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Big bang darkleosynthesis

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ABSTRACT

In a popular class of models, dark matter comprises an asymmetric population of composite particles with short range interactions arising from a confined nonabelian gauge group. We show that coupling this sector to a well-motivated light mediator particle yields efficient *darkleosynthesis*, a dark-sector version of big-bang nucleosynthesis (BBN), in generic regions of parameter space. Dark matter self-interaction bounds typically require the confinement scale to be above Λ_{QCD}, which generically yields large ($\gg$ MeV/dark-nucleon) binding energies. These bounds further suggest the mediator is relatively weakly coupled, so repulsive forces between dark-sector nuclei are much weaker than Coulomb repulsion between standard-model nuclei, which results in an exponential barrier-tunneling enhancement over standard BBN. Thus, *darklei* are easier to make and harder to break than visible species with comparable mass numbers. This process can efficiently yield a dominant population of states with masses significantly greater than the confinement scale and, in contrast to dark matter that is a fundamental particle, may allow the dominant form of dark matter to have high spin ($S \gg 3/2$), whose discovery would be smoking gun evidence for dark nuclei.

1. Introduction

There is abundant evidence for the existence of dark matter (DM) but its particle nature is still unknown [1]. A popular, well-motivated class of models [2–7] features a composite dark sector with asymptotically free confinement and a matter asymmetry in analogy with standard model (SM) quantum chromodynamics (QCD). At temperatures below the confinement scale Λ_D, this sector comprises hadron-like particles with short-range self-interactions and requires no ad hoc discrete or global symmetries to protect its cosmological abundance from decays.

In this paper we consider the implications of big bang *darkleosynthesis* (BBD) – the synthesis of *darklei* (dark-sector nuclei) from *darkleons* (dark-sector nucleons) in the early universe – in an asymmetric nonabelian sector coupled to a lighter "mediator" ($m_{\text{med.}} \ll \Lambda_D$) particle. A mediator is well motivated in asymmetric DM as it facilitates annihilation in the early universe to avoid a higher than observed dark-matter abundance [8,9] and allows for DM self-interactions, which can resolve puzzles in simulations of large scale structure formation [10], and may explain anomalies in direct and indirect detection experiments (see [11,12] and the references therein).

In the limit where the mediator is sufficiently weakly coupled, the initial conditions in the dark sector are analogous to those considered in the "alphabetical article" by Alpher and Gamow [15], who sought to build up all the observed chemical elements from only an initial population of SM neutrons during big bang nucleosynthesis (BBN). Although this proposal ultimately failed as an efficient and complete model of nucleosynthesis, we show here that this need not be the case when considering the build-up of darklei from darkleons. In the dark sector, such a setup can be realized more generically and need not encounter the (perhaps accidental) coincidences (e.g., $m_n - m_p \sim T_{BBN}$) that prevent visible BBN from building up species with large mass numbers. Though other work has considered the cosmology of dark-sector bound states via dark "recombination" [16–24], and in the context of mirror matter [25–27], to our knowledge this is the first demonstration that dark-sector nucleosynthesis is a generic possibility for confined dark matter scenarios.

We assume only that the dark sector is populated with self-interacting, non-annihilating darkleons that also couple to a light mediator, which enables di-darkleon formation; in the absence of this coupling, there is no available energy loss mechanism for di-darkleon formation. Although in principle the coupling to the

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mediator state can induce both attractive and repulsive interactions between darklei, to be conservative and demonstrate viable phenomenology despite Coulomb repulsion, we assume here that all dark-nuclear formation rates feature repulsive barriers.

The outline of this paper is as follows. Section 2 outlines the basic ingredients of our scenario, Section 3 outlines a concrete UV complete realization, and Section 4 offers some concluding remarks and speculations.

2. Basic ingredients

Nonabelian sector: Our starting point is to consider a matter asymmetric dark sector with a single species of fermionic dark-"quarks" charged under an $SU(N)$ gauge group. We assume this group becomes confining at some scale Λ_D at which the quarks form darkleons χ. In the simplest scenario, the darkleon mass comes predominantly from strong dynamics, so the constituent quark masses can be neglected. However, we assume them to be nonzero, so if an approximate chiral symmetry is broken by confinement, the dark "pions" will be massive and decay to the visible sector through the mediator described below.

Light mediator: To demonstrate nucleosynthesis in the dark sector, we couple our darklei to a lighter particle V that enables di-nucleon formation $\chi + \chi \to {}^2\chi + V$, where ${}^A\chi$ denotes a darkleus with mass number A; in the absence of V emission this process is kinematically forbidden. Furthermore, in order for any dark matter scenario to have observable consequences, there needs to be an operator that connects dark and visible sectors.

Both problems can be solved with a light mediator particle uncharged under the confining gauge group. One well-motivated example identifies the mediator ϕ with a kinetically-mixed $U(1)_D$ gauge boson [28] V whose lagrangian is

$$\mathcal{L} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu + \bar{\chi}(i\gamma^\mu D_\mu + m_\chi)\chi , \qquad (1)$$

where $F'_{\mu\nu} \equiv \partial_{[\mu,} V_{\nu]}$ is its field strength, m_V is its mass, α_D is the dark fine-structure constant, and χ is a dark-nucleon with $U(1)_D$ charge Z_χ and mass m_χ. Independently of the connection to BBD this mediator can resolve the persistent $(g-2)_\mu$ anomaly [29]. Phenomenologically, V must decay before visible BBN, which can easily be accommodated in our regime of interest $\Lambda_D \gg \Lambda_{QCD}, m_V$ [30], where $\Lambda_{QCD} = 200$ MeV.

In a matter asymmetric sector, $U(1)_D$ charge neutrality requires at least one additional species with opposite charge, which yields a variety of net nuclear charges after darkleosynthesis. We will return to this possibility in Section 3, but note that having identical, repulsive charges under the mediator is a conservative choice that yields the maximum repulsion between fusing species to suppress formation rates.

Binding model: In the visible sector, the liquid drop model [31,32] gives the approximate binding energy for a species with mass number A

$$\mathcal{B}(A) = a_V A - a_S A^{2/3} - a_C Z^2 A^{-1/3} - \delta(A),$$

where a_V, a_S, and a_C, are respectively the volume, surface, and Coulomb terms, while $\delta(A) = \pm a_P A^{-1/2}$ is the pairing term with $+(-)$ for A odd (even). Since we will only consider a single-species of dark-nucleon, we neglect isospin by setting $A = Z$ in the familiar parametrization.

Some intuition into the physical relationship between these coefficients in this binding model can be gained by calculating the Yukawa self-energy $\mathcal{B}_{SE}$ of a uniform-density sphere in an effective theory of nuclear reactions mediated by pion-like scalars of mass m_Π. For finite $m_\Pi \sim O(\Lambda_D)$ it is straightforward to show that $\mathcal{B}_{SE} \simeq \kappa_V (\Lambda_D^3/m_\Pi^2) A - \kappa_S (\Lambda_D^4/m_\Pi^3) A^{2/3}$, and thus the relative importance of the surface term compared to the volume term depends on the range of nuclear forces (parametrized as Λ_D/m_Π).

We adopt this simple model (along with the notation) to calculate dark nuclear binding energies for species with mass number A and interpret Z to be the number of constituents with unit charge under $U(1)_D$. Note that for large A, where $\delta \ll a_S, a_C$ the most tightly bound species has mass number $A^* \simeq a_S/2a_C$, which maximizes $A^{-1}\mathcal{B}(A)$, the binding energy per darkleon. We note for a fixed volume term smaller A^* occur for a shorter nuclear range (smaller a_S) or larger α_D (larger a_C). For our numerical studies, we take the inputs a_V, a_S, and a_P to be of order the confinement scale Λ_D, but take the $U(1)_D$ Coulomb term to be parametrically smaller to reflect the absence of long range self-interactions at late times.

Formation & destruction rates: The generic "strong" reaction involving species A and B with net darkleon transfer C is ${}^A\chi + {}^B\chi \to {}^{(A+C)}\chi + {}^{(B-C)}\chi$. We adopt the prescription in [33] (and the references therein) to parametrize the strong cross-section for this process as

$$\sigma(E; A, B) = \frac{(A^{1/3} + B^{1/3})^2}{\Lambda_D^2} e^{-F(A,B)/E^{1/2}}, \qquad (2)$$

where E is the *kinetic* energy and $F(A, B) \equiv \alpha_D AB(2\mu)^{1/2}$ is the Coulomb-barrier tunneling coefficient for repulsive $U(1)_D$ interactions between initial-state particles, and μ is their reduced mass. In the $\alpha_D \to 0$ limit, this expression recovers the geometric scattering limit.[1] Thermal averaging with the Maxwell–Boltzmann distribution yields

$$\langle \sigma v \rangle_{A,B} = \frac{2(A^{1/3} + B^{1/3})^2}{\sqrt{\pi}\Lambda_D^2 T^{3/2}} \int_0^\infty dE E^{1/2} v(E) e^{-U(E,T;A,B)}, \qquad (3)$$

where the angle-averaged relative velocity between fusing species is $v(E) = \sqrt{v_A^2 + v_B^2}$, $v_i = \sqrt{1 - m_i^2/(m_i + E)^2}$ is the center-of-momentum velocity for species i and

$$U(E, T; A, B) = E/T + F(A, B)/E^{1/2}, \qquad (4)$$

includes the usual Boltzmann factor and Coulomb barrier. Although we include the latter for completeness (and for comparison with standard BBN), we always work in the regime $\alpha_D \ll 1$, $F(A, B)/\sqrt{T} \ll 1$, so this correction is negligible and our interactions are thermally-averaged geometric hard-sphere scatters.

To distinguish between strong-darklear and V-mediator induced interactions, we will add a Λ or V superscript respectively. In standard BBN [33], thermal averaging is evaluated using the "Gamow peak" approximation, which fails in the $\alpha_D \ll \alpha_{EM}$ regime, so we perform the integral in Eq. (3) directly.

Since we require a population of light mediators to initiate di-darkleon formation via $\chi + \chi \to {}^2\chi + V$, there will also be a V-emission processes ${}^A\chi + {}^B\chi \to {}^{(A+B)}\chi + V$, in which a mediator particle is radiated off an initial or final state particle. This process is modeled using the simple prescription $\langle \sigma_V v \rangle_{A,B} = \alpha_D \langle \sigma_\Lambda v \rangle_{A,B}$ in accordance with the α_{EM} scaling of analogous visible-sector processes (e.g. $p + n \to d + \gamma$). We define $\Gamma^V_{A,B} \equiv n_D \langle \sigma_V v \rangle_{A,B}$ to be

[1] Although the cross section increases with the A and B, this ansatz never violates self-scattering unitarity bounds because the cross section in Eq. (2) is of the form $\sigma \sim R^2$, where $R \sim A^{1/3}/\Lambda_D$ is the radius of an incident nucleus, so the bound [34] on geometric cross sections being $\sigma \lesssim 16\pi R^2$ weakens for larger objects if other couplings are perturbative.