

Dark nuclei

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Dark nuclei

- Dark nuclear physics of QCD like theory with $N_c=2$ and $N_f=2$
- Based on two recent papers in collaboration with $\mathcal{L}_{\mathcal{A}}$ *Matthew McCullough* & *Andrew Pochinsky*
	- *Dark Nuclei I: Cosmology and Indirect Detection* —1406.2276 L.
	- *Dark Nuclei II: Nuclear Spectroscopy* in Two-Colour QCD —1406.4116 \mathbb{R}^n
- Motivation n.
	- Understand what is "nuclear physics" in a general context What are generic features, what is special?
	- Dark matter model building: interesting new phenomenology

Two-colour QCD

- Two-colour QCD with two flavours of fundamental fermions T.
	- Numerically feasible (simpler than QCD) \mathbb{R}^n
	- Emergent complexity: novel phenomenological aspects
- Single hadron aspects already considered in DM context [Lewis et al., Neil & Buckley, Hietanen et al.]
- Also lattice investigations of quenched $N_c = 4$ QCD and other theories in this context [LSD collaboration]
	- Sigma terms, polarisabilities,…
- Global flavour symmetry $SU(2)_L \times SU(2)_R$ enlarges to $SU(4)$
	- Pseudo-reality of SU(2) left and right handed quarks can be combined into multiplets

$$
\Psi = \begin{pmatrix} u_L \\ d_L \\ -i\sigma_2 C \bar{u}_R^\top \\ -i\sigma_2 C \bar{d}_R^\top \end{pmatrix} \qquad \Psi \stackrel{SU(4)}{\longrightarrow} \exp\left(i\sum_{j=1}^{15} \theta_j T_j\right) \Psi
$$

- Strong interactions result in condensate that spontaneously breaks the global symmetry: $SU(4) \rightarrow Sp(4) \sim SO(5)$ [Peskin 1980]
- Numerical calculations have significant explicit symmetry a a breaking: m_u=m_d~Λ_{QC2D}

Spectrum

- Simplest colour singlets
	- $\overline{\mathbf{u}}$ "Pions": π ⁻~ūγ5d, π ⁰~ūγ5u + d̄γ5d, π ⁺~d̄γ5u J^P=0-} $\mathcal{L}_{\mathcal{A}}$ Degenerate
	- (anti-)"Nucleons": ud, $\overline{u}d$ $J^P=0^+$ SO(5) multiplet $-\overline{a}$
	- $\overline{\Pi}$ "Rhos": ρ ∇ $\nabla \psi$ μd, ρ $\nabla \psi$ μu + $\overline{d} \gamma$ μd, ρ $\nabla \psi$ μu J ψ =1 } $\mathcal{L}_{\mathcal{A}}$ Degenerate SO(5) multiplet
	- (anti-)"Deltas": uγ_μγ₅d, \overline{u} γ_μγ₅d J^P=1⁺ $\overline{\Pi}$
	- Axial vector, scalar, tensor mesons + associated baryons
- Single hadron spectrum studied by [Hietanen et al. [1404.2794](http://arxiv.org/abs/arXiv:1404.2794)]
	- Pion multiplet are pseudoGoldstone bosons of χSB : SU(4) \rightarrow Sp(4)
	- Rho stable for masses considered

Spectrum

Colour singlets can combine

the dark U(1)*^B* baryon number in the same units as the pions. In this notation the various

- Two-, three-, ... particle scattering states p.
- ²*,*⁰ *^S^µ ^D^µ* 1*,*⁰ *^D^µ* 1*,*¹ *^D^µ* 1*,*1 er
- S *a priori* obvior, "Nuclei" for sufficiently attractive interactions-not *a priori* obvious ⁰*,*¹ *^S^µ*
- Two "pions" combine to give 25 states: 5⊗5=1⊕10⊕14 1*,*¹ *^D^µ*
	- J=0 systems, contains B=2, I,0,-1,-2 states where a latter are real and the subscript denotes that the subscript denotes the states that the states that the diagonal states that the sta
- "pion"+ "rho": J=1 systems with same flavour breakdown pion inc is representative various various systems with same flavour breakdown real SO(5) representations may be written as

$$
\pmb{D}^{\mu} = \left(\begin{array}{cccc} S^{\mu}_{+} & D^{\mu}_{2,0} & D^{\mu}_{1,0} & D^{\mu}_{1,-1} & D^{\mu}_{1,1} \\ \overline{D}^{\mu}_{2,0} & S^{\mu}_{-} & D^{\mu}_{-1,0} & D^{\mu}_{-1,-1} & D^{\mu}_{-1,1} \\ \overline{D}^{\mu}_{1,0} & \overline{D}^{\mu}_{-1,0} & S^{\mu}_{0} & D^{\mu}_{0,-1} & D^{\mu}_{0,1} \\ \overline{D}^{\mu}_{1,-1} & \overline{D}^{\mu}_{-1,-1} & \overline{D}^{\mu}_{0,-1} & S^{\mu}_{B} & D^{\mu}_{0,2} \\ \overline{D}^{\mu}_{1,1} & \overline{D}^{\mu}_{-1,1} & \overline{D}^{\mu}_{0,1} + & \overline{D}^{\mu}_{0,2} & S^{\mu}_{\overline{B}} \end{array} \right) \qquad \qquad \pmb{D}^{\mu}_{\mathbf{1}} = \text{Tr}(\pmb{D}^{\mu}) \ ,
$$

Higher body systems: J=0,1, flavour = $\boxed{}\boxed{}\cdots\boxed{}$, n=2,...,8 where a linear are real and the subscript denotes the subscript denotes the subscript denotes that the diagonal \sim **Elements couple to intervents of the notation of the pion fields.** The pion \mathbb{R}^2 vectors for which the first subscript denotes the global U(1)*^D* charge and the second subscript The lattice calculation considered the nuclei in the symmetric representation, *D*14, finding bound states for a range of quark masses, but did not investigate the singlet or anti-… symmetric representations. To simplify the calculations relevant for \sim assume that all nuclei representations are stable and equality massive. This is purely for the this purely for the theorem in Γ n

Simulations

SU(2) multi-baryon contractions equivalent to maximal isospin multimeson contractions as indicated in Fig. 7. The meson contractions in Fig. 7. The meson contraction of the main \sim

n Clear from degeneracies but explicitly $S(y,x) = C^{\dagger}(-i\sigma_2)^{\dagger}S(x,y)^T(-i\sigma_2)C$ $S(y, x) = \gamma_5 S^{\dagger}(x, y) \gamma_5$

first relation specific to $N_c=2$

- **relations replace the multi-meson correlator for baryons that** \sim \sim \sim \sim \sim [WD & Savage 2011,;WD, Orginos, Shi 2012]
- (n-1)*N*Δ ~ mixed pion-kaon contractions Group theoretically, we consider the *n*th tensor product of fundamental representations $(11-1)1\sqrt{\Delta} \approx 1111 \times 1011 - 18$ and $\Delta = 111 \times 1011$ and $\Delta = 111$ formula $\Delta = 111$ formula multiplets of size (*n* + 1)(*n* + 2)(2*n* + 3)*/*6 [23]. In what follows, we will refer to the *I* = 0,

contractions and so have corresponding degenerate multi-baryon partners. The relation is matrix (the first relation is specific to the two colour theory). Multiple applications of these

> Ex: three types of contractions for I=3 πππ and *NNN*

N
N₁ A₂ A₂ A₂ Example effective mass shift plots to limit of propagators to limit **n 1** in the present calculation.

that these correlators encompass are performed using the methods of Refs. [18, 26, 27]. Since

the number of the number of the number of the single space-time point is single space-time point in the single

Energy shifts for different volumes

Assess support for each hypothesis using the Bayes factor

$$
K = \frac{P(D|H_1)}{P(D|H_2)} = \frac{\int P(D|H_1, p_1) P(p_1|H_1) dp_1}{\int P(D|H_2, p_2) P(p_2|H_2) dp_2}
$$

where $\log P(D|H_i, p_i) = -\frac{1}{2} \sum_{j=1}^{N} \frac{[d_j - H_i(x_j; p_i)]^2}{\sigma_j^2}$

and P(pi|H_i) are broad prior distributions for convergence an exponential distribution for with widths 10, 10⁵, 0*.*1, 10, respectively (the extracted and P(p_i|H_i) are broad prior distributions for convergence

If $2 \ln[K] \ge 6$: "strong evidence" of preference for H₁ over H₂ then ask what are the bounds on the binding energy the *H*² model, the integral over *B* is Gaussian, but the integral over *A* requires numerical

a

*a*DE4N,D

 $\beta = 2.2 m_0 = -0.6000 n = 4 2 \ln K = 9.81$

Having extrapolations and the binding extrapolations of the binding energies o binding momenta are expected to be rather small on these ensembles.

conclusions in both cases. The continuum limit fits discussed below also indicate that the

the continuum limit by comparing the various ensembles. We focus on the *B* = 2*,* 3*,* 4,

Simple continuum limit extrapolation of binding momentum, γ FIG. 22: Continuum limit fit to the binding momentum of the *J^P* = 1⁺ *B* = 4 nucleus as a

 FSP , PTP sical scale set by definanting $m \geq 10$ arise from the arbitrary choice of *f*⇡ = 246 GeV). For clarity, we again show the continuum NB: physical scale set by demanding f_{π} =246 GeV (arbitrary) of *m*² \mathcal{C} \mathcal{C} and \mathcal{C} uncertainty.

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0.4

Simple continuum limit extrapolation of binding momentum, γ Fig. 2
Fig. 2012: Continuum limit extranglation of binding momentum \bm{v}

Dark nuclei

J=0 nuclei: very likely unbound (all positively shifted)

- \vert =1, strong evidence for bound states for B=2,3, 4(?) \mathbb{R}^n B=5,..,8 seem unbound
	- Bindings decrease with quark mass and increase towards continuum
	- Binding is few $\%$ w.r.t. mass $\frac{y}{M}$ $\mathcal{L}_{\mathcal{A}}$
- Nuclear states with other n. quantum #s may also be bound

The ubiquity of nuclei?

N_c=2, *m*π = 1 TeV *N_c*=3, *m*π = 400–800 MeV NPLQCD/PACS-CS

The ubiquity of nuclei?

- So far appears that nuclei are rather generic and not an accident of parameters
- **Notable 10 Notable** Mussen are nuclei? e.g. shell-model like states vs quark blobs
	- More detailed studies necessary (eg magnetic moments) $\mathcal{L}_{\mathcal{A}}$
- How generic are layers of effective degrees of freedom?
	- nucleons → alpha clusters → nuclei ….

Building upon these lattice investigations, a demonstrative model of dark nucleosynthesis

- Extend strongly-interacting dark sector to talk minimally to SM all of these fields are contained within a 5 ⇥ 5 matrix of real fields where each field interacts the coupled system of Boltzmann equations down to 3 individual equations down to 3 ann 40 km in number density of any ⇡*^a* must be equal to the number density of any other ⇡*^b* and so on
- Simple extension: add scalar particle that kinematically mixes with Higgs The field content of the model is shown in Table I and the model is shown in Table I and the Lagrangian i Thermal freeze-out of the coupled system involves the ⇡ and ⇢ nucleons and *D* nuclei of sistemation of the solar popularly that lynami

$$
\mathcal{L} = \mathcal{L}_{\text{strong}} - \frac{\lambda}{4} (v_D - H_D^2)^2 - \left(\kappa H_D (u_R^{\dagger} u_L + d_L^{\dagger} d_R) + h.c.\right) + \delta H_D^2 |H|^2
$$

The Sunner Strong Dark Higgs vev gives quark masses N illiggs vuv givus quali N illiassus. μ μ iggo vou givoo gurpos maccoo

is now presented.

 $\rho_{\mathfrak{p}}$

 ρ

للتمحل

 h_D

symmetric DM. Rearrangements of the final diagram involving dark nuclear capture *D* + (⇡*,* ⇢) !

 π

 $\mathcal{S}=\int d^2\theta \, d^2\theta$

*h*D → (͡͡͡͡͡/͡ː/ international possible...)

⇡

h^D

 h_D

h^D

Kinematic mixing controlled by δ **: must be small ~10-3** characterized by a scale ⇤QC2^D. *H^D* is a 'dark' Higgs boson as this model could be UV α designthesis nucleosynthesis, α

E Hadronic theory: consider only pions, rhos, "deuterons" (LQCD calculation Interacti ⇢ *D* hD \overline{L} \therefore *h*_D D $\sqrt{ }$ \overline{V} *h^D h^D h^D h^D h^D* h_D ہے
ج *h^D* ⇡ $D_{\frac{b}{2}}$ ρ ρ *h^D* h_D
چ ا
البہ ρ π_{\ast} ⇢ ρ _{\sim} D ρ ρ *h^D* h_D π π ⇢ *D* **D** *h^D* FIG. 1: A dark nucleosynthesis event. This is realized in the model of Sec. III and is analogous to the SM process *n*+*p* ! *D*+. Such dark nucleosynthesis processes are important in early Universe $c \circ \rho_{\rm b}$ as the present day $\rho_{\rm b}$ and $\rho_{\rm b}$ be $\pi_{\rm s}$

لانيج

symmetric DM. Rearrangements of the final diagram involving dark nuclear capture *D* + (⇡*,* ⇢) !

⇢ *D*

 $\bigwedge h_D$ *D*

h^D

FIG. 6: Annihilation and dark nucleosynthesis processes leading to indirect detection signatures of FIG. 6: Annihilation and dark nucleosynthesis processes leading to indirect detection signatures of ⇢ *D* FIG. 6: Annihilation and dark nucleosynthesis processes leading to indirect detection signatures of FIG. 1: A dark nucleosynthesis event. This is realized in the model of Sec. III and is analogous to

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 \overline{L}

⇢

 \overline{D}

 h_D

the SM process *n*+*p* ! *D*+. Such dark nucleosynthesis processes are important in early Universe

Annihilation **Nucleosynthesis**

 π

remain) nucleosynthesis allows indirect detection signals asymmetric DM scenarios \mathcal{L} as ymmetric DM scenarios \mathcal{L} emain) nucleosynthesis allows indirect detection signals

Compact Objects

- Significant modifications to physics of astrophysical bodies
	- Dark matter gravitationally captured after scattering on visible matter
	- Helioseismology and neutron star lifetimes strongly modified – strongly constrains asymmetric DM models
- **Very rich phenomenology!**
	- Liberation of binding energy may allow ejection of dark matter ⇡*^D* ⇡*^D*
	- Star develops a co-located dark nuclear process site

Summary

Two-flavour, two-colour QCD has a complex spectrum F. exhibiting the analogues of nuclei

Ubiquity of nuclei?

- Composite dark matter is a natural scenario to consider
	- Composite doesn't just mean simple hadrons Need to consider "nuclei"
	- Nuclear binding provides a scale for free that is small relative $\mathcal{L}^{\text{max}}_{\text{max}}$ to the QCD scale in a natural way
	- Predicts a range of different phenomenology that beyond what is possible in simpler models

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