \to \varkappa_\pm$, $\tilde{\kappa} \to \tilde{\kappa}_\pm$, $\alpha_n \to \alpha_n^\pm$
gives real instantaneous energy expectation values

$$\begin{aligned} E^{n,m}(t) &= \left\langle \Psi_h^{n,m}(t)\right| h(t) \left|\Psi_h^{n,m}(t)\right\rangle = \left\langle \Psi_H^{n,m}(t)\right| \rho(t)\tilde{H}(t) \left|\Psi_H^{n,m}(t)\right\rangle \\ &= f_+(t)\left(n+\frac{1}{2}\right)\sqrt{1+\tilde{\kappa}_+^2} + f_-(t)\left(m+\frac{1}{2}\right)\sqrt{1+\tilde{\kappa}_-^2} \end{aligned}$$

for any given fields $a(t)$, $\lambda(t) \in \mathbb{R}$, constants $\tilde{\kappa}_\pm \in \mathbb{R}$, $|q_3| < 1$

Symmetry ensuring reality of $E(t)$

Back to time-dependent two-level system

$$H(t) = -\frac{1}{2}\left[\omega\mathbb{I} + \alpha\kappa(t)\sigma_z + i\kappa(t)\sigma_x\right] \quad h(t) = -\frac{1}{2}\left[\omega\mathbb{I} + \chi(t)\sigma_z\right]$$

either known $\kappa(t)$ unknown $\chi(t)$ or unknown $\kappa(t)$ known $\chi(t)$.

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Energy operator

$$\tilde{H}(t) = -\frac{1}{2}\left\{\omega\mathbb{I} + \frac{\chi}{\delta}\left[i\left(\alpha\xi - 1\right)\sigma_x + i\left(\hat{\xi}\sqrt{1-\alpha^2}\right)\sigma_y + (\xi - \delta)\sigma_z\right]\right\}$$

with instantaneous expectation values

$$\tilde{E}_\pm(t) = \left\langle \psi_\pm(t) \middle| \tilde{H}(t)\eta^2\psi_\pm(t) \right\rangle = -\frac{1}{2}\left[\omega \pm \chi(t)\right]$$

Time-dependent $\widetilde{\mathcal{PT}}$-symmetry

Solve

$$\left[\widetilde{\mathcal{PT}}, \tilde{H}\right] = 0, \qquad \widetilde{\mathcal{PT}}\tilde{\varphi}_{\pm} = e^{i\tilde{\omega}_{\pm}}\tilde{\varphi}_{\pm}, \qquad \widetilde{\mathcal{PT}}^{2} = \mathbb{I}.$$

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We find

$$\widetilde{\mathcal{PT}} = \frac{1}{\sqrt{(\xi-\delta)^2 + (\alpha^2-1)\hat{\xi}^2}} \left[i\left(\sqrt{1-\alpha^2}\hat{\xi}\right)\sigma_y + (\xi-\delta)\sigma_z \right]\tau$$

$$\tilde{\varphi}_{\pm} \sim \begin{pmatrix} (1\mp 1)\delta - \xi \\ \sqrt{1-\alpha^2}\hat{\xi} + i(1-\alpha\xi) \end{pmatrix}$$

$$\tilde{\omega}_{+} = \arctan\left[\frac{2\sqrt{1-\alpha^2}(1-\alpha\xi)\hat{\xi}}{1+\xi(\xi-2\alpha+\xi\alpha^2)+(\alpha^2-1)\hat{\xi}^2}\right],$$

$$\tilde{\omega}_{-} = \arctan\left[\frac{\sqrt{1-\alpha^2}(1-\alpha\xi)\hat{\xi}}{2\delta^2-3\delta\xi+\xi^2+(\alpha^2-1)\hat{\xi}^2}\right] + \pi$$

Systems solved so far:

- non-Hermitian Swanson model
- one-site lattice Yang-Lee model
- non-Hermitian spin 1/2, 1 and 3/2 models
- two dimensional systems with infinite Hilbert space
- general Lie algebraic Hamiltonians (quasi-exactly solvable)

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- XXZ-spin-chain in a magnetic field

$$\mathcal{H}_{XXZ} = \frac{1}{2}\sum_{i=1}^{N-1}\left[(\sigma_i^x\sigma_{i+1}^x + \sigma_i^y\sigma_{i+1}^y + \Delta_+(\sigma_i^z\sigma_{i+1}^z - 1)\right] + \frac{\Delta_-}{2}(\sigma_1^z - \sigma_N^z),$$

$$\Delta_\pm = (q \pm q^{-1})/2 \qquad \Rightarrow \mathcal{H}_{XXZ}^\dagger \neq \mathcal{H}_{XXZ} \text{ for } q \notin \mathbb{R}$$

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These possibilities reflect the ambiguities in the observables.

$\mathcal{PT}$-symmetry $\Rightarrow$ domains in the parameter space of λ and κ

Broken and unbroken $\mathcal{PT}$-symmetry

$$[\mathcal{PT}, \mathcal{H}] = 0 \quad \bigwedge \quad \mathcal{PT}\Phi(\lambda,\kappa) \begin{cases} = \Phi(\lambda,\kappa) & \text{for } (\lambda,\kappa) \in U_{\mathcal{PT}} \\ \neq \Phi(\lambda,\kappa) & \text{for } (\lambda,\kappa) \in U_{b\mathcal{PT}} \end{cases}$$

$(\lambda,\kappa) \in U_{\mathcal{PT}} \Rightarrow$ real eigenvalues
$(\lambda,\kappa) \in U_{b\mathcal{PT}} \Rightarrow$ eigenvalues in complex conjugate pairs

- The two site Hamiltonian

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$$\mathcal{H} = -\frac{1}{2}\left[\sigma_1^z + \sigma_2^z + 2\lambda\sigma_1^x\sigma_2^x + i\kappa\left(\sigma_2^x + \sigma_1^x\right)\right]$$

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Deformed quantum spin chains (Exact Results, $N = 2$)

- The two site Hamiltonian

$$
\begin{aligned}
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&= -\begin{pmatrix} -1 & \frac{i\kappa}{2} & \frac{i\kappa}{2} & \lambda \\ \frac{i\kappa}{2} & 0 & \lambda & \frac{i\kappa}{2} \\ \frac{i\kappa}{2} & \lambda & 0 & \frac{i\kappa}{2} \\ \lambda & \frac{i\kappa}{2} & \frac{i\kappa}{2} & -1 \end{pmatrix}
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- domain of unbroken $\mathcal{PT}$-symmetry:

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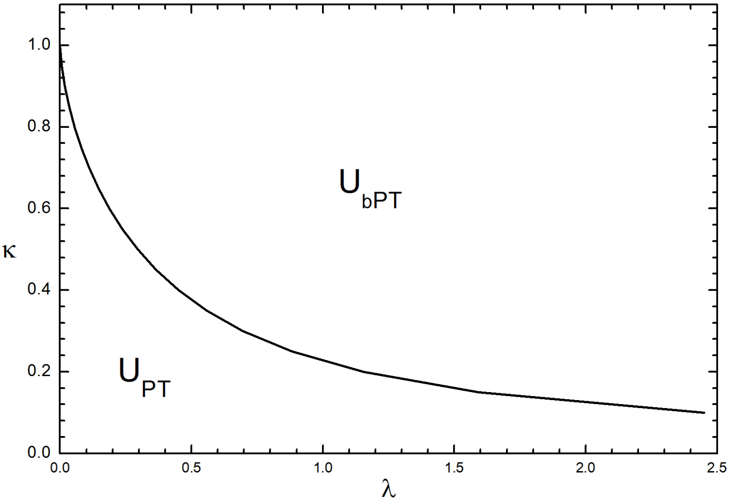
- domain of unbroken $\mathcal{PT}$-symmetry:
  char. polynomial factorises into 1st and 3rd order
  discriminant: $\Delta = r^2 - q^3$

$$q = \frac{1}{9}\left(-3\kappa^2 + 4\lambda^2 + 3\right), \quad r = \frac{\lambda}{27}\left(18\kappa^2 + 8\lambda^2 + 9\right)$$

Deformed quantum spin chains (Exact Results, $N = 2$)

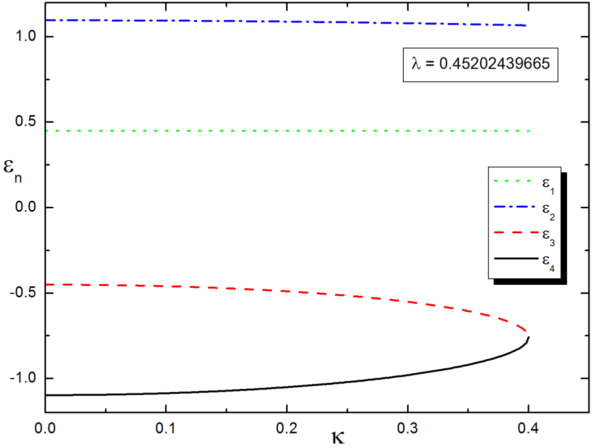
$$U_{\mathcal{PT}} = \left\{ \lambda, \kappa : \kappa^6 + 8\lambda^2\kappa^4 - 3\kappa^4 + 16\lambda^4\kappa^2 + 20\lambda^2\kappa^2 + 3\kappa^2 - \lambda^2 \leq 1 \right\}$$



Real eigenvalues: $\left[\theta = \arccos\left(r/q^{3/2}\right)\right]$

$$\varepsilon_1 = \lambda, \quad \varepsilon_2 = 2q^{\frac{1}{2}} \cos\left(\frac{\theta}{3}\right) - \frac{\lambda}{3}, \quad \varepsilon_{3/4} = 2q^{\frac{1}{2}} \cos\left(\frac{\theta}{3} + \pi \mp \frac{1\pi}{3}\right) - \frac{\lambda}{3}$$

Avoided level crossing:



Real eigenvalues: $\left[\theta = \arccos\left(r/q^{3/2}\right)\right]$

$$\varepsilon_1 = \lambda, \quad \varepsilon_2 = 2q^{\frac{1}{2}} \cos\left(\frac{\theta}{3}\right) - \frac{\lambda}{3}, \quad \varepsilon_{3/4} = 2q^{\frac{1}{2}} \cos\left(\frac{\theta}{3} + \pi \mp \frac{1\pi}{3}\right) - \frac{\lambda}{3}$$

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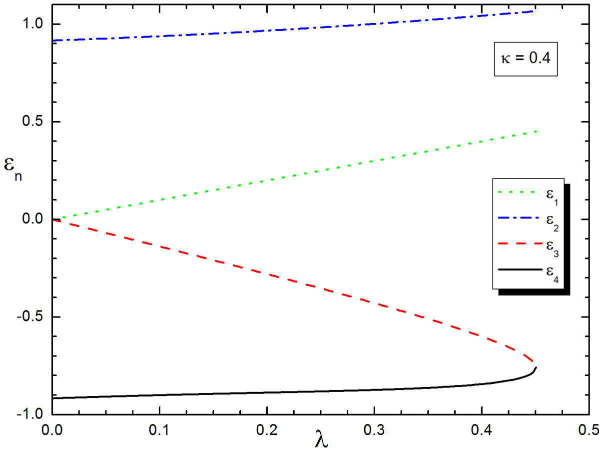

Deformed quantum spin chains (Exact Results, $N = 2$)

- Right eigenvectors of $\mathcal{H}$:

$$|\Phi_1\rangle = (0, -1, -1, 0) \quad |\Phi_n\rangle = (\gamma_n, -\alpha_n, -\alpha_n, \beta_n) \quad n = 2, 3, 4$$

$$\alpha_n = i\kappa(\lambda - \varepsilon_n + 1)$$
$$\beta_n = \kappa^2 + 2\lambda^2 + 2\lambda\varepsilon_n$$
$$\gamma_n = -\kappa^2 - 2\varepsilon_n^2 + 2\lambda - 2\lambda\varepsilon_n + 2\varepsilon_n$$

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- signature: $s = (+, -, +, -)$

$$\mathcal{P}\,|\Phi_n\rangle = s_n\,|\Psi_n\rangle$$

from relating left and right eigenvectors

Deformed quantum spin chains (Exact Results, $N = 2$)

- $\mathcal{C}$-operator:

$$
\begin{aligned}
\mathcal{C} &= \sum_n s_n \left|\Phi_n\right\rangle \left\langle \Psi_n\right| \\
&= \begin{pmatrix} C_5 & -C_3 & -C_3 & C_4 \\ -C_3 & -C_1 - 1 & -C_1 & C_2 \\ -C_3 & -C_1 & -C_1 - 1 & C_2 \\ C_4 & C_2 & C_2 & 2(C_1 + 1) - C_5 \end{pmatrix}
\end{aligned}
$$

$$
C_1 = \frac{\alpha_4^2}{N_4^2} - \frac{\alpha_2^2}{N_2^2} - \frac{\alpha_3^2}{N_3^2} - \frac{1}{2}, \qquad C_2 = \frac{\alpha_4\beta_4}{N_4^2} - \frac{\alpha_2\beta_2}{N_2^2} - \frac{\alpha_3\beta_3}{N_3^2},
$$

$$
C_3 = \frac{\alpha_2\gamma_2}{N_2^2} + \frac{\alpha_3\gamma_3}{N_3^2} - \frac{\alpha_4\gamma_4}{N_4^2}, \qquad C_4 = \frac{\beta_2\gamma_2}{N_2^2} + \frac{\beta_3\gamma_3}{N_3^2} - \frac{\beta_4\gamma_4}{N_4^2},
$$

$$
C_5 = \frac{\gamma_2^2}{N_2^2} + \frac{\gamma_3^2}{N_3^2} - \frac{\gamma_4^2}{N_4^2}
$$

$$
N_1 = \sqrt{2},\ N_n = \sqrt{2\alpha_n^2 + \beta_n^2 + \gamma_n^2} \text{ for } n =, 2, 3, 4
$$

- metric operator:

- metric operator:

$$\rho = \mathcal{P}\mathcal{C} = \begin{pmatrix} C_5 & -C_3 & -C_3 & C_4 \\ C_3 & 1 + C_1 & C_1 & -C_2 \\ C_3 & C_1 & 1 + C_1 & -C_2 \\ C_4 & C_2 & C_2 & 2(1 + C_1) - C_5 \end{pmatrix}$$

- metric operator:

$$\rho = \mathcal{PC} = \begin{pmatrix} C_5 & -C_3 & -C_3 & C_4 \\ C_3 & 1 + C_1 & C_1 & -C_2 \\ C_3 & C_1 & 1 + C_1 & -C_2 \\ C_4 & C_2 & C_2 & 2(1 + C_1) - C_5 \end{pmatrix}$$

- since $i\alpha_i, \beta_i, \gamma_i \in \mathbb{R}$

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- EV of ρ:

$$y_1 = y_2 = 1, \qquad y_{3/4} = 1 + 2C_1 \pm 2\sqrt{C_1(1 + C_1)}$$

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- EV of ρ:

$$y_1 = y_2 = 1, \qquad y_{3/4} = 1 + 2C_1 \pm 2\sqrt{C_1(1 + C_1)}$$

since $C_1 > 0$ $\Rightarrow \rho$ is positive

- square root of the metric operator:

$$\eta = \rho^{1/2} = UD^{1/2}U^{-1}$$

where $D = \mathrm{diag}(y_{1,}y_{2,}, y_{3,}, y_4)$, $U = \{r_1, r_2, r_3, r_4\}$

$$|r_1\rangle = (0, -1, 1, 0)$$
$$|r_2\rangle = (C_4, 0, 0, 1 - C_5),$$
$$\left|r_{3/4}\right\rangle = (\tilde{\gamma}_{3/4}, \tilde{\alpha}_{3/4}, \tilde{\alpha}_{3/4}, \tilde{\beta}_{3/4})$$

$$\tilde{\alpha}_{3/4} = y_{3/4}(C_3C_4 + C_2(-4C_1 + C_5 - 1))/2 - C_3C_4$$
$$\tilde{\beta}_{3/4} = -C_3^2 - C_1 - C_1C_5 + \left(C_3^2 + C_1(4C_1 - C_5 + 3)\right) y_{3/4},$$
$$\tilde{\gamma}_{3/4} = C_1C_4 - C_2C_3 + (C_2C_3 + C_1C_4)y_{3/4}$$

Deformed quantum spin chains (Exact Results, $N = 2$)

- isospectral Hermitian counterpart:

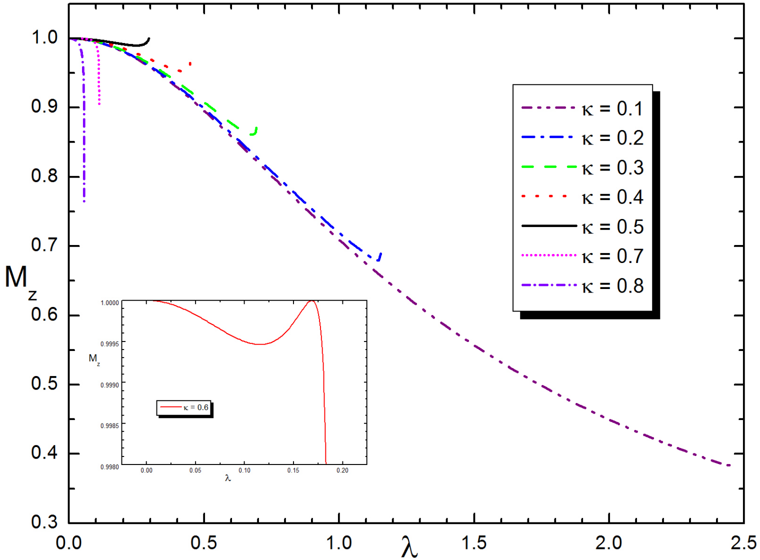
$$\begin{aligned} h &= \eta \mathcal{H} \eta^{-1} \\ &= \mu_1 \sigma_x \otimes \sigma_x + \mu_2 \sigma_y \otimes \sigma_y + \mu_3 \sigma_z \otimes \sigma_z + \mu_4 (\sigma_z \otimes \mathbb{I} + \mathbb{I} \otimes \sigma_z) \end{aligned}$$

$\mu_1, \mu_2, \mu_3, \mu_4 \in \mathbb{R}$

for $\lambda = 0.1, \kappa = 0.5$:

$$h = \begin{pmatrix} -0.829536 & 0 & 0 & -0.0606492 \\ 0 & -0.0341687 & -0.1341687 & 0 \\ 0 & -0.1341687 & -0.0341687 & 0 \\ -0.0606492 & 0 & 0 & 0.897873 \end{pmatrix}$$

The magnetization in the z-direction for $N = 2$:



Deformed quantum spin chains ($N \neq 2$, perturbation theory)

- Perturbation theory about the Hermitian part

$$H(\lambda, \kappa) = h_0(\lambda) + i\kappa h_1 \qquad h_0 = h_0^\dagger, h_1 = h_1^\dagger \quad \kappa \in \mathbb{R}$$

- Perturbation theory about the Hermitian part

$$H(\lambda,\kappa) = h_0(\lambda) + i\kappa h_1 \qquad h_0 = h_0^\dagger, h_1 = h_1^\dagger \quad \kappa \in \mathbb{R}$$

assume $\eta = \eta^\dagger = e^{q/2} \Rightarrow$ solve for q

$$H^\dagger = e^q H e^{-q} = H + [q,H] + \frac{1}{2}[q,[q,H]] + \frac{1}{3!}[q,[q,[q,H]]] + \cdots$$

- Perturbation theory about the Hermitian part

$$H(\lambda,\kappa) = h_0(\lambda) + i\kappa h_1 \qquad h_0 = h_0^\dagger, h_1 = h_1^\dagger \quad \kappa \in \mathbb{R}$$

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for $c_q^{(\ell+1)}(h_0) = [q,\ldots[q,[q,h_0]]\ldots] = 0$ closed formulae:

$$h = h_0 + \sum_{n=1}^{[\frac{\ell}{2}]} \frac{(-1)^n E_n}{4^n (2n)!} c_q^{(2n)}(h_0) \quad H = h_0 - \sum_{n=1}^{[\frac{\ell+1}{2}]} \frac{\kappa_{2n-1}}{(2n-1)!} c_q^{(2n-1)}(h_0)$$

$E_n \equiv$ Euler numbers, e.g. $E_1 = 1$, $E_2 = 5$, $E_3 = 61, \ldots$

$$\kappa_n = \frac{1}{2^n} \sum_{m=1}^{[(n+1)/2]} (-1)^{n+m} \binom{n}{2m} E_m$$

$\kappa_1 = 1/2, \kappa_3 = -1/4, \kappa_5 = 1/2, \kappa_7 = -17/8, \ldots$

[C. F. de Morisson Faria, A.F., J. Phys. A39 (2006) 9269] further assumption

$$q = \sum_{k=1}^{\infty} \kappa^{2k-1} q_{2k-1}$$

solve recursively:

$$[h_0, q_1] = 2ih_1$$

$$[h_0, q_3] = \frac{i}{6}[q_1, [q_1, h_1]]$$

$$[h_0, q_5] = \frac{i}{6}[q_1, [q_3, h_1]] + \frac{i}{6}[q_3, [q_1, h_1]] - \frac{i}{360}[q_1, [q_1, [q_1, [q_1, h_1]]]]$$

Here

$$h_0(\lambda) = -\sum_{i=1}^{N} (\sigma_i^z + \lambda \sigma_i^x \sigma_{i+1}^x)/2, \qquad h_1 = -\sum_{i=1}^{N} \sigma_i^x/2$$

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- Perturbation theory in λ

$$H(\lambda, \kappa) = h_0(\kappa) + \lambda h_1 \qquad h_0 \neq h_0^\dagger, h_1 = h_1^\dagger \quad \lambda \in \mathbb{R}$$

exact result for $N = 2$:

$\lambda = 0.1$, $\kappa = 0.5$:

$$h = \begin{pmatrix} -0.829536 & 0 & 0 & -0.0606492 \\ 0 & -0.0341687 & -0.1341687 & 0 \\ 0 & -0.1341687 & -0.0341687 & 0 \\ -0.0606492 & 0 & 0 & 0.897873 \end{pmatrix}$$

$\lambda = 0.9$, $\kappa = 0.1$:

$$h = \begin{pmatrix} -0.985439 & 0 & 0 & -0.890532 \\ 0 & -0.0094167 & -0.909417 & 0 \\ 0 & -0.909417 & -0.0094167 & 0 \\ -0.890532 & 0 & 0 & 1.00427 \end{pmatrix}$$

perturbative result 4th order for $N = 2$:

$\lambda = 0.1$, $\kappa = 0.5$:

$$h = \begin{pmatrix} -0.829534 & 0 & 0 & -0.0606716 \\ 0 & -0.0341688 & -0.134169 & 0 \\ 0 & -0.134169 & -0.0341688 & 0 \\ -0.0606716 & 0 & 0 & 0.897872 \end{pmatrix}$$

$\lambda = 0.9$, $\kappa = 0.1$:

$$h = \begin{pmatrix} -0.985439 & 0 & 0 & -0.890532 \\ 0 & -0.0094167 & -0.909417 & 0 \\ 0 & -0.909417 & -0.0094167 & 0 \\ -0.890532 & 0 & 0 & 1.00427 \end{pmatrix}$$

- new notation:

$$S^N_{a_1 a_2 \ldots a_p} := \sum_{k=1}^{N} \sigma_k^{a_1} \sigma_{k+1}^{a_2} \ldots \sigma_{k+p-1}^{a_p}, \qquad a_i = x, y, z, u; i = 1, \ldots, p \leq N$$

with $\sigma^u = \mathbb{I}$ to allow for non-local interactions

- for instance:

$$H(\lambda, \kappa) = -\frac{1}{2} \sum_{j=1}^{N} (\sigma_j^z + \lambda \sigma_j^x \sigma_{j+1}^x + i\kappa \sigma_j^x), \qquad \lambda, \kappa \in \mathbb{R}$$
$$= -\frac{1}{2}(S_z^N + \lambda S_{xx}^N) - i\kappa \frac{1}{2} S_x^N$$

- perturbative result for $N = 3$:

$$h = \mu^3_{xx}(\lambda,\kappa) S^3_{xx} + \mu^3_{yy}(\lambda,\kappa) S^3_{yy} + \mu^3_{zz}(\lambda,\kappa) S^3_{zz} + \mu^3_{z}(\lambda,\kappa) S^3_{z}$$
$$+ \mu^3_{xxz}(\lambda,\kappa) S^3_{xxz} + \mu^3_{yyz}(\lambda,\kappa) S^3_{yyz} + \mu^3_{zzz}(\lambda,\kappa) S^3_{zzz}$$

- perturbative result for $N = 4$:

$$\begin{aligned} h \;=\; & \mu^4_{xx}(\lambda,\kappa)S^4_{xx} + \nu^4_{xx}(\lambda,\kappa)S^4_{xux} + \mu^4_{yy}(\lambda,\kappa)S^4_{yy} + \nu^4_{yy}(\lambda,\kappa)S^4_{yuy} \\ & + \mu^4_{zz}(\lambda,\kappa)S^4_{zz} + \nu^4_{zz}(\lambda,\kappa)S^4_{zuz} + \mu^4_{z}(\lambda,\kappa)S^4_{z} + \mu^4_{xzx}(\lambda,\kappa)S^4_{xzx} \\ & + \mu^4_{xxz}(\lambda,\kappa)(S^4_{xxz} + S^4_{zxx}) + \mu^4_{yyz}(\lambda,\kappa)(S^4_{yyz} + S^4_{zyy}) \\ & + \mu^4_{yzy}(\lambda,\kappa)S^4_{yzy} + \mu^4_{zzz}(\lambda,\kappa)S^4_{zzz} + \mu^4_{xxxx}(\lambda,\kappa)S^4_{xxxx} \\ & + \mu^4_{yyyy}(\lambda,\kappa)S^4_{yyyy} + \mu^4_{zzzz}(\lambda,\kappa)S^4_{zzzz} + \mu^4_{xxyy}(\lambda,\kappa)S^4_{xxyy} \\ & + \mu^4_{xyxy}(\lambda,\kappa)S^4_{xyxy} + \mu^4_{zzyy}(\lambda,\kappa)S^4_{zzyy} + \mu^4_{zyzy}(\lambda,\kappa)S^4_{zyzy} \\ & + \mu^4_{xxzz}(\lambda,\kappa)S^4_{xxzz} + \mu^4_{xzxz}(\lambda,\kappa)S^4_{xzxz} \end{aligned}$$

- perturbative result for $N = 4$:

$$
\begin{aligned}
h \;=\;& \mu^4_{xx}(\lambda,\kappa)S^4_{xx} + \nu^4_{xx}(\lambda,\kappa)S^4_{xux} + \mu^4_{yy}(\lambda,\kappa)S^4_{yy} + \nu^4_{yy}(\lambda,\kappa)S^4_{yuy} \\
&+\mu^4_{zz}(\lambda,\kappa)S^4_{zz} + \nu^4_{zz}(\lambda,\kappa)S^4_{zuz} + \mu^4_{z}(\lambda,\kappa)S^4_{z} + \mu^4_{xzx}(\lambda,\kappa)S^4_{xzx} \\
&+\mu^4_{xxz}(\lambda,\kappa)(S^4_{xxz} + S^4_{zxx}) + \mu^4_{yyz}(\lambda,\kappa)(S^4_{yyz} + S^4_{zyy}) \\
&+\mu^4_{yzy}(\lambda,\kappa)S^4_{yzy} + \mu^4_{zzz}(\lambda,\kappa)S^4_{zzz} + \mu^4_{xxxx}(\lambda,\kappa)S^4_{xxxx} \\
&+\mu^4_{yyyy}(\lambda,\kappa)S^4_{yyyy} + \mu^4_{zzzz}(\lambda,\kappa)S^4_{zzzz} + \mu^4_{xxyy}(\lambda,\kappa)S^4_{xxyy} \\
&+\mu^4_{xyxy}(\lambda,\kappa)S^4_{xyxy} + \mu^4_{zzyy}(\lambda,\kappa)S^4_{zzyy} + \mu^4_{zyzy}(\lambda,\kappa)S^4_{zyzy} \\
&+\mu^4_{xxzz}(\lambda,\kappa)S^4_{xxzz} + \mu^4_{xzxz}(\lambda,\kappa)S^4_{xzxz}
\end{aligned}
$$

non-local terms

Three possibilities to obtain PT-invariant Calogero models

1. Extended Calogero-Moser-Sutherland models

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2. From constraint field equations

Three possibilities to obtain PT-invariant Calogero models

1. Extended Calogero-Moser-Sutherland models
2. From constraint field equations
3. Deformed Calogero-Moser-Sutherland models

Calogero-Moser-Sutherland models (extended)

$$\mathcal{H}_{BK} = \frac{p^2}{2} + \frac{\omega^2}{2} \sum_i q_i^2 + \frac{g^2}{2} \sum_{i \neq k} \frac{1}{(q_i - q_k)^2} + i\tilde{g} \sum_{i \neq k} \frac{1}{(q_i - q_k)} p_i$$

with $g, \tilde{g} \in \mathbb{R}, q, p \in \mathbb{R}^{\ell+1}$

[B. Basu-Mallick, A. Kundu, Phys. Rev. B62 (2000) 9927]

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1. Representation independent formulation?
2. Other potentials apart from the rational one?
3. Other algebras apart from A_n, B_n or Coxeter groups?
4. Is it possible to include more coupling constants?
5. Are the extensions still integrable?

- Generalize Hamiltonian to:

$$\mathcal{H}_\mu = \frac{1}{2}p^2 + \frac{1}{2}\sum_{\alpha\in\Delta} g_\alpha^2 V(\alpha\cdot q) + i\mu\cdot p$$

· Now Δ is any root system

· $\mu = 1/2\sum_{\alpha\in\Delta}\tilde{g}_\alpha f(\alpha\cdot q)\alpha$, $f(x) = 1/x$ $V(x) = f^2(x)$

[A. F., Mod. Phys. Lett. A21 (2006) 691, Acta P. 47 (2007) 44]

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- Not so obvious that one can re-write

$$\mathcal{H}_\mu = \frac{1}{2}(p+i\mu)^2+\frac{1}{2}\sum_{\alpha\in\Delta}\hat{g}_\alpha^2 V(\alpha\cdot q), \quad \hat{g}_\alpha^2 = \begin{cases} g_s^2 + \alpha_s^2\tilde{g}_s^2 & \alpha\in\Delta_s \\ g_l^2 + \alpha_l^2\tilde{g}_l^2 & \alpha\in\Delta_l \end{cases}$$

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$$\Rightarrow \mathcal{H}_\mu = \eta^{-1}h_{\mathrm{Cal}}\eta \qquad \text{with} \quad \eta = e^{-q\cdot\mu}$$

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$$\mathcal{H}_\mu = \frac{1}{2}(p+i\mu)^2 + \frac{1}{2}\sum_{\alpha\in\Delta}\hat{g}_\alpha^2 V(\alpha\cdot q), \quad \hat{g}_\alpha^2 = \begin{cases} g_s^2 + \alpha_s^2\tilde{g}_s^2 & \alpha\in\Delta_s \\ g_l^2 + \alpha_l^2\tilde{g}_l^2 & \alpha\in\Delta_l \end{cases}$$

$$\Rightarrow \mathcal{H}_\mu = \eta^{-1}h_{\mathrm{Cal}}\eta \qquad \text{with} \quad \eta = e^{-q\cdot\mu}$$

- integrability follows trivially $\dot{L} = [L, M]$: $L(p) \to L(p + i\mu)$

- Generalize Hamiltonian to:

$$\mathcal{H}_\mu = \frac{1}{2}p^2 + \frac{1}{2}\sum\nolimits_{\alpha\in\Delta} g_\alpha^2 V(\alpha\cdot q) + i\mu\cdot p$$

· Now Δ is any root system

· $\mu = 1/2\sum_{\alpha\in\Delta}\tilde{g}_\alpha f(\alpha\cdot q)\alpha$, $f(x) = 1/x \; V(x) = f^2(x)$

[A. F., Mod. Phys. Lett. A21 (2006) 691, Acta P. 47 (2007) 44]

- Not so obvious that one can re-write

$$\mathcal{H}_\mu = \frac{1}{2}(p+i\mu)^2 + \frac{1}{2}\sum\nolimits_{\alpha\in\Delta}\hat{g}_\alpha^2 V(\alpha\cdot q), \quad \hat{g}_\alpha^2 = \begin{cases} g_s^2 + \alpha_s^2\tilde{g}_s^2 & \alpha\in\Delta_s \\ g_l^2 + \alpha_l^2\tilde{g}_l^2 & \alpha\in\Delta_l \end{cases}$$

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- integrability follows trivially $\dot{L} = [L, M]$: $L(p) \to L(p + i\mu)$
- computing backwards for any CMS-potential

$$\mathcal{H}_\mu = \frac{1}{2}p^2 + \frac{1}{2}\sum\nolimits_{\alpha\in\Delta}\hat{g}_\alpha^2 V(\alpha\cdot q) + i\mu\cdot p - \frac{1}{2}\mu^2$$

- $\mu^2 = \alpha_s^2\tilde{g}_s^2 \sum_{\alpha\in\Delta_s} V(\alpha\cdot q) + \alpha_l^2\tilde{g}_l^2 \sum_{\alpha\in\Delta_l} V(\alpha\cdot q)$ only for V rational

- From real fields to complex particle systems

  i) No restrictions
  e.g. Benjamin-Ono equation

$$u_t + uu_x + \lambda H u_{xx} = 0 \qquad (*)$$

$H \equiv$ Hilbert transform, i.e. $Hu(x) = \frac{P}{\pi}\int_{-\infty}^{\infty} \frac{u(x)}{z-x} dz$
Then

$$u(x,t) = \frac{\lambda}{2}\sum_{k=1}^{\ell}\left(\frac{i}{x-z_k} - \frac{i}{x-z_k^*}\right) \in \mathbb{R}$$

satisfies (*) iff z_k obeys the A_n-Calogero equ. of motion

$$\ddot{z}_k = \frac{\lambda^2}{2}\sum_{k\neq j}(z_j - z_k)^{-3}$$

[H. Chen, N. Pereira, Phys. Fluids 22 (1979) 187]
[talk by J. Feinberg, PHHQP workshop VI, 2007, London]

ii) restrict to submanifold

Theorem: [Airault, McKean, Moser, CPAM, (1977) 95]

Given a Hamiltonian $H(x_1, \ldots, x_n, \dot{x}_1, \ldots, \dot{x}_n)$ with flow

$$x_i = \partial H / \partial \dot{x}_i \qquad \text{and} \qquad \ddot{x}_i = -\partial H / \partial x_i \qquad i = 1, \ldots, n$$

and conserved charges I_j in involution with H,i.e. $\{I_j, H\} = 0$. Then the locus of $\operatorname{grad} I = 0$ is invariant.

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Example: Boussinesq equation

$$v_{tt} = a(v^2)_{xx} + b v_{xxxx} + v_{xx} \qquad (**)$$

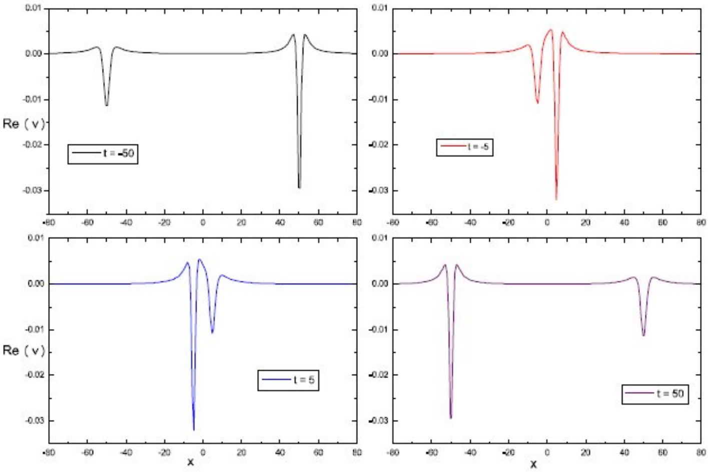
Then

$$v(x,t) = c \sum\nolimits_{k=1}^{\ell} (x - z_k)^{-2}$$

satisfies (**) iff b=1/12, c=-a/2 and z_k obeys

$$\begin{aligned} \ddot{z}_k &= 2 \sum\nolimits_{j \neq k} (z_j - z_k)^{-3} \qquad \Leftrightarrow \qquad \ddot{z}_k = -\frac{\partial H}{\partial z_i} \\ \dot{z}_k &= 1 - \sum\nolimits_{j \neq k} (z_j - z_k)^{-2} \qquad \Leftrightarrow \qquad \operatorname{grad}(I_3 - I_1) = 0 \end{aligned}$$

Constrained field equations → complex Calogero models



[P. Assis and A.F., J. Phys. A42 (2009) 425206]

Consider

Antilinearly invariant deformed Calogero model

$$\mathcal{H}_{\mathcal{PT}\text{CMS}} = \frac{p^2}{2} + \frac{m^2}{16} \sum_{\alpha \in \Delta_s} (\alpha \cdot \tilde{q})^2 + \frac{1}{2} \sum_{\alpha \in \Delta} g_\alpha V(\alpha \cdot \tilde{q}), \quad m, g_\alpha \in \mathbb{R}$$

Define deformed coordinates (A_2)

$$\begin{aligned} q_1 &\rightarrow \tilde{q}_1 = q_1 \cosh\varepsilon + i\sqrt{3}(q_2 - q_3)\sinh\varepsilon \\ q_2 &\rightarrow \tilde{q}_2 = q_2 \cosh\varepsilon + i\sqrt{3}(q_3 - q_1)\sinh\varepsilon \\ q_3 &\rightarrow \tilde{q}_3 = q_3 \cosh\varepsilon + i\sqrt{3}(q_1 - q_2)\sinh\varepsilon \end{aligned}$$

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With standard 3D representation for the simple A_2-roots $\alpha_1 = \{1, -1, 0\}$, $\alpha_2 = \{0, 1, -1\}$, $q_{ij} := q_i - q_j$ compute

$$\begin{aligned} \alpha_1 \cdot \tilde{q} &= q_{12} \cosh\varepsilon - \frac{\imath}{\sqrt{3}}(q_{13} + q_{23})\sinh\varepsilon, \\ \alpha_2 \cdot \tilde{q} &= q_{23} \cosh\varepsilon - \frac{\imath}{\sqrt{3}}(q_{21} + q_{31})\sinh\varepsilon, \\ (\alpha_1 + \alpha_2) \cdot \tilde{q} &= q_{13} \cosh\varepsilon + \frac{\imath}{\sqrt{3}}(q_{12} + q_{32})\sinh\varepsilon. \end{aligned}$$

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Symmetries:

$$\begin{aligned} \mathcal{S}_1 &: \quad q_1 \leftrightarrow q_2,\ q_3 \leftrightarrow q_3,\ \imath \to -\imath, \\ \mathcal{S}_2 &: \quad q_2 \leftrightarrow q_3,\ q_1 \leftrightarrow q_1,\ \imath \to -\imath. \end{aligned}$$

Note, this Hamiltonian also results from deforming the roots:

$$\begin{aligned}\alpha_1 &\to \tilde{\alpha}_1 = \alpha_1 \cosh\varepsilon + i\sqrt{3}\sinh\varepsilon\lambda_2 \\ \alpha_2 &\to \tilde{\alpha}_2 = \alpha_2 \cosh\varepsilon - i\sqrt{3}\sinh\varepsilon\lambda_1\end{aligned}$$

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Thus

$$\begin{aligned}\mathcal{H}_{\mathcal{PT}\mathrm{CMS}} &= \frac{p^2}{2} + \frac{m^2}{16}\sum_{\tilde{\alpha}\in\tilde{\Delta}_s}(\tilde{\alpha}\cdot q)^2 + \frac{1}{2}\sum_{\tilde{\alpha}\in\tilde{\Delta}} g_{\tilde{\alpha}} V(\tilde{\alpha}\cdot q), \;\; m, g_{\tilde{\alpha}} \in \mathbb{R} \\ &= \frac{p^2}{2} + \frac{m^2}{16}\sum_{\alpha\in\Delta_s}(\alpha\cdot\tilde{q})^2 + \frac{1}{2}\sum_{\alpha\in\Delta} g_{\alpha} V(\alpha\cdot\tilde{q}), \;\; m, g_{\alpha} \in \mathbb{R}\end{aligned}$$

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$$\begin{aligned} \sigma_1^{\varepsilon} &: \tilde{\alpha}_1 \leftrightarrow -\tilde{\alpha}_1, \tilde{\alpha}_2 \leftrightarrow \tilde{\alpha}_1 + \tilde{\alpha}_2 \quad \Leftrightarrow \quad q_1 \leftrightarrow q_2, q_3 \leftrightarrow q_3, \imath \rightarrow -\imath \\ \sigma_2^{\varepsilon} &: \tilde{\alpha}_2 \leftrightarrow -\tilde{\alpha}_2, \tilde{\alpha}_1 \leftrightarrow \tilde{\alpha}_1 + \tilde{\alpha}_2 \quad \Leftrightarrow \quad q_2 \leftrightarrow q_3, q_1 \leftrightarrow q_1, \imath \rightarrow -\imath \end{aligned}$$

Construction of antilinear deformations

- Involution $\in \mathcal{W} \equiv$ Coxeter group $\Rightarrow$ deform in antilinear way

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$$\delta: \ \Delta \to \tilde{\Delta}(\varepsilon) \qquad \alpha \mapsto \tilde{\alpha} = \theta_\varepsilon \alpha$$

$$\alpha_i \in \Delta \subset \mathbb{R}^n, \quad \tilde{\alpha}_i(\varepsilon) \in \tilde{\Delta}(\varepsilon) \subset \mathbb{R}^n \oplus \imath\mathbb{R}^n, \quad \varepsilon \in \mathbb{R}$$

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- Find a second map that leaves $\tilde{\Delta}(\varepsilon)$ invariant

$$\varpi : \tilde{\Delta}(\varepsilon) \to \tilde{\Delta}(\varepsilon), \qquad \tilde{\alpha} \mapsto \omega\tilde{\alpha}$$

(i) $\varpi : \tilde{\alpha} = \mu_1\alpha_1 + \mu_2\alpha_2 \mapsto \mu_1^*\omega\alpha_1 + \mu_2^*\omega\alpha_2$ for $\mu_1, \mu_2 \in \mathbb{C}$
(ii) $\varpi \circ \varpi = \mathbb{I}$

Make the following assumptions

(i) ω decomposes as

$$\omega = \tau\hat{\omega} = \hat{\omega}\tau$$

with $\hat{\omega} \in \mathcal{W}$, $\hat{\omega}^2 = \mathbb{I}$ and complex conjugation τ

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Many solutions were constructed

$\tilde{\Delta}(\varepsilon)$ for A_3

$$\theta_\varepsilon = r_0 \mathbb{I} + r_2 \sigma^2 + \imath r_1 \left(\sigma - \sigma^3 \right)$$

with explicit representation

$$\sigma_1 = \begin{pmatrix} -1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \sigma_2 = \begin{pmatrix} 1 & 1 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & 1 \end{pmatrix},$$

$$\sigma_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & -1 \end{pmatrix}, \sigma = \begin{pmatrix} -1 & -1 & 0 \\ 1 & 1 & 1 \\ 0 & -1 & -1 \end{pmatrix},$$

$\sigma_- = \sigma_1 \sigma_3$, $\sigma_+ = \sigma_2$, $\sigma = \sigma_- \sigma_+$

$$\theta_\varepsilon = \begin{pmatrix} r_0 - \imath r_1 & -2\imath r_1 & -\imath r_1 - r_2 \\ 2\imath r_1 & r_0 - r_2 + 2\imath r_1 & 2\imath r_1 \\ -\imath r_1 - r_2 & -2\imath r_1 & r_0 - \imath r_1 \end{pmatrix}$$

all constraints require

$$\begin{aligned}(r_0+r_2)\left[(r_0+r_2)^2-4r_1^2\right] &= 1\\ r_0-r_2+2r_1 &= (r_0-r_2+2r_1)(r_0+r_2)\\ (r_0+r_2) &= (r_0-r_2)^2-4r_1^2\end{aligned}$$

these are solved by

$$r_0(\varepsilon)=\cosh\varepsilon,\quad r_1(\varepsilon)=\pm\sqrt{\cosh^2\varepsilon-\cosh\varepsilon},\quad r_2(\varepsilon)=1-\cosh\varepsilon$$

$\Rightarrow$ simple deformed roots

$$\tilde{\alpha}_1=\cosh\varepsilon\alpha_1+(\cosh\varepsilon-1)\alpha_3-\imath\sqrt{2}\sqrt{\cosh\varepsilon}\sinh\left(\frac{\varepsilon}{2}\right)(\alpha_1+2\alpha_2+\alpha_3),$$

$$\tilde{\alpha}_2=(2\cosh\varepsilon-1)\alpha_2+2\imath\sqrt{2}\sqrt{\cosh\varepsilon}\sinh\left(\frac{\varepsilon}{2}\right)(\alpha_1+\alpha_2+\alpha_3),$$

$$\tilde{\alpha}_3=\cosh\varepsilon\alpha_3+(\cosh\varepsilon-1)\alpha_1-\imath\sqrt{2}\sqrt{\cosh\varepsilon}\sinh\left(\frac{\varepsilon}{2}\right)(\alpha_1+2\alpha_2+\alpha_3).$$

remaining positive roots

$\tilde{\alpha}_4:=\tilde{\alpha}_1+\tilde{\alpha}_2$, $\tilde{\alpha}_5:=\tilde{\alpha}_2+\tilde{\alpha}_3$, $\tilde{\alpha}_6:=\tilde{\alpha}_1+\tilde{\alpha}_2+\tilde{\alpha}_3$.

$\tilde{\Delta}(\varepsilon)$ for A_{4n-1}-subseries

closed solution

$$\theta_\varepsilon = r_0 \mathbb{I} + r_{2n} \sigma^{2n} + \imath r_n \left(\sigma^n - \sigma^{-n} \right) ,$$

- with $r_{2n} = 1 - r_0$, $r_n = \pm\sqrt{r_0^2 - r_0}$
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$\tilde{\Delta}(\varepsilon)$ for E_6

$$\theta_\varepsilon = \begin{pmatrix} r_0 & -2\imath r_2 & 0 & -2\imath r_2 & -2\imath r_2 & -\imath r_2 \\ 2\imath r_2 & r_0 + \imath r_2 & 2\imath r_2 & 2\imath r_2 & 2\imath r_2 & 2\imath r_2 \\ 0 & 2\imath r_2 & r_0 + 2\imath r_2 & 4\imath r_2 & 3\imath r_2 & 2\imath r_2 \\ -2\imath r_2 & -2\imath r_2 & -4\imath r_2 & r_0 - 5\imath r_2 & -4\imath r_2 & -2\imath r_2 \\ 2\imath r_2 & 2\imath r_2 & 3\imath r_2 & 4\imath r_2 & r_0 + 2\imath r_2 & 0 \\ -\imath r_2 & -2\imath r_2 & -2\imath r_2 & -2\imath r_2 & 0 & r_0 \end{pmatrix}$$

$r_2 = \pm 1/\sqrt{3}\sqrt{r_0^2 - 1}$, $r_0 = \cosh\varepsilon$

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$\tilde{\Delta}(\varepsilon)$ for B_{2n+1}-subseries

no solution based on factorisation of the Coxeter element with different ω_i we find for instance for B_{2n+1}

$$
\begin{aligned}
\tilde{\alpha}_{2j-1} &= \cosh\varepsilon\alpha_{2j-1} + i\sinh\varepsilon\left(\alpha_{2j-1} + 2\sum_{k=2j}^{\ell}\alpha_k\right) \quad \text{for } j = 1,\ldots, \\
\tilde{\alpha}_{2j} &= \cosh\varepsilon\alpha_{2j} - i\sinh\varepsilon\left(\sum_{k=2j}^{2j+2}\alpha_k + 2\sum_{k=2j+3}^{\ell}2\alpha_k\right) \quad \text{for } j = 1,\ldots \\
\tilde{\alpha}_{\ell-1} &= \cosh\varepsilon(\alpha_{\ell-1} + \alpha_\ell) - \alpha_\ell - i\sinh\varepsilon\left(\alpha_{\ell-2} + \alpha_{\ell-1} + \alpha_\ell\right), \\
\tilde{\alpha}_\ell &= \alpha_\ell .
\end{aligned}
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with different ω_i we find for instance for B_{2n+1}

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\end{aligned}
$$

in dual space

$$
\theta_\varepsilon^\star = \begin{pmatrix} R & & & & \\ & R & & 0 & \\ & & R & & \\ & 0 & & \ddots & \\ & & & & 1 \end{pmatrix} \qquad \text{with } R = \begin{pmatrix} \cosh\varepsilon & i\sinh\varepsilon \\ -i\sinh\varepsilon & \cosh\varepsilon \end{pmatrix}
$$

For **any** model based on roots, these deformed roots can be used to define new invariant models simply by

$$\alpha \to \tilde{\alpha}.$$

For instance Calogero models:

- Physical properties (A_2, G_2)
  - The deformed model can be solved by separation of variables as the undeformed case.
  - Some restrictions cease to exist, as the wavefunctions are now regularized.
  - $\Rightarrow$ modified energy spectrum:

$$E = 2\,|\omega|\,(2n + \lambda + 1)$$

becomes

$$E_{n\ell}^{\pm} = 2|\omega|\left[2n + 6(\kappa_s^{\pm} + \kappa_l^{\pm} + \ell) + 1\right] \qquad \text{for } n, \ell \in \mathbb{N}_0,$$

with $\kappa_{s/l}^{\pm} = (1 \pm \sqrt{1 + 4g_{s/l}})/4$

[A. Fring and M. Znojil, J. Phys. A41 (2008) 194010]

- generalized Calogero Hamiltonian (undeformed)

$$\mathcal{H}_C(p,q) = \frac{p^2}{2} + \frac{\omega^2}{4} \sum_{\alpha\in\Delta^+} (\alpha \cdot q)^2 + \sum_{\alpha\in\Delta^+} \frac{g_\alpha}{(\alpha \cdot q)^2},$$

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- define the variables

$$z := \prod_{\alpha\in\Delta^+}(\alpha\cdot q) \qquad \text{and} \qquad r^2 := \frac{1}{\hat{h}t_\ell}\sum_{\alpha\in\Delta^+}(\alpha\cdot q)^2,$$

$\hat{h} \equiv$ dual Coxeter number, $t_\ell \equiv \ell$-th symmetrizer of I

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- Ansatz:

$$\psi(q) \to \psi(z,r) = z^{\kappa+1/2}\varphi(r)$$

$\Rightarrow$ solution for $\kappa = 1/2\sqrt{1+4g}$.

$$\varphi_n(r) = c_n \exp\left(-\sqrt{\frac{\hat{h}t_\ell}{2}}\frac{\omega}{2}r^2\right) L_n^a\left(\sqrt{\frac{\hat{h}t_\ell}{2}}\omega r^2\right).$$

$L_n^a(x) \equiv$ Laguerre polynomial, $a = \left(2+h+h\sqrt{1+4g}\right) l/4 - 1$

- eigenenergies

$$E_n = \frac{1}{4}\left[\left(2 + h + h\sqrt{1+4g}\right) l + 8n\right]\sqrt{\frac{\hat{h}t_\ell}{2}}\omega$$

- anyonic exchange factors

$$\psi(q_1, \ldots, q_i, q_j, \ldots q_n) = e^{\imath\pi s}\psi(q_1, \ldots, q_j, q_i, \ldots q_n), \quad \text{for } 1 \leq i, j \leq n,$$

with

$$s = \frac{1}{2} + \frac{1}{2}\sqrt{1+4g}$$

$\because$ r is symmetric and z antisymmetric

The construction is based on the identities:

$$\sum_{\alpha,\beta\in\Delta^+} \frac{\alpha\cdot\beta}{(\alpha\cdot q)(\beta\cdot q)} = \sum_{\alpha\in\Delta^+} \frac{\alpha^2}{(\alpha\cdot q)^2},$$

$$\sum_{\alpha,\beta\in\Delta^+} (\alpha\cdot\beta)\frac{(\alpha\cdot q)}{(\beta\cdot q)} = \frac{\hat{h}h\ell}{2}t_\ell,$$

$$\sum_{\alpha,\beta\in\Delta^+} (\alpha\cdot\beta)\,(\alpha\cdot q)(\beta\cdot q) = \hat{h}t_\ell \sum_{\alpha\in\Delta^+} (\alpha\cdot q)^2,$$

$$\sum_{\alpha\in\Delta^+} \alpha^2 = \ell\hat{h}t_\ell.$$

Strong evidence on a case-by-case level, but no rigorous proof.

- antilinearly deformed Calogero Hamiltionian

$$\mathcal{H}_{adC}(p,q) = \frac{p^2}{2} + \frac{\omega^2}{4} \sum_{\tilde{\alpha} \in \tilde{\Delta}^+} (\tilde{\alpha} \cdot q)^2 + \sum_{\tilde{\alpha} \in \Delta^+} \frac{g_{\tilde{\alpha}}}{(\tilde{\alpha} \cdot q)^2}$$

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when identies still hold $\Rightarrow$

$$\psi(q) = \psi(\tilde{z},r) = \tilde{z}^s\varphi_n(r)$$

eigenenergies with different constraints (only performed for ground state)

Deformed A_3-models

- potential from deformed Coxeter group factors

  $\alpha_1 = \{1, -1, 0, 0\}$, $\alpha_2 = \{0, 1, -1, 0\}$, $\alpha_3 = \{0, 0, 1, -1\}$

$$
\begin{aligned}
\tilde{\alpha}_1 \cdot q &= q_{43} + \cosh\varepsilon(q_{12} + q_{34}) - \imath\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}(q_{13} + q_{24}) \\
\tilde{\alpha}_2 \cdot q &= q_{23}(2\cosh\varepsilon - 1) + \imath 2\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}q_{14} \\
\tilde{\alpha}_3 \cdot q &= q_{21} + \cosh\varepsilon(q_{12} + q_{34}) - \imath\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}(q_{13} + q_{24}) \\
\tilde{\alpha}_4 \cdot q &= q_{42} + \cosh\varepsilon(q_{13} + q_{24}) + \imath\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}(q_{12} + q_{34}) \\
\tilde{\alpha}_5 \cdot q &= q_{31} + \cosh\varepsilon(q_{13} + q_{24}) + \imath\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}(q_{12} + q_{34}) \\
\tilde{\alpha}_6 \cdot q &= q_{14}(2\cosh\varepsilon - 1) - \imath\sqrt{2\cosh\varepsilon}\sinh\frac{\varepsilon}{2}q_{23}
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notation $q_{ij} = q_i - q_j$,

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\end{aligned}
$$

notation $q_{ij} = q_i - q_j$, **No longer singular for $q_{ij} = 0$**

- $\mathcal{PT}$-symmetry for $\tilde{\alpha}$

$$\sigma_-^\varepsilon : \; \tilde{\alpha}_1 \to -\tilde{\alpha}_1, \tilde{\alpha}_2 \to \tilde{\alpha}_6, \tilde{\alpha}_3 \to -\tilde{\alpha}_3, \tilde{\alpha}_4 \to \tilde{\alpha}_5, \tilde{\alpha}_5 \to \tilde{\alpha}_4, \tilde{\alpha}_6 \to \tilde{\alpha}_2$$

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- $\mathcal{PT}$-symmetry in dual space

$$\sigma_-^\varepsilon: q_1 \to q_2, q_2 \to q_1, q_3 \to q_4, q_4 \to q_3, \imath \to -\imath$$
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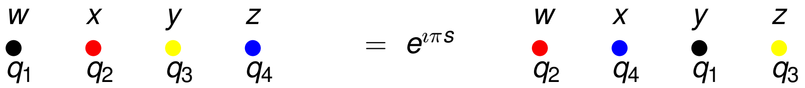
$\Rightarrow$

$$\sigma_-^\varepsilon \tilde{z}(q_1, q_2, q_3, q_4) = \tilde{z}^*(q_2, q_1, q_4, q_3) = \tilde{z}(q_1, q_2, q_3, q_4)$$
$$\sigma_+^\varepsilon \tilde{z}(q_1, q_2, q_3, q_4) = \tilde{z}^*(q_1, q_3, q_2, q_4) = -\tilde{z}(q_1, q_2, q_3, q_4)$$

$$\psi(q_1, q_2, q_3, q_4) = e^{\imath\pi s}\psi(q_2, q_4, q_1, q_3).$$

Anyonic exchange factors in the 4-particle scattering process



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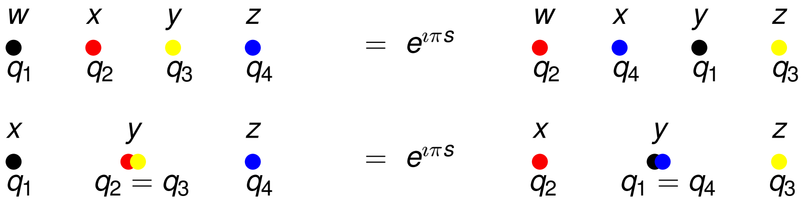

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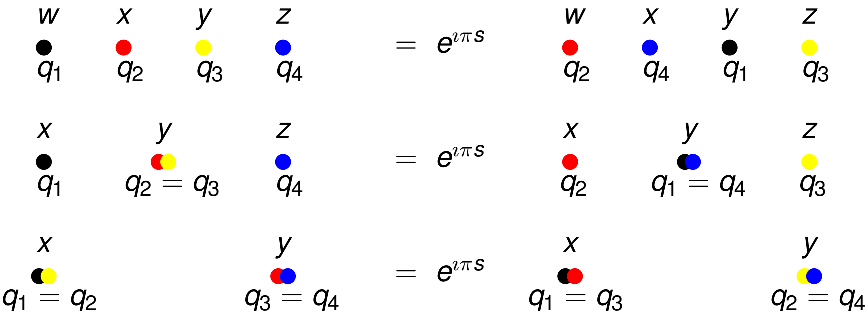

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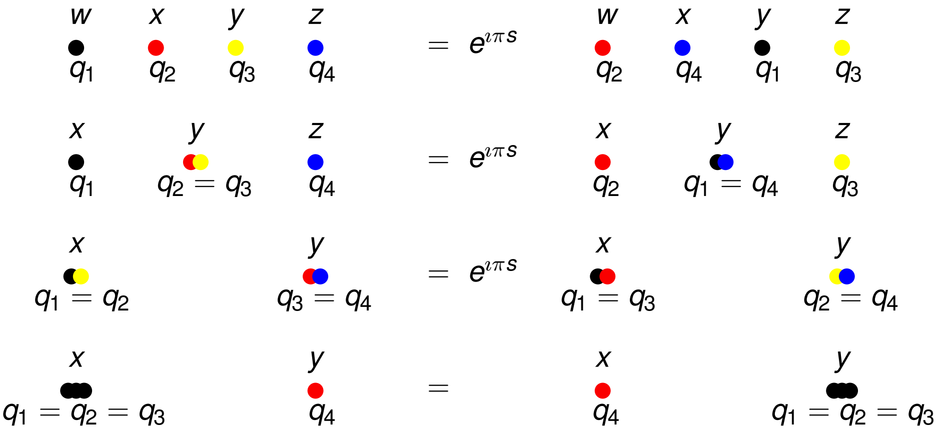

Find Hermitian counterpart h, Dyson map η and metric ρ:

$$h = \eta H \eta^{-1} = h^{\dagger} = (\eta^{-1})^{\dagger} H^{\dagger} \eta^{\dagger} \quad \Leftrightarrow \quad H^{\dagger}\rho = \rho H \;\text{ with } \rho = \eta^{\dagger}\eta$$

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Some B_ℓ-models correspond to complex rotations

$$\begin{pmatrix} \tilde{z}_i \\ \tilde{z}_j \end{pmatrix} = R_{ij} \begin{pmatrix} z_i \\ z_j \end{pmatrix} = \eta_{ij} \begin{pmatrix} z_i \\ z_j \end{pmatrix} \eta_{ij}^{-1}, \qquad \text{for } z \in \{x, p\},\; \eta_{ij} = e^{\varepsilon(x_i p_j - x_j p_i)}$$

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For instance for:

$$\theta_\varepsilon^\star = \begin{pmatrix} R & & & & \\ & R & & 0 & \\ & & R & & \\ & 0 & & \ddots & \\ & & & & 1 \end{pmatrix} \qquad \text{with } R = \begin{pmatrix} \cosh\varepsilon & i\sinh\varepsilon \\ -i\sinh\varepsilon & \cosh\varepsilon \end{pmatrix}$$

we have

$$\mathcal{H}_0(p, x) = \eta \mathcal{H}_\varepsilon(p, x) \eta^{-1}$$

with

$$\eta = \eta_{12}^{-1} \eta_{34}^{-1} \eta_{56}^{-1} \cdots \eta_{(\ell-2)(\ell-1)}^{-1}$$

For B_5

$$\theta_\varepsilon^\star = \begin{pmatrix} r_0 & -i\vartheta & i\vartheta & 1-r_0 & 0 \\ i\vartheta & r_0 & 1-r_0 & -i\vartheta & 0 \\ -i\vartheta & 1-r_0 & r_0 & i\vartheta & 0 \\ 1-r_0 & i\vartheta & -i\vartheta & r_0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

we find

$$\tilde{x} = \theta_\varepsilon^\star x = R_{24}^{-1} R_{13} R_{34} R_{12}^{-1} x = \eta x \eta^{-1}, \qquad \text{with } \eta = \eta_{24}^{-1}\eta_{13}\eta_{34}\eta_{12}^{-1}.$$

In general this is an open problem.

General deformation prescription:

$\mathcal{PT}$-anti-symmetric quantities:

$$\mathcal{PT}: \phi(x,t) \mapsto -\phi(x,t) \quad \Rightarrow \quad \delta_\varepsilon : \phi(x,t) \mapsto -i[i\phi(x,t)]^\varepsilon$$

Two possibilities for the KdV Hamiltonian

$$\delta_\varepsilon^+ : u_x \mapsto u_{x,\varepsilon} := -i(iu_x)^\varepsilon \qquad \text{or} \qquad \delta_\varepsilon^- : u \mapsto u_\varepsilon := -i(iu)^\varepsilon,$$

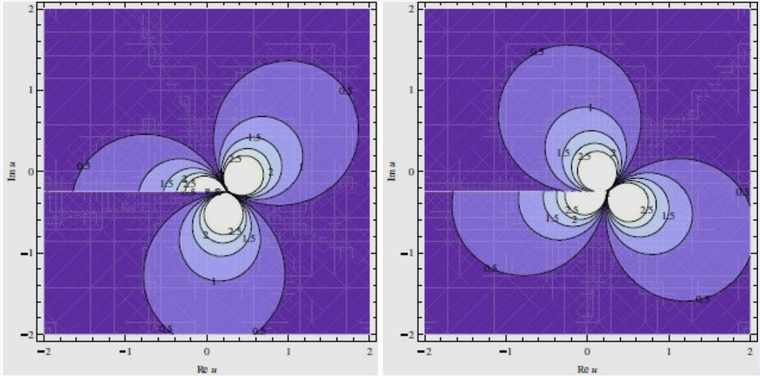
such that

$$\mathcal{H}_\varepsilon^+ = -\frac{\beta}{6}u^3 - \frac{\gamma}{1+\varepsilon}(iu_x)^{\varepsilon+1} \qquad \mathcal{H}_\varepsilon^- = \frac{\beta}{(1+\varepsilon)(2+\varepsilon)}(iu)^{\varepsilon+2} + \frac{\gamma}{2}u_x^2$$

with equations of motion

$$u_t + \beta u u_x + \gamma u_{xxx,\varepsilon} = 0 \qquad u_t + i\beta u_\varepsilon u_x + \gamma u_{xxx} = 0$$

Broken $\mathcal{PT}$-symmetric rational solutions for $\mathcal{H}_{1/3}^+$

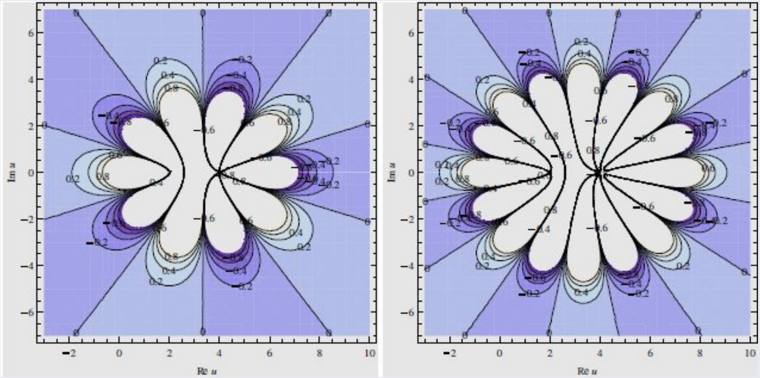


Different Riemann sheets for $A = (1-i)/4$, $c = 1$, $\beta = 2 + 2i$ and $\gamma = 3$

(a) $u^{(1)}$

(b) $u^{(2)}$

$\mathcal{PT}$-symmetric trigonometric/hyperbolic solutions

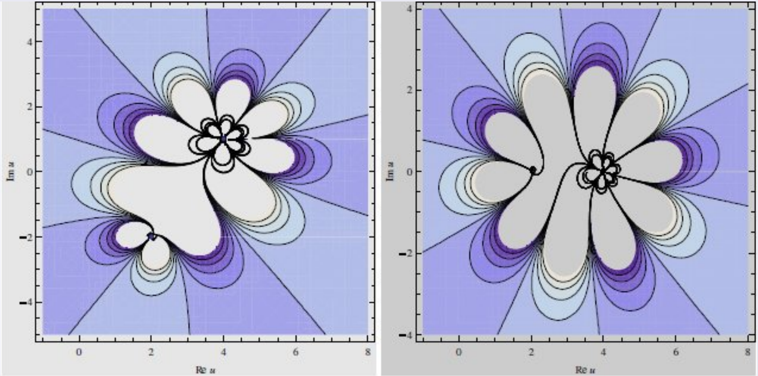


$A = 4, B = 2, c = 1, \beta = 2$ and $\gamma = 3$

(a) $\mathcal{H}^+_{-1/2}$

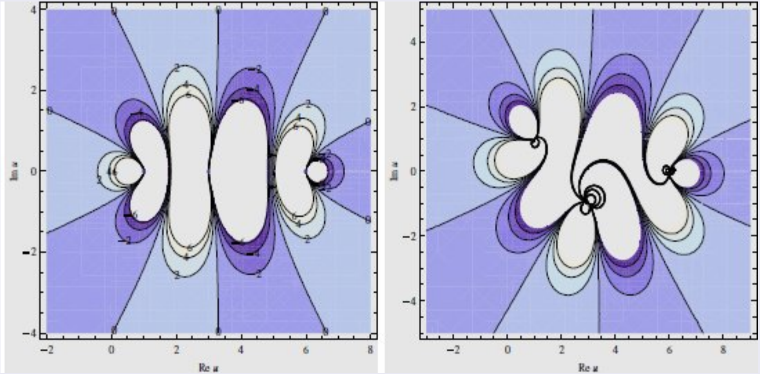
(b) $\mathcal{H}^+_{-2/3}$

Broken $\mathcal{PT}$-symmetric trigonometric solutions for $\mathcal{H}_{-1/2}^{+}$



(a) Spontaneously broken $\mathcal{PT}$-symmetry with $A = 4 + i$, $B = 2 - 2i$, $c = 1$, $\beta = 3/10$ and $\gamma = 3$
(b) broken $\mathcal{PT}$-symmetry with $A = 4$, $B = 2$, $c = 1$, $\beta = 3/10$ and $\gamma = 3 + i$

Elliptic solutions for $\mathcal{H}_{-1/2}^{+}$:



(a) $\mathcal{PT}$-symmetric with $A = 1$, $B = 3$, $C = 6$, $\beta = 3/10$, $\gamma = -3$ and $c = 1$
(b) spontaneously broken $\mathcal{PT}$-symmetry with $A = 1 + i$, $B = 3 - i$, $C = 6$, $\beta = 3/10$, $\gamma = -3$ and $c = 1$

The $\mathcal{H}_\varepsilon^-$-models

Integrating twice gives now:

$$u_\zeta^2 = \frac{2}{\gamma}\left(\kappa_2 + \kappa_1 u + \frac{c}{2}u^2 - \beta\frac{i^\varepsilon}{(1+\varepsilon)(2+\varepsilon)}u^{2+\varepsilon}\right) =: \lambda Q(u)$$

where

$$\lambda = -\frac{2\beta i^\varepsilon}{\gamma(1+\varepsilon)(2+\varepsilon)}$$

For $\kappa_1 = \kappa_2 = 0$

$$u(\zeta) = \left(\frac{c(\varepsilon+1)(\varepsilon+2)}{i^\varepsilon\beta\left[\cosh\left(\frac{\sqrt{c}\varepsilon(\zeta-\zeta_0)}{\sqrt{\gamma}}\right)+1\right]}\right)^{1/\varepsilon}$$

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  $\equiv$ complex version of the modified KdV-equation

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  assume $Q(u) = u^2(u^2 - B^2)(u^2 - C^2)$, possible for

$$\kappa_1 = \kappa_2 = 0, \qquad B = iC \qquad \text{and} \qquad C^4 = \frac{15c}{\beta}$$

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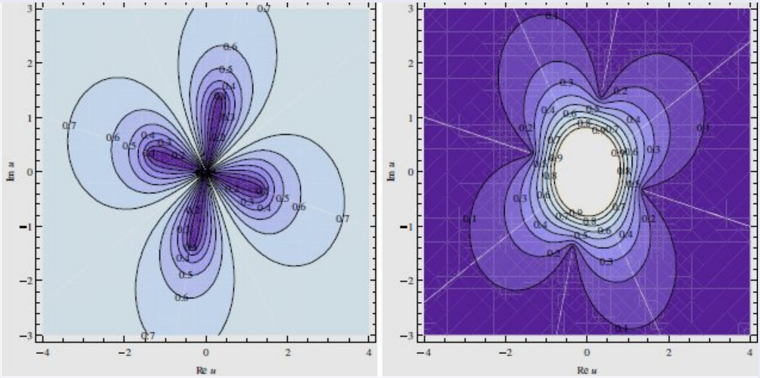
eigenvalues of Jacobian:

$$\begin{aligned} j_1 &= \pm i\sqrt{r_\lambda} r_B^2 \exp\left[\frac{i}{2}(4\theta_B + \theta_\lambda)\right] \\ j_2 &= \mp i\sqrt{r_\lambda} r_B^2 \exp\left[-\frac{i}{2}(4\theta_B + \theta_\lambda)\right] \end{aligned}$$

Broken $\mathcal{PT}$-symmetric solution for $\mathcal{H}_4^{-}$:



(a) star node at the origin for $c = 1$, $\beta = 2 + i3$, $\gamma = 1$ and $B = (15/2 + i3)^{1/4}$
(b) centre at the origin for $c = 1$, $\beta = 2 + i3$, $\gamma = -1$ and $B = (30/13 - i45/13)^{1/4}$

Reduction to quantum mechanical Hamiltonians:
Again we can relate to simple quantum mechanical models:
The identification

$$u \to x, \quad \zeta \to t, \quad \kappa_1 = 0, \quad \kappa_2 = \gamma E, \quad \text{and} \quad \beta = \gamma g(1+\varepsilon)(2+\varepsilon)$$

relates $\mathcal{H}_\varepsilon^-$ to

$$H = E = \frac{1}{2}p^2 - \frac{c}{2\gamma}x^2 + gx^2(ix)^\varepsilon$$

For $c = 0$ these are the "classical models" studied in
[C. Bender, S. Boettcher, Phys. Rev. Lett. 80 (1998) 5243]

Reduction of the $\mathcal{H}_2^-$-model

$$\mathcal{H}_2^-[u] = \frac{\beta}{12}u^4 + \frac{\gamma}{2}u_x^2$$

Twice integrated equation of motion:

$$u_\zeta^2 = \frac{2}{\gamma}\left(\kappa_2 + \kappa_1 u + \frac{c}{2}u^2 + \beta\frac{1}{12}u^4\right) =: \lambda Q(u)$$

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Reduction $u \to x$, $\zeta \to t$

$$\kappa_1 = -\gamma\tau, \quad \kappa_2 = \gamma E_x, \quad \beta = -3\gamma g \quad \text{and} \quad c = -\gamma\omega^2$$

Quartic harmonic oscillator of the form

$$H = E_x = \frac{1}{2}p^2 + \tau x + \frac{\omega^2}{2}x^2 + \frac{g}{4}x^4$$

Boundary cond.: $\kappa_1 = \tau = 0$, $\lim_{\zeta\to\infty} u(\zeta) = 0$, $\lim_{\zeta\to\infty} u_x(\zeta) = \sqrt{2E_x}$

[A.G. Anderson, C. Bender, U. Morone, arXiv:1102.4822]

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[A.G. Anderson, C. Bender, U. Morone, arXiv:1102.4822]

Note: $E_x \neq E_u(a)$

Ito type systems and its deformations

Coupled nonlinear system

$$
\begin{aligned}
u_t + \alpha v v_x + \beta u u_x + \gamma u_{xxx} &= 0, \qquad && \alpha, \beta, \gamma \in \mathbb{C}, \\
v_t + \delta (uv)_x + \phi v_{xxx} &= 0, \qquad && \delta, \phi \in \mathbb{C}
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Hamiltonian for $\delta = \alpha$

$$\mathcal{H}_I = -\frac{\alpha}{2} u v^2 - \frac{\beta}{6} u^3 + \frac{\gamma}{2} u_x^2 + \frac{\phi}{2} v_x^2$$

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$\mathcal{PT}$-symmetries:

$$\begin{aligned} &\mathcal{PT}_{++} : x \mapsto -x, t \mapsto -t, i \mapsto -i, u \mapsto u, v \mapsto v && \text{for } \alpha, \beta, \gamma, \phi \in \mathbb{R} \\ &\mathcal{PT}_{+-} : x \mapsto -x, t \mapsto -t, i \mapsto -i, u \mapsto u, v \mapsto -v && \text{for } \alpha, \beta, \gamma, \phi \in \mathbb{R} \\ &\mathcal{PT}_{-+} : x \mapsto -x, t \mapsto -t, i \mapsto -i, u \mapsto -u, v \mapsto v && \text{for } i\alpha, i\beta, \gamma, \phi \in \mathbb{R} \\ &\mathcal{PT}_{--} : x \mapsto -x, t \mapsto -t, i \mapsto -i, u \mapsto -u, v \mapsto -v && \text{for } i\alpha, i\beta, \gamma, \phi \in \mathbb{R} \end{aligned}$$

Deformed models

$$\mathcal{H}^{++}_{\varepsilon,\mu} = -\frac{\alpha}{2}uv^2 - \frac{\beta}{6}u^3 - \frac{\gamma}{1+\varepsilon}(iu_x)^{\varepsilon+1} - \frac{\phi}{1+\mu}(iv_x)^{\mu+1}$$

$$\mathcal{H}^{+-}_{\varepsilon,\mu} = \frac{\alpha}{1+\mu}u(iv)^{\mu+1} - \frac{\beta}{6}u^3 - \frac{\gamma}{1+\varepsilon}(iu_x)^{\varepsilon+1} + \frac{\phi}{2}v_x^2$$

$$\mathcal{H}^{-+}_{\varepsilon,\mu} = -\frac{\alpha}{2}uv^2 - \frac{i\beta}{(1+\varepsilon)(2+\varepsilon)}(iu)^{2+\varepsilon} + \frac{\gamma}{2}u_x^2 - \frac{\phi}{1+\mu}(iv_x)^{\mu+1}$$

$$\mathcal{H}^{--}_{\varepsilon,\mu} = \frac{\alpha}{1+\mu}u(iv)^{\mu+1} - \frac{i\beta}{(1+\varepsilon)(2+\varepsilon)}(iu)^{2+\varepsilon} + \frac{\gamma}{2}u_x^2 + \frac{\phi}{2}v_x^2$$

with equations of motion

$$u_t + \alpha v v_x + \beta u u_x + \gamma u_{xxx,\varepsilon} = 0, \quad u_t + \alpha v_\mu v_x + \beta u u_x + \gamma u_{xxx,\varepsilon} = 0,$$
$$v_t + \alpha(uv)_x + \phi v_{xxx,\mu} = 0, \quad v_t + \alpha(uv_\mu)_x + \phi v_{xxx} = 0,$$

$$u_t + \alpha v v_x + \beta u_\varepsilon u_x + \gamma u_{xxx} = 0, \quad u_t + \alpha v_\mu v_x + \beta u_\varepsilon u_x + \gamma u_{xxx} = 0,$$
$$v_t + \alpha(uv)_x + \phi v_{xxx,\mu} = 0, \quad v_t + \alpha(uv_\mu)_x + \phi v_{xxx} = 0.$$

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- Non-Hermitian Hamiltonians describe physical systems within a self-consistent quantum mechanical framework.
- One can use this possibility to explore deformations of well studied models, e.g. integrable systems.
- There exist now experiments, especially in optics, for the broken PT-regime.

Thank you for your attention

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