Snowmass2021 - Letter of Interest

Accelerator Search for a Stable, Neutral Long-Interaction-Length Dark Matter Particle

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) *[RF3,RF6, EF6-10]*

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Abstract: The Dark Matter particle may be a stable, neutral, as-yet-undiscovered hadron in the standard model. The existence of a compact color-flavor-spin singlet $uuddss$ bound state (sexaquark, S) with mass of order $2\,m_p$ is compatible with all present particle physics and cosmology constraints. If it exists, the S is a very attractive DM candidate. The relic abundance of S Dark Matter (SDM) is established when the Universe transitions from the quark-gluon plasma to the hadronic phase at ≈ 150 MeV and is in remarkable agreement with the observed $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$; this is a no-free-parameters result because it follows from statistical physics with parameters known from QCD. The S interacts with baryons primarily via a Yukawa interaction of coupling strength α_{SN}, mediated by exchange of the flavor-singlet superposition of the ω and ϕ vector mesons, having mass ≈ 1 GeV. Constraints from dark matter direct detection and cosmology suggest an attractive Yukawa interaction with coupling strength α_{SN} 0.03 - 1, a natural range from the particle physics standpoint. By contrast, the S *breakup* vertex, $\tilde{g}$, is dynamically highly suppressed. Survival of the relic DM abundance to low temperature requires $\tilde{g} \lesssim 2\times 10^{-6}$, which is comfortably compatible with theory expectations and observational bounds. Detecting the sexaquark in accelerator experiments is surprisingly difficult and experiments to date would not have discovered it. The most promising approaches are to search for a component of long-interaction-length neutral particles in the central region of relativistic heavy ion or other high energy collisions, and to search for evidence of missing particle production characterized by unbalanced baryon number and strangeness using Belle-II or possibly GLUEX at J-Lab. The work foreseen in this LoI is the investigation of possible realizations of a long-interaction-length neutral particle search, with the aim of developing a detailed proposal. Such a search capability is of generic value, beyond the specific sexaquark DM model which precipitated it.

The sexaquark, S, is a conjectured stable bound state of six light quarks ($uuddss$) with mass $m_S \approx 2m_p$. If it exists, the sexaquark is an excellent dark matter candidate. The S is neutral and absolutely stable for $m_S < m_D + m_e$, and as long as $m_S \lesssim 2$ GeV its lifetime is greater than the age of the Universe. The potential existence of this state and its compatibility with accelerator experiments was pointed out in [1]. The name sexaquark with Latinate prefix was adopted to distinguish it from the loosely bound H-dibaryon [2], with the initial "s" signaling its being a *s*trange, spin- and flavor- *s*inglet, whereas the term hexaquark is used for a generic 6-quark or $(q\bar{q})^3$ state. An in-depth discussion of the particle physics, astrophysics and cosmological constraints on sexaquark DM (SDM) and its interactions can be found in [3].

The relic abundance of SDM is predicted to be $\Omega_{DM}/\Omega_b \approx 5$ (left panel Fig. 1), using general arguments of statistical physics and known standard model parameters (the quark masses and the temperature of the transition from quark-gluon to hadronic phases)[4, 3], in excellent agreement with the observed value $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$ [5]. Preservation of this abundance ratio as the Universe cools requires that the rate for breaking up S's in hadronic collisions be less than the expansion rate of the Universe. This condition is satisfied[4] if the effective Yukawa vertex for breakup, $\tilde{g}, \lesssim$ few $\times 10^{-6}$. The predicted value of $\tilde{g}$ is even smaller than this, due to the low probability of fluctuation between di-baryon and sexaquark configurations, as originally pointed out in [6] and further explored in [3] (center panel Fig. 1).

Scattering between SDM and baryons is primarily mediated by flavor-singlet vector meson exchange. The Yukawa coupling α_{SN} is constrained by cosmological considerations to be $\lesssim 1$ (right panel Fig. 1). If the interaction is attractive, SDM binds to nuclei and direct detection searches to date do not constrain the interesting parameter space, except for the limited range $0.03 \gtrsim \alpha_{SN} \gtrsim 0.01$. [3]

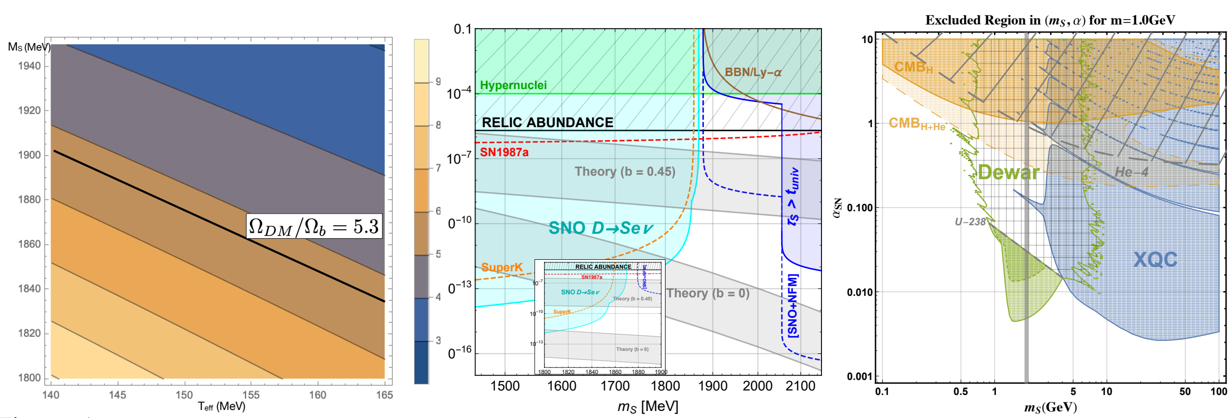

Figure 1: Left: Ω_{DM}/Ω_b versus m_S (in MeV, vertical axis) vs. the effective freezeout temperature (in MeV, horizontal axis). Center: Predicted and excluded regions for $\tilde{g}$ as a function of m_S; the horizontal black line is the maximum value of $\tilde{g}$ compatible with non-destruction of sexaquark DM in the hot hadronic phase. Right: Excluded regions in the α_{SN}-m_S plane from XQC (blue), CMB (tan) [7]. Within the checkerboard region the dewar limits are inapplicable when the interaction is attractive, because DM would hybridize with nuclei in Earth's crust. For other content of plots see [3].

The great challenge to using accelerator experiments to discover or exclude a stable sexaquark is its resemblance to neutrons, which are more abundantly produced by a factor $300 - 10^6$. The two most promising options are *i)* searching in final states of $\Upsilon_{1S,2S,3S}$ decay, for events with missing strangeness ± 2 and baryon number ∓ 2 (according to whether an S or $\bar{S}$ was produced) and *ii)* the search for a new, neutral long-interaction-length particle in the final states of high energy proton or heavy ion collisions. See [3, 1, 8] for a discussion of other approaches.

Here we focus on the strategy of searching for evidence of a neutral component with interaction length longer than that of neutrons and not attributable to known neutral long-lived particles. Due to the small value of $\tilde{g}$, the $\bar{S}$ annihilation channel is much smaller than its scattering channel, so $\bar{S}$ interactions are effectively indistinguishable from S interactions. We can roughly estimate the S and $\bar{S}$ interaction length relative to that of neutrons in this energy regime as $\lambda_S^{\rm int} \approx (\alpha_{NN}/\alpha_{SN})^2\, \lambda_n^{\rm int} \approx 6 \times 10^3\, (0.2/\alpha_{SN})^2\, \lambda_n^{\rm int}$, with coupling α_{SN} taken to be roughly the same as the α_{SN} which enters the potential scattering problem relevant for dark matter, for which the most interesting region is $0.03 < \alpha_{SN} \lesssim 1$ (Fig. 1).

An attractive environment to search for production of S and $\bar{S}$ is the central region of relativistic heavy ion collisions. The similarity of hadron production from a cooling Quark-Gluon Plasma produced in a collider and from the QGP of the Early Universe, argues that statistical physics and thermodynamics governs both processes. Indeed, ref. [9] obtains an excellent fit to the abundances of final particles in central Pb-Pb collisions based on statistical equilibrium at a temperature $T = 156$ MeV. The main uncertainty in the analysis is associated with treatment of the resonances. A similar approach applied to S and $\bar{S}$ production taking their mass to be $\approx 2m_p$ implies an abundance similar to deuterons and anti-deuterons: $dN/dY \approx 10^{-1}$ in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This is only a factor about 300 less than p and $\bar{p}$ and n and $\bar{n}$ production – a much more favorable ratio of S relative to neutrons than if baryon-fusion via the $\tilde{g}$ vertex were required. Thus production in a heavy ion collision has two virtues: *i)* relatively reliable prediction of the rate and *ii)* potentially higher level of S and $\bar{S}$ production relative to n and $\bar{n}$.

The strategy of looking for an anomalous component of long-interaction-length neutral stable particles could be implemented with a relatively simple setup. Conceptually, a beam is directed onto a target, followed by sweeping magnets and decay region to eliminate charged particles and short-lived neutral components. This would be followed by an instrumented region with particle tracking interleaved with absorber. The function of the tracking is to ensure the interaction is initiated by a neutral particle, to discriminate between interactions and decays, e.g. K_L's, which need to be rejected, to reject interactions initiated by neutrinos and cosmic rays and to measure the longitudinal position of n- and S- and $\bar{S}$-initiated events. Employing time-of-flight and energy deposit as in [10] might also be useful. After a distance z of material, the ratio of S- and n- induced interactions is:

$$\frac{dN_S^{\rm int}/dz}{dN_n^{\rm int}/dz} = \frac{\sigma_S^{\rm prod}}{\sigma_n^{\rm prod}} \frac{\lambda_S^{-1} \exp[-z/\lambda_S]}{\lambda_n^{-1} \exp[-z/\lambda_n]}. \tag{1}$$

The n-Pb (n-Fe) interaction lengths at 10 GeV/c, typical of central region particles, are $\lambda_n = 9.64\,(9.78)$ cm, based on the cross-sections measured by [11]. Thus the distance $z_{\rm eq}$ at which the number of interactions initiated by n's and S's are equal, is:

$$z_{\rm eq} = \lambda_n \ln \left[\frac{\sigma_n^{\rm prod} \sigma_n^{\rm int}}{\sigma_S^{\rm prod} \sigma_S^{\rm int}} \right] = 1.4\,{\rm m} + 0.1{\rm m} \left(\ln \left[\frac{\sigma_n^{\rm prod}/\sigma_S^{\rm prod}}{300} (0.2/\alpha_{SN})^2 \right] \right) . \tag{2}$$

Quantifying the onset of a deviation from pure exponential would determine $\sigma_S^{\rm prod} \sigma_S^{\rm int}$. If the detector is long enough and background low enough that the interaction length of S's can be measured, both the production and scattering cross sections can be separately determined. However the interaction length of S's as estimated above is $\lambda_S^{\rm int} \approx (\alpha_{NN}/\alpha_{SN})^2\, \lambda_n^{\rm int} \approx 580\,{\rm m}\,(0.2/\alpha_{SN})^2$, so measuring it may be difficult.

Summary: This LoI proposes to develop the preliminary design of an apparatus for detecting the interactions of a new neutral particle of mass $\approx 2m_p$, produced with an abundance relative to neutrons $\lesssim$1:300, and to identify the optimal site to deploy it. (Clearly, site and design are strongly coupled.) Unambiguously establishing the existence of a component of new, long-interaction-length neutral particles, and measuring the product of their production and interaction cross sections – even without accurately measuring their interaction length – would be an important smoking gun and adequate justification for the endeavor. If it is possible to locate the detector in conjunction with one of the LHC or RHIC experiments recording heavy ion collisions, that would yield a significant benefit by tagging collisions creating a QGP, for which there is a benchmark sensitivity target. Theoretical work will include identifying and delineating other types of new physics which can be addressed by such an apparatus, to ensure its widest possible utility.

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