# Twin Higgs Asymmetric Dark Matter

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We study asymmetric dark matter (ADM) in the context of the minimal (fraternal) twin Higgs solution to the little hierarchy problem, with a twin sector with gauged $SU(3)' \times SU(2)'$, a twin Higgs doublet, and only third-generation twin fermions. Naturalness requires the QCD′ scale $\Lambda'_{\rm QCD} \simeq 0.5$–20 GeV, and that $t'$ is heavy. We focus on the light $b'$ quark regime, $m_{b'} \lesssim \Lambda'_{\rm QCD}$, where QCD′ is characterized by a single scale $\Lambda'_{\rm QCD}$ with no light pions. A twin baryon number asymmetry leads to a successful dark matter (DM) candidate: the spin-3/2 twin baryon, $\Delta' \sim b'b'b'$, with a dynamically determined mass ($\sim 5\Lambda'_{\rm QCD}$) in the preferred range for the DM-to-baryon ratio $\Omega_{\rm DM}/\Omega_{\rm baryon} \simeq 5$. Gauging the $U(1)'$ group leads to twin atoms ($\Delta'$-$\bar{\tau}'$ bound states) that are successful ADM candidates in significant regions of parameter space, sometimes with observable changes to DM halo properties. Direct detection signatures satisfy current bounds, at times modified by dark form factors.

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*Introduction.*—Despite overwhelming evidence for the existence of dark matter (DM), its precise nature remains a mystery. Moreover, the closeness of DM and baryon energy densities, $\Omega_{\rm DM} \simeq 5\Omega_{\rm baryon}$, is fundamentally puzzling: There seems to be no reason for these two quantities, *a priori* unrelated, to be so close to each other. This motivates the idea of asymmetric dark matter (ADM) [1–13], based on the assumption that the present DM density is set by an asymmetry $\eta_{\rm DM}$ in the DM sector, analogous to the baryon asymmetry $\eta_{\rm baryon}$. Then

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm baryon}} = \frac{m_{\rm DM}}{m_N}\frac{\eta_{\rm DM}}{\eta_{\rm baryon}} \qquad (1)$$

where $m_N, m_{\rm DM}$ are the nucleon and DM masses. A linked asymmetry of the same order, $|\eta_{\rm DM}| \sim |\eta_{\rm baryon}|$, is relatively easy to achieve, but a successful explanation of $\Omega_{\rm DM}/\Omega_{\rm baryon}$ requires a *reason* for $m_{\rm DM} \sim m_N$.

Another pressing worry is the LHC naturalness problem: Why has the new dynamics that stabilizes the weak scale not been observed? The twin Higgs (TH) solution to this little hierarchy problem is based on the realization of the Higgs boson as a pseudo-Nambu-Goldstone boson (pNGB) of an approximate global $SU(4)$ symmetry [14–18]. The TH mechanism introduces a standard model (SM) neutral sector, the twin sector, that is an approximate copy of the SM, with the Higgs sector respecting, at tree level, an $SU(4)$ global symmetry that acts on the two (visible and twin-sector) Higgs doublets. A $\mathbb{Z}_2$ between sectors imposes on all couplings to be equal and ensures that radiative corrections to the Higgs soft mass squared are $SU(4)$ symmetric. The global $SU(4)$ is only broken at one-loop and the $\mathbb{Z}_2$ must be broken, explicitly or otherwise, for the vacuum expectation value of the twin and visible sector Higgs (denoted as $f$ and $v \approx 246$ GeV) to be different. As $f = v$ is ruled out by Higgs coupling measurements, the minimal fine-tuning in the electroweak sector is given by $\sim 2v^2/f^2$ (only $\sim 20\%$ for $f/v \approx 3$, the minimum experimentally allowed ratio).

The TH mechanism does not require the twin sector to be an exact copy of the SM. A minimal realization, the fraternal twin Higgs (FTH) [19], only requires the following in the twin sector: $SU(3)' \times SU(2)'$ interactions, top and bottom quarks ($Q'$, $t'_R$, $b'_R$), and lepton ($L'$) and Higgs ($H'$) doublets. Twin right-handed leptons are not required but may be added, and a $U(1)'$ gauge group is *not* required by naturalness, although it remains an accidental global symmetry. Masses of twin fermions are set by their Yukawa couplings and the ratio $f/v$. Naturalness requires a twin top Yukawa $y_{t'} \simeq y_t$, but only imposes $y_{i'} \ll 1$ ($i' \neq t'$). Most important for us, values of the $g'_3$ gauge coupling consistent with naturalness imply a QCD′ scale $\Lambda'_{\rm QCD} \sim 0.5$–20 GeV for a 5 TeV cutoff [19]. (The theory needs UV completion at some scale $M_{\rm UV} \lesssim 4\pi f$).

The purpose of this Letter is to explore the possibility of ADM in the FTH context [20]. We work in the regime $m_{b'} \lesssim \Lambda'_{\rm QCD}$, where the twin QCD′ theory is determined by a single scale, and we argue that the baryon $\Delta' \sim b'b'b'$, either on its own or in an atomic bound state with a $\bar{\tau}'$ in the gauged $U(1)'$ case, is a successful ADM candidate.

*Stable and Relativistic Twins.*—Within the FTH scenario, the twin sector respects three accidental global symmetries: twin baryon number $B'$, lepton number $L'$ and "charge" $Q'$. If these are not too badly broken by higher-dimensional operators (HDOs), as we will assume, then the lightest twin particles carrying these quantum numbers will be cosmologically stable. Twin $CP$ could be a good symmetry, although both twin $P$ and $C$ are violated by $SU(2)'$ interactions.

We consider massive $\tau'$ but allow heavy or massless $\nu'$, usually with $m_{\tau'} + m_{\nu'} < m_{W'}$, although an interesting scenario arises if $m_{\tau'} + m_{\nu'} > m_{W'}$ and $W'^{\pm}$ are stable. For $m_{b'} \lesssim \Lambda'_{\rm QCD}$, the lowest QCD$'$ states are $\bar{b}'b'$ mesons, the lightest being a pseudoscalar $\hat{\eta}$ and a scalar $\hat{\chi}$ with masses $m_{\hat{\eta}} \approx (2\text{–}3)\Lambda'_{\rm QCD}$ and $m_{\hat{\chi}} \approx 1.5 m_{\hat{\eta}}$ [23]. (A distinctive feature is the absence of pNGBs due to the chiral anomaly.) The glueball spectrum is heavier and only weakly mixed with the mesons, with the lightest being a $0^{++}$ state of mass $m_0 \sim 7\Lambda'_{\rm QCD}$ [24,25]. Meson or glueball states decay quickly via $SU(2)'$ interactions to $\bar{\nu}'\nu'$ pairs if $m_{\nu'} \approx 0$ [and multi-$\gamma'$ states if $U(1)'$ is gauged] and lighter mesons or glueballs, or to SM states via twin-scalar-Higgs mixing [19,26]. Independently of $m_{\nu'}$, the lightest twin meson $\hat{\eta}$ may decay very fast via dimension-six HDOs that preserve total $CP$, of the form $\sim(\bar{q}\gamma^5 q\bar{b}'\gamma^5 b')/M^2$, where $q$ denotes SM quarks (for $M \sim 10$ TeV, this gives a lifetime $\tau_{\hat{\eta}}^{-1} \sim 10^{-14}$ s).

The spin-3/2 twin $\Delta'$ baryon with mass $m_{\Delta'} \approx 5\Lambda'_{\rm QCD}$ [23] is naturally extremely long lived since it is the lightest $B' \neq 0$ object. Moreover, the leading HDO that violates SM and twin baryon numbers but preserves a linear combination is dimension-12, resulting in a lifetime $\tau_{\Delta'} \sim 10^{26}$ s for $m_{\Delta'} \sim 10$ GeV and $M \sim 10$ TeV. Thus, even in the presence of HDOs, $\Delta'$ can be cosmologically stable. We assume that the $\Delta'$ is the only twin baryon-number-carrying state with a cosmologically relevant lifetime. (The presence of heavier stable twin baryon states would not qualitatively change our conclusions).

Dark radiation (DR) contributions to the number of effective neutrino species, $\Delta N_{\rm eff}$, can arise from light twin neutrinos, and twin photons when $U(1)'$ is gauged. Because of the extremely fast decay of the lightest twin meson $\hat{\eta}$ into SM states naturally present via HDOs, we expect the $\nu'$ and $\gamma'$ sectors to remain in equilibrium with the SM after the QCD$'$ phase transition, even for values of $\Lambda'_{\rm QCD}$ as small as $\sim$0.5 GeV. As a result, in the case of $m_{\nu'} \approx 0$ and no gauged $U(1)'$ we expect $\Delta N_{\rm eff} \approx 0.075$ (as argued in Sec. VIII of [27]) and $\Delta N_{\rm eff} \approx 0.16$ when twin photons are also present. Notice these are the minimum possible contributions to $\Delta N_{\rm eff}$ and are compatible with current measurements $\Delta N_{\rm eff} - \Delta N_{\rm eff,SM} \simeq 0.1 \pm 0.2$ [28], although future experiments may achieve an accuracy $\sim$0.05 [29,30] and may therefore probe these scenarios.

*Twin Baryon and $W'$ Dark Matter.*—The ADM scenario has a linked asymmetry in SM- and twin-sector quantum numbers, whose generation is a UV issue; here we simply assume it is present. In addition, ADM requires efficient annihilation of the symmetric component of stable DM states, so that the final DM abundance is set by the asymmetry. Here, annihilation of the twin baryon symmetric component happens efficiently via twin strong interactions. Sufficiently heavy $\tau'$ and $\nu'$ species also annihilate efficiently, mainly to $\bar{b}'b'$ (see Fig. 2 in [27]). The QCD$'$ phase transition for $m_{b'} \lesssim \Lambda'_{\rm QCD}$ is a smooth crossover [31–33], so we expect neither significant nonequilibrium dynamics nor entropy production affecting relic densities.

A twin baryon asymmetry implies an asymmetric relic population of $\Delta'$ baryons. If $\eta_{Q'} = 0$, then the (ungauged) charge density of the $\Delta'$ population must be balanced by a population of twin charged states. So, if $\Delta'$ baryons are to be the only significant DM component, either $m_{\tau'} \approx 0$ so that an asymmetric abundance of these can exist as DR, or we must have a compensating asymmetry in (global) twin charge, $\eta_{Q'} \simeq -\eta_{B'}$. Depending on UV dynamics there may be a twin lepton asymmetry setting an asymmetric $\nu'$ DR relic density (the $\tau'$ density is fixed by $\eta_{B'}$ and $\eta_{Q'}$).

As $m_{\Delta'} \approx 5\Lambda'_{\rm QCD}$ [23], then $\eta_{\rm B'}/\eta_{\rm baryon} \approx m_N/\Lambda'_{\rm QCD}$ (with $\Lambda'_{\rm QCD} = 0.5$–$20$ GeV [19]). Thus, this framework allows for a successful realization of ADM in which the DM mass is not tuned to be $\mathcal{O}(10~\text{GeV})$, but rather is set by the twin confinement scale, whose range is restricted directly by naturalness. The value of $y_{b'}$ is irrelevant for the DM mass as long as $m_{b'} \lesssim \Lambda'_{\rm QCD}$ is realized. DM is then made of individual $\Delta'$ baryons. Bound states, if they exist in the spectrum, will not form in the early Universe, since the only states parametrically lighter that could be emitted in the binding processes are $\nu'$ or light SM states, but these both only interact via tiny subweak interactions. Moreover, we find that even in the presence of twin photons, radiative capture does not give a significant population of $\Delta' - \Delta'$ bound states as the electric and magnetic dipole radiative capture rates vanish. (This situation can be different when lighter generations are present, allowing for a nuclear DM scenario [34,35].) Regarding $\Delta'$ self-interactions we have, parametrically, $\sigma_{\Delta'}/m_{\Delta'} \sim (\Lambda'_{\rm QCD})^{-3} \sim 10^{-3}$–$10^{-8}$ cm$^2$ g$^{-1}$ for $\Lambda'_{\rm QCD} = 0.5$–$20$ GeV, well below the current upper bound of $\sim$0.5 cm$^2$ g$^{-1}$ [36].

Finally, if $m_{\tau'} + m_{\nu'} > m_{W'}$, then $W'^{\pm}$ are also stable states, and even if $\eta_{B'} = -\eta_{Q'}$, an asymmetric population of $\tau'$ ($\bar{\tau}'$) states could survive, whose charge is balanced by an equal number of asymmetric $W'^{+}$ ($W'^{-}$) states. Notice that for small values $f/v \approx 3$–$5$ (see Fig. 4 in [27]), annihilation of the symmetric populations of $\tau'$, $\nu'$, and $W'^{\pm}$ occurs very efficiently. For this latter possibility to be realized without introducing significant extra tuning one needs $m_{\tau'}, m_{\nu'} \sim 10^2$ GeV [since $m_{W'} \approx (f/v)m_W$], above the mass range where ADM scenarios work most naturally. (Scattering cross sections of such states off SM nucleons via the Higgs portal are $\lesssim 10^{-45}$ cm$^2$ for $f/v \gtrsim 4$, close to current bounds).

*Direct detection:* Scattering of $\Delta'$ baryons off SM nucleons happens via Higgs exchange or via a twin scalar state ($\hat{\chi}$ meson or $0^{++}$ glueball) that mixes with the Higgs boson. Couplings between scalar mesons or glueballs and a pair of twin baryons are unknown and require dedicated lattice computation. We find that within a reasonable range for the couplings and mixing angles either Higgs exchange or meson or glueball exchange can dominate the scattering. We therefore consider the processes separately (ignoring interference effects) to give an idea of the possible cross sections.

When Higgs exchange dominates, the spin-independent cross section is

$$\sigma_h^{\rm SI} \approx \frac{1}{\pi}\mu_{N\Delta'}^2 \frac{(f_N m_N)^2}{m_h^4 v^4}\frac{(m_{\Delta'} f_{\Delta'})^2}{(f/v)^4}, \qquad (2)$$

where $\mu_{N\Delta'} = m_N m_{\Delta'}/(m_N + m_{\Delta'})$. $f_N \approx 0.32$ [37–39] and $f_{\Delta'} = (2 + 87 f_{b'})/31$ (following [40]) are the effective Higgs couplings to nucleons and $\Delta'$ baryons, respectively, where $f_{b'}$ is the dimensionless part of the matrix element of $b'$ in $\Delta'$. In the light $b'$ case, one expects $f_{b'} \ll 1$, albeit its exact value requires dedicated lattice study. If the dominant process is meson exchange, the cross section reads

$$\sigma_{\hat\chi}^{\rm SI} \approx \frac{1}{\pi}\mu_{N\Delta'}^2 \frac{(f_N m_N)^2}{m_{\hat\chi}^4 v^2}\lambda'^2\theta'^2, \qquad (3)$$

where $\lambda'$ is the coupling between $\hat\chi$ and a pair of $\Delta'$ baryons and $\theta'$ is the Higgs-$\hat\chi$ mixing angle

$$\theta' = \frac{f_{\hat\chi} m_{\hat\chi}}{2f(f/v)}\frac{\mathcal{F}_{\hat\chi}}{m_h^2 - m_{\hat\chi}^2}, \qquad (4)$$

with $\mathcal{F}_{\hat\chi}$ the $0^{++}$ meson decay constant defined as $\mathcal{F}_{\hat\chi} \equiv a' m_{\hat\chi}^2$ (with $a'$ an unknown dimensionless constant) and $f_{\hat\chi} = (2 + 58\tilde f_{b'})/31$ accounts for the effective coupling between a meson and a Higgs boson. Numerical evaluation shows that for $\lambda' \lesssim 1$ Higgs exchange dominates, whereas for $\lambda' \gtrsim 4\pi$ (the naive dimensional analysis value) meson exchange wins. If glueball exchange dominates, the cross section is given by Eq. (3) after performing the appropriate substitutions.

Figure 1 shows these spin-independent cross sections for particular choices of the unknown parameters. To illustrate the possible range we have chosen the minimum Higgs-exchange cross section (i.e., $f_{b'} = 0$), while for meson exchange we have selected reasonably large values of the parameters. Different choices allow Higgs or glueball exchange to dominate. A significant region is covered by the neutrino floor, in particular $m_{\Delta'} \approx 5$ GeV, which allows for $\eta_{B'} \approx \eta_{\rm baryon}$. For $m_{\Delta'} \approx 10$–50 GeV, corresponding to $\eta_{B'}/\eta_{\rm baryon} \approx 0.5 - 0.1$, predicted cross sections escape the neutrino background and sit close to (or within) the region that will be probed by next-generation experiments such as LZ [41].

*Twin Atoms.*—Once the $U(1)'$ group is gauged, the physics becomes substantially richer. Twin-charge neutrality of the Universe requires $\eta_{Q'} = 0$, which means that a $B'$

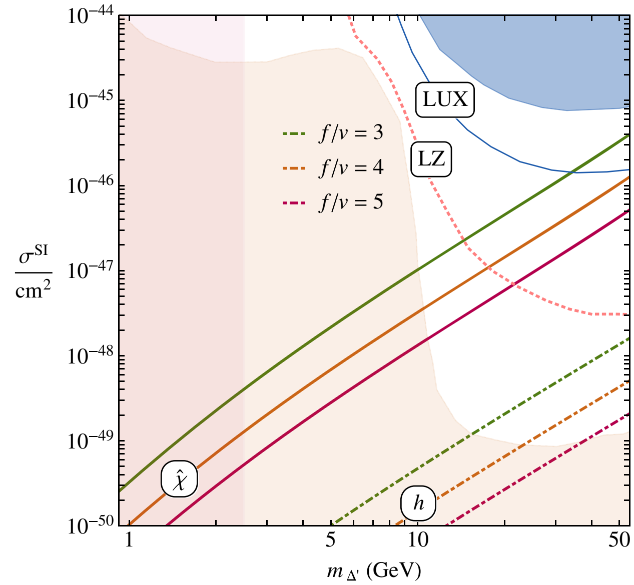


FIG. 1 (color online). Range of possible spin-independent scattering cross sections of $\Delta'$ baryons off SM nucleons when either Higgs or $\hat\chi$-meson exchange dominates (dashed and thick lines, respectively). We take $m_{\hat\chi} = 3\Lambda'_{\rm QCD}$, $\lambda' = 4\pi$, $a' = 1$, $f_{b'} = 0$, and $\tilde f_{b'} = 0.1$ for illustration. Blue: LUX excluded [42]; blue line: LUX projected sensitivity (300 live days) [43]; orange: neutrino background [41]; pink dotted line: LZ sensitivity [41]; pink: values of $m_{\Delta'}$ that imply extra tuning [19].

asymmetry resulting in a nonzero asymmetric population of $\Delta'$ baryons must be balanced by an $L'$ asymmetry, such that an equal asymmetric population of $\bar\tau'$ is present (we here assume that $W'^{\pm}$ are unstable). Because of twin electromagnetic interactions, the asymmetric populations of $\Delta'$ and $\bar\tau'$ states may form bound states. In fact, the late-time DM population *must* consist of overall-neutral "twin atoms," rather than a plasma of charged states, for values of the twin electromagnetic coupling $\alpha'$ that are not extremely small; otherwise, the long-range interactions between DM particles result in plasma instabilities that strongly affect bullet-cluster-like collisions [44–46]. Requiring that efficient twin recombination takes place imposes nontrivial constraints on the sizes of $\alpha'$ and the mass of the twin atom $\hat H$ [47]. Further constraints are present due to DM self-interactions: Low-energy atom-atom scattering processes have cross sections $\sigma \approx 10^2(a'_0)^2$, where $a'_0 = (\alpha'\mu_{\hat H})^{-1}$ is the atomic Bohr radius and $\mu_{\hat H}$ the reduced mass of the atomic system, although the exact value of $\sigma$ depends strongly on the ratio $R \equiv m_{\Delta'}/m_{\tau'}$ for values $R \gtrsim 15$ [48]. We impose the constraint $\sigma/m_{\hat H} \lesssim 0.5\ {\rm cm^2\ g^{-1}}$ [36] applicable to contactlike DM scattering, since the effect of hard scatterings generally dominates over soft or dissipative processes for atom-atom scattering in the regimes we consider. Figure 2 shows constraints from recombination [47] and DM self-interactions, for $R \equiv m_{\Delta'}/m_{\tau'} = 1$.

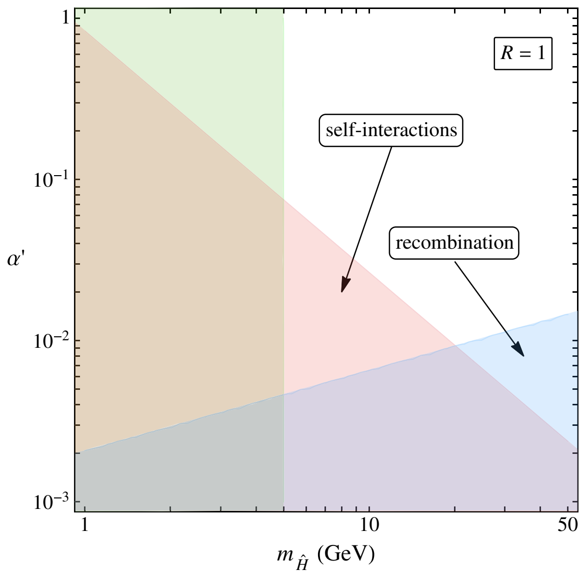


FIG. 2 (color online). Constraints in the $\alpha'$, $m_{\hat{H}}$ plane, for a ratio $R = m_{\Delta'}/m_{\tau'} = 1$. Blue: twin recombination is inefficient, with an ionized fraction $\gtrsim 0.1$ remaining; pink: self-interaction cross section is $\gtrsim 0.5\ \mathrm{cm}^2\,\mathrm{g}^{-1}$; green: twin atom masses small enough that significant extra tuning is present.

For values of $\alpha'$ and $m_{\hat{H}}$ satisfying recombination and self-interaction constraints, annihilation of the symmetric populations of $\Delta'$ and $\tau'$ happens very efficiently. The minimum value of $\alpha'$ consistent with all constraints is $\alpha' \approx 10^{-2}$ (Fig. 2), in which case $m_{\hat{H}} \approx 20$ GeV. This results in binding energies of order $\mathcal{O}(10^2)$ keV, and a hyperfine splitting of order $\Delta E \sim 10$ eV.

Before twin-sector recombination occurs, the $\Delta'$ and $\bar{\tau}'$ are coupled to the twin photon bath, constituting a dark plasma that can undergo "dark acoustic oscillations" [47]. If twin-sector recombination is late enough, these oscillations can leave an imprint in the power spectrum of baryonic matter. However, since $\alpha' \gtrsim 10^{-2}$ in our allowed regions, the binding energy of our twin atoms is sufficiently high ($\gg 10$ keV) that twin recombination is always too early to realize this possibility.

Another possibility is that, after dark recombination, molecular bound states may form at lower temperatures. However, radiative capture of two neutral atoms to a "dark hydrogen molecule" is very suppressed [49], with molecule formation requiring that there be an abundance of charged particles to catalyze the reactions. Given the constraints that must already be satisfied, our estimates indicate that a significant proportion of molecules will not be formed, either in the early Universe or in halos.

Most of the physics discussed in this section is not specific to FTH models, relying only on asymmetric DM charged under a dark $U(1)$. There is a large body of literature on the physics of such "dark atoms," e.g., [50–53], which arise in many "mirror world" models [54,55].

*Direct detection:* Regarding direct detection (DD) signatures, we first neglect kinetic mixing between sectors and focus on the process of scattering purely via Higgs exchange or via a twin scalar that mixes with the Higgs scalar. An interesting situation arises for $R \approx 1$. In this case, $m_{\Delta'} \approx m_{\tau'}$ and, therefore, the Higgs boson couples to both states with equal strength. Additionally, the size of the atom is set by $a_0' = (\alpha' \mu_{\hat{H}})^{-1}$, which is $\approx 4$ fm for $\alpha' \approx 10^{-2}$ and $m_{\hat{H}} \approx 20$ GeV, values consistent with all constraints (see Fig. 2). The size of the atomic system is thus comparable to that of SM nuclei relevant for DD experiments, and the possibility of a detectable "dark form factor" arises (with the form factor approximately given by the Fourier transform of the ground-state atomic wave function squared). While such a signal would be degenerate with modifications to the DM halo velocity distribution for data from a single DD experiment [56], multiple experiments with different SM target nuclei could allow the dark form factor contribution to be disentangled [57].

Alternatively, if $R \gg 1$, then the atom's coupling to the Higgs is dominantly through the $\Delta'$, whose structure is on smaller scales than SM nuclei, since $\Lambda'_{\mathrm{QCD}} > \Lambda_{\mathrm{QCD}}$. Thus, in this case, we would have a basically momentum-independent dark form factor, and spin-independent cross sections would be like those shown in Fig. 1.

Kinetic mixing between sectors can arise via $(\epsilon/2)F_{\mu\nu}F'^{\mu\nu}$. Low-energy radiative contributions to $\epsilon$ appear to be absent up to three-loop order [14,19], giving $\epsilon \sim (16\pi^2)^{-4} \sim 10^{-9}$ if a four-loop contribution exists. Our DM atoms are neutral under both visible and twin-sector electromagnetism and have vanishing permanent electric dipole moments. Nevertheless, they have magnetic dipole moments under both sectors, with the visible sector moment suppressed by a factor of $\epsilon$. Constraints on $\epsilon$ arise from astrophysical, accelerator, and direct detection considerations [58–62]. The dominant constraint depends strongly on the values of $\alpha'$, $m_{\hat{H}}$, and $R$ chosen, but for the range of parameters considered here, $\epsilon \lesssim 10^{-9}$ seemingly satisfies all current bounds.

*Conclusions.*—We have shown that for the values of $\Lambda'_{\mathrm{QCD}}$ allowed by naturalness, and in the ungauged $U(1)'$ case, the twin hadron $\Delta' \sim b'b'b'$ is a successful ADM candidate, with a mass, $\mathcal{O}(10\ \mathrm{GeV})$, automatically in the most attractive regime for ADM theories to explain the $\mathcal{O}(1)$ ratio of DM-to-baryon energy densities. If $U(1)'$ is gauged, an asymmetric population of $\Delta'$ baryons is balanced by an equal number of $\bar{\tau}'$. In significant parameter regions, twin atoms form and are successful DM candidates consistent with all current constraints, although modified halo dynamics and direct detection signals are possible.

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