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Interpretation of neutral charm mesons near threshold as unparticles

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Outline

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- Unparticles and Schrödinger symmetry
- Nuclear reactions with neutrons
- Neutral charm mesons and the $X(3872)$
- Summary and Outlook

References:

HWH, **D.T. Son**, Proc. Nat. Acad. Sci. **118**, e2108716118 (2021) [arXiv:2103.12610]

Braaten, HWH, Phys. Rev. Lett. **128**, 032002 (2022) [arxiv:2107.02831]

Unparticle physics

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- (Relativistic) unparticle (Georgi, Phys. Rev. Lett. **98**, 221601 (2007))
  - field ψ in relativistic conformal field theory
  - ψ characterized by scaling dimension Δ, massless
  - hidden conformal symmetry sector beyond Standard model (weakly coupled)
  - no evidence at LHC so far
    (CMS Coll., EPJC **75**, 235 (2015), PRD **93**, 052011, JHEP **03**, 061 (2017))
- (Non-relativistic) unparticle/unnucleus
  - non-relativistic analog of Georgi's unparticle
  - field ψ in non-relativistic conformal field theory $\Rightarrow$ Schrödinger symmetry
    (cf. Nishida, Son, Phys. Rev. D **76**, 086004 (2007))
  - ψ characterized by scaling dimension Δ and mass M
  - free field has $\Delta = 3/2$ $\Longleftrightarrow$ mass dimension

    $\Rightarrow$ lowest possible value (unitarity)
  - N neutrons are (approximate) unparticle with mass Nm_N and scaling dimension $\Delta = ?$

Schrödinger symmetry

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- Non-relativistic conformal symmetry: Schrödinger symmetry
  - Galilei symmetry

    space + time translations

    rotations

    Galilei boosts
  - Scale transformations

$$\boldsymbol{x} \to e^{\lambda}\boldsymbol{x}, \qquad t \to e^{2\lambda}t, \qquad \psi \to e^{-\lambda\Delta}\psi$$

  - Special conformal transformations

$$\boldsymbol{x} \to \frac{\boldsymbol{x}}{1+\xi t}, \qquad t \to \frac{t}{1+\xi t}, \qquad \psi \to \psi' = \ldots$$

  $\Rightarrow$ preserves angles
- 12 Parameters
- Generators: $H, \boldsymbol{P}, \boldsymbol{L}, \boldsymbol{K}, D, C,$ satisfy Schrödinger algebra

Conformal field theory

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- Two-point function of primary field operator $\mathcal{U}$ ("unnucleus")

$$G_{\mathcal{U}}(t,\boldsymbol{x}) = -i\langle T\mathcal{U}(t,\boldsymbol{x})\mathcal{U}^\dagger(0,\boldsymbol{0})\rangle = C\,\frac{\theta(t)}{(it)^\Delta}\exp\left(\frac{iM\boldsymbol{x}^2}{2t}\right)$$

- Determined by symmetry up to overall constant C
- Two-point function in momentum space

$$G_{\mathcal{U}}(\omega,\boldsymbol{p}) = -C\left(\frac{2\pi}{M}\right)^{3/2}\Gamma\left(\frac{5}{2}-\Delta\right)\left(\frac{\boldsymbol{p}^2}{2M}-\omega\right)^{\Delta-\frac{5}{2}}$$

  - pole only for $\Delta = 3/2$ (free field)
  - branch cut for $\Delta > 3/2$
- General unnucleus/unparticle does not behave like a particle

$\Rightarrow$ continuous energy spectrum

Scaling dimension for neutrons

- How to calculate scaling dimension Δ?

  (1) Δ can be obtained from field theory calculation

  (2) Δ can be obtained from operator state correspondence

Δ of primary operator = (Energy of state in HO)/$\hbar\omega$

(Nishida, Son, Phys. Rev. D **76**, 086004 (2007))

N	S	L	$\mathcal{O}$	Δ
2	0	0	$\psi_1\psi_2$	2
3	1/2	1	$\psi_1\psi_2\nabla_j\psi_2$	4.27272
3	1/2	0	$\psi_1\nabla_j\psi_2\nabla_j\psi_2$	4.66622
4	0	0	$\psi_1\psi_2\nabla_j\psi_1\nabla_j\psi_2$	5.07(1)
5	1/2	1	...	7.6(1)

$\Rightarrow$ connection between Δ and energy of particles in a trap

Reactions with neutrons

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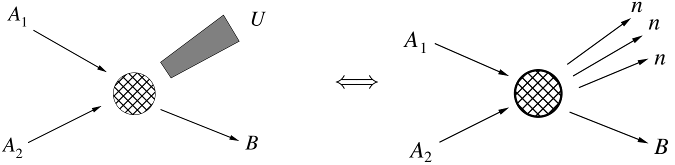
- Application: High-energy nuclear reaction with final state neutrons



$$E_{\text{kin}} = (M_{A_1} + M_{A_2} - M_B - M_{\mathcal{U}})c^2 + \frac{p_{A_1}^2}{2M_{A_1}} + \frac{p_{A_2}^2}{2M_{A_2}} = E_B + E_{\mathcal{U}}$$

- Assumption: energy scale of primary reaction $\gg E_{\mathcal{U}} - \frac{\boldsymbol{p}^2}{2M_{\mathcal{U}}} = E_n^{cms}$
- Factorization: $\frac{d\sigma}{dE} \sim |\mathcal{M}_{primary}|^2 \, \mathrm{Im}\, G_{\mathcal{U}}(E_{\mathcal{U}}, \boldsymbol{p})$
- Reproduces Watson-Migdal treatment of FSI for $2n$
  (Watson, Phys. Rev. **88**, 1163 (1952); Migdal, Sov. Phys. JETP **1**, 2 (1955))

Neutral charm mesons and $X(3872)$

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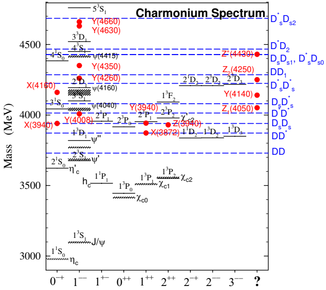
- New $c\bar{c}$ states at B factories: X, Y, Z
  (cf. Godfrey, arXiv:0910.3409)
  - Challenge for understanding of QCD
  - Unitary limit relevant?
- $X(3872)$ (Belle, CDF, BaBar, D0, LHCb)
- Nature of $X(3872)$?
  - $\bar{D}^0 D^{0*}$-molecule, tetraquark, charmonium hybrid, ...



$m_X = (3871.65 \pm 0.06)$ MeV, $\Gamma = (1.19 \pm 0.21)$ MeV, $J^{PC} = 1^{++}$ (PDG 2021)

- Assumption: $X(3872)$ is weakly-bound D^0-$\bar{D}^{0*}$-molecule

$\Rightarrow \quad |X\rangle = (|D^0\bar{D}^{0*}\rangle + |\bar{D}^0 D^{0*}\rangle)/\sqrt{2}\,, \qquad B_X = (0.07 \pm 0.12)\text{ MeV} \approx 1/(2\mu_{DD^*} a^2)$

$\Rightarrow$ universal properties (Braaten et al., 2003-2008; ...)

Neutral charm mesons and $X(3872)$

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- Approximate unparticles of three D^0/D^{0*} mesons
- Interaction of $X(3872)$ with D^0, $\bar{D}^0$, D^{0*}, $\bar{D}^{0*}$ determined by large a

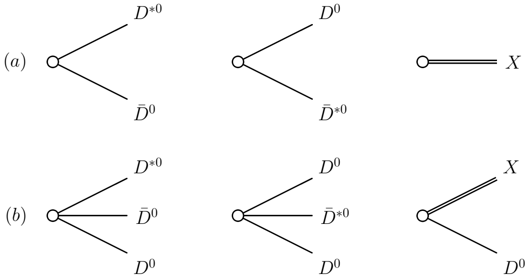
(Canham, HWH, Springer, PRD **80**, 014009 (2009))

$$a_{D^0X} = -9.7a \qquad a_{D^{*0}X} = -16.6\,a$$

- Richer structure because of $X(3872)$ (bound state)

two charm mesons

three charm mesons



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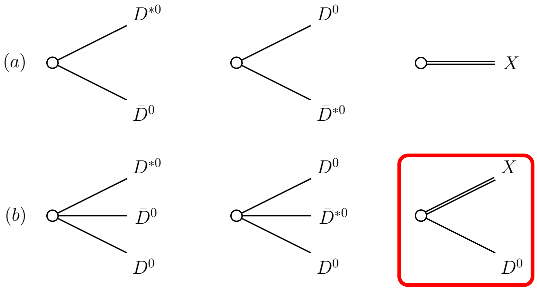

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- Universal scaling for unparticles of three neutral charm mesons

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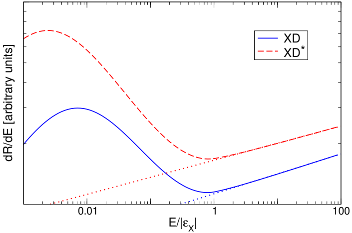
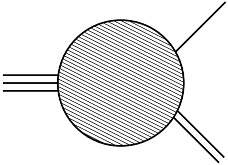


XD point production



$$\frac{dR}{dE} \sim \left(E^{-(\Delta_1+\Delta_2-\Delta_3)/2}\right)^2 \sqrt{E} \approx E^{0.1}$$

from conformal 3-pt. function

$\Delta_1 = 3/2, \quad \Delta_2 = 2, \quad \Delta_3 \approx 3.10119/3.08697$

Scaling Behavior

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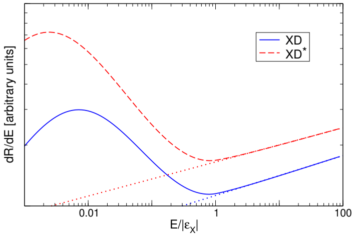
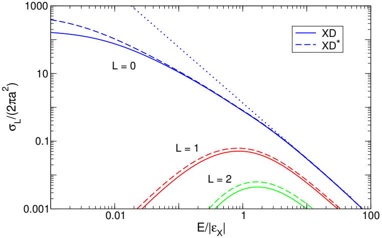


XD point production



XD elastic scattering

$$\frac{dR}{dE} \sim (E^{-(\Delta_1+\Delta_2-\Delta_3)/2})^2\sqrt{E} \approx E^{0.1}$$

$\Delta_1 = 3/2, \quad \Delta_2 = 2, \quad \Delta_3 \approx 3.10119/3.08697$

$$\sigma \sim E^{-1.6}$$

Summary and Outlook

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- Universality in the unitary limit $\Leftrightarrow$ Unparticles

  $\Rightarrow$ (approximate) conformal symmetry

  $\Rightarrow$ power law behavior of observables determined by Δ

- Application to high-energy nuclear reactions with neutrons
- Connection between reactions & properties of trapped particles
- Neutral charm mesons can be interpreted as unparticles

  $\Rightarrow$ different scaling regions

Summary and Outlook

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- Neutral charm mesons can be interpreted as unparticles

  $\Rightarrow$ different scaling regions
- Other applications & extensions
  - Systems with the Efimov effect?

    $\Rightarrow$ complex scaling dimensions

    $\Rightarrow$ scale symmetry broken

Additional Slides

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Conformal field theory

- Imaginary part of propagator

$$\mathrm{Im}\, G_{\mathcal{U}}(\omega, \boldsymbol{p}) \sim \begin{cases} \delta\left(\omega - \frac{\boldsymbol{p}^2}{2M}\right), & \Delta = \frac{3}{2}\,, \\ \left(\omega - \frac{\boldsymbol{p}^2}{2M}\right)^{\Delta - \frac{5}{2}} \theta\left(\omega - \frac{\boldsymbol{p}^2}{2M}\right), & \Delta > \frac{3}{2} \end{cases}$$

- Examples of unnuclei
  - free field: $\mathcal{U} = \psi$, $M = m_\psi$, $\Delta = 3/2$
  - N free fields: $\mathcal{U} = \psi_1 \ldots \psi_N$, $M = Nm_\psi$, $\Delta = 3N/2$
  - N interacting fields: $\mathcal{U} = \psi_1 \ldots \psi_N$, $M = Nm_\psi$, $\Delta > 3/2$
- In our case: unnucleus is strongly interacting multi-neutron state with

$$\underbrace{1/(ma^2)}_{0.1\,\text{MeV}} \ll E_n^{cms} \ll \underbrace{1/(mr_e^2)}_{5\,\text{MeV}}$$