Letter

Baryon asymmetry from dark matter decay in the vicinity of a phase transition

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We propose a novel framework where baryon asymmetry of the Universe can arise due to forbidden decay of dark matter (DM) enabled by finite-temperature effects in the vicinity of a first-order phase transition (FOPT). In order to implement this novel cogenesis mechanism, we consider the extension of the standard model by one scalar doublet η, three right-handed neutrinos (RHNs), all odd under an unbroken Z_2 symmetry, popularly referred to as the scotogenic model of radiative neutrino mass. While the lightest RHN N_1 is the DM candidate and stable at zero temperature, there arises a temperature window prior to the nucleation temperature of the FOPT assisted by η, where N_1 can decay into η and leptons, generating a nonzero lepton asymmetry which gets converted into baryon asymmetry subsequently by sphalerons. The requirement of successful cogenesis together with a first-order electroweak phase transition not only keeps the mass spectrum of new particles in the sub-TeV ballpark within reach of collider experiments, but also leads to observable stochastic gravitational wave spectrum which can be discovered in planned experiments like the Laser Interferometer Space Antenna.

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Introduction. The presence of dark matter (DM) and baryon asymmetry in the Universe (BAU) has been suggested by several astrophysical and cosmological observations [1,2]. While the standard model (SM) of particle physics fails to solve these two long-standing puzzles, several beyond standard model proposals have been put forward. Among them, the weakly interacting massive particle paradigm of DM [3–8] and baryogenesis or leptogenesis [9–11] have been the most widely studied ones. While these frameworks solve the puzzles independently, the similar abundances of DM ($\Omega_{\rm DM}$) and baryon ($\Omega_{\rm B}$), that is, $\Omega_{\rm DM} \approx 5\Omega_{\rm B}$, has also led to efforts in finding a common origin or cogenesis mechanism. The popular list of such cogenesis mechanisms includes, but is not limited to, asymmetric dark matter [12–18], baryogenesis from DM annihilation [19–32], and Affleck-Dine [33] cogenesis [34–39]. Recently, there have also been attempts to generate DM and BAU together via a first-order phase transition (FOPT)[1] by utilizing the mass-gain mechanism [43]. In [44,45], a supercooled phase transition was considered where both DM and the right-handed neutrino (RHN) responsible for leptogenesis acquire masses in a FOPT by crossing the relativistic bubble walls. While the genesis of DM and BAU are aided by a common FOPT in these works, they have separate sources of production. Nevertheless, the advantage of such FOPT-related scenarios lies in the complementary detection prospects via stochastic gravitational waves (GWs).

In this paper, we propose a novel scenario where DM and BAU have a common source of origin in the vicinity of a FOPT. Though DM is cosmologically stable, it can decay in the early Universe due to finite-temperature effects and could be a viable source of baryon asymmetry. To illustrate the idea, we consider a scenario where a nonzero lepton asymmetry is generated from decay of DM during a short period just before a FOPT and subsequently gets converted into baryon asymmetry. The role of such forbidden decays on DM relic was discussed in several earlier works [46–49]. To the best of our knowledge, this is the first time such forbidden decay of DM facilitated by a FOPT has been considered to be the source of baryon asymmetry of the

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[1] See recent reviews [40–42] on FOPT in cosmology.

Universe. During a finite epoch in the early Universe, just before the nucleation temperature of a FOPT, such forbidden decays of DM, considered to be a gauge singlet RHN, into lepton and a second Higgs doublet are allowed, generating a nonzero lepton asymmetry which later gets converted into baryon asymmetry via electroweak sphalerons. The second Higgs doublet not only assists in making the electroweak phase transition (EWPT) first order, but also generates light neutrino masses at one-loop level together with the RHNs via the scotogenic mechanism [50,51]. With all the new fields in the sub-TeV ballpark and a strong FOPT, our cogenesis mechanism also has promising detection prospects at particle physics as well as GW experiments.

The framework. In order to realize the idea, we consider three RHNs $N_{1,2,3}$ and a new Higgs doublet η in addition to the SM particles. Similar to the minimal scotogenic model [50,51], these newly introduced fields are odd under an unbroken Z_2 symmetry, while all SM fields are even. The relevant part of the Lagrangian is given by

$$-\mathcal{L} \supset \frac{1}{2} M_{ij} \overline{N_i^c} N_j + Y_{\alpha i} \overline{L_\alpha} \tilde{\eta} N_i + \text{H.c.} \tag{1}$$

While neutrinos remain massless at tree level, the Z_2-odd particles give rise to a one-loop contribution to light neutrino mass [51,52]. The possibility of FOPT in this model was discussed earlier in [49,53]. While [53] considered single-step FOPT and relevant scalar as well as fermion DM studies, the authors of [49] studied both single- and two-step FOPT and their impact on fermion singlet DM by considering finite-temperature masses. In this work, we assume the FOPT to be single-step for simplicity.

We calculate the complete potential including the tree-level potential V_{tree} and one-loop Coleman-Weinberg potential V_{CW} [54] along with the finite-temperature potential V_{th} [55,56]. The thermal field-dependent masses of different components of η, namely, neutral scalar H, pseudoscalar A, and charged scalar $\eta^\pm$ along with other SM particles, are incorporated in the full potential. The zero-temperature masses of RHN and η components are denoted by $M_i, M_{H,A,\eta^\pm}$ in our discussions. Considering a one-step phase transition, where only the neutral component of the SM Higgs doublet (denoted as ϕ) acquires a nonzero vacuum expectation value, we then calculate the critical temperature T_c at which the potential acquires another degenerate minima at $v_c = \phi(T = T_c)$. The order parameter of the FOPT is conventionally defined as v_c/T_c such that a larger v_c/T_c indicates a stronger FOPT. The FOPT proceeds via tunneling, the rate of which is estimated by calculating the bounce action S_3 using the prescription in [57,58]. The nucleation temperature T_n is then calculated by comparing the tunneling rate with the Hubble expansion rate of the Universe $\Gamma(T_n) = \mathcal{H}^4(T_n)$.

As usual, such FOPT can lead to generation of stochastic gravitational wave background due to bubble collisions [59–63], the sound wave of the plasma [64–67], and the turbulence of the plasma [68–73]. The total GW spectrum is then given by

$$\Omega_{\text{GW}}(f) = \Omega_\phi(f) + \Omega_{\text{sw}}(f) + \Omega_{\text{turb}}(f).$$

While the peak frequency and peak amplitude of such a GW spectrum depend upon specific FOPT-related parameters, the exact nature of the spectrum is determined by numerical simulations. The two important quantities relevant for GW estimates, namely, the duration of the phase transition and the latent heat released, are calculated and parametrized in terms of [74]

$$\frac{\beta}{\mathcal{H}(T)} \simeq T \frac{d}{dT}\left(\frac{S_3}{T}\right)$$

and

$$\alpha_* = \frac{1}{\rho_{\text{rad}}}\left[\Delta V_{\text{tot}} - \frac{T}{4}\frac{\partial \Delta V_{\text{tot}}}{\partial T}\right]_{T=T_n},$$

respectively, where ΔV_{tot} is the energy difference in true and false vacua. The bubble wall velocity v_w is estimated from the Jouguet velocity [68,75,76]

$$v_J = \frac{1/\sqrt{3} + \sqrt{\alpha_*^2 + 2\alpha_*/3}}{1+\alpha_*}$$

according to the prescription outlined in [77].[2] We also estimate the reheat temperature T_{RH} after the FOPT due to the release of energy. T_{RH} is defined as $T_{\text{RH}} = \text{Max}[T_n, T_{\text{inf}}]$ [43], where T_{inf} is determined by equating density of radiation energy to that of energy released from the FOPT or, equivalently, ΔV_{tot}. A large reheat temperature can dilute the lepton or baryon asymmetry produced prior to the nucleation temperature by a factor of $(T_n/T_{\text{RH}})^3$. Since we are not in the supercooled regime, such entropy dilution is negligible in our case, as we can infer by comparing T_n and T_{RH} for the benchmark points given in Table I. In the same table, we also show the relevant parameters related to the model and related FOPT and GW phenomenology.

Cogenesis of baryon and dark matter. We first discuss the temperature dependence of relevant particle masses leading to the temperature window which enables forbidden decay of DM. The left panel in Fig. 1 shows the temperature dependence of masses of inert scalar doublet components, lepton doublet L, and the lightest RHN N_1 plotted as a function of $z = M_1/T$ for benchmark point BP1 given in

[2]See [78] for a recent model-independent determination of bubble wall velocity.

TABLE I. Benchmark model parameters along with the corresponding FOPT and GW related parameters. Here, μ_η is the bare mass of the inert scalar doublet η.

	T_c (GeV)	v_c (GeV)	T_n (GeV)	M_1 (GeV)	μ_η (GeV)	$M_{\eta^\pm} \sim M_A$ (GeV)	M_H (GeV)	α_*	$\beta/\mathcal{H}$	v_J	$T_{\rm RH}$ (GeV)
BP1	60.05	217.22	29.27	859.50	760.25	951.51	931.26	1.29	20.21	0.94	30.37
BP2	73.55	187.62	68.54	866.70	787.07	958.89	944.72	0.04	2862.35	0.71	68.54
BP3	71.30	199.28	64.33	676.64	579.36	774.96	743.73	0.06	1829.84	0.74	64.33
BP4	63.35	216.65	38.49	493.74	368.04	608.38	548.60	0.45	159.33	0.88	38.49

Table I. Clearly, η remains heavier than N_1 at low temperatures, especially after acquiring a new contribution to its mass (in addition to bare mass μ_η) from SM Higgs Φ as a result of the EWPT. This makes N_1 the lightest Z_2-odd particle at low temperatures and, hence, cosmologically stable to contribute to DM relic. As seen from the left panel in Fig. 1, just before the nucleation temperature T_n of EWPT, η is lighter than N_1 but again becomes heavier at high temperature $T > T_s$ due to large thermal correction. This gives rise to a finite window $(T_n < T < T_s)$ in the vicinity of EWPT where N_1 remains heavier than η and L, enabling the forbidden decay $N_1 \to \eta L$. Depending upon the duration of this decay and CP asymmetry, it is possible to generate sufficient lepton asymmetry while satisfying DM relic as a result of this forbidden decay. Since we are relying on electroweak sphalerons to convert the lepton asymmetry to baryon asymmetry, we require $T_s > T_{\rm sph} \sim 130$ GeV. Generation of lepton asymmetry from the lightest RHN decay in the minimal scotogenic model was studied in several earlier works [79–88]. Here, we use the finite-temperature corrections which allow N_1 to be DM while being responsible for generating lepton asymmetry at high scale, leading to a novel cogenesis possibility in this minimal model.

In order to find baryon asymmetry and DM relic, the relevant Boltzmann equations for comoving number densities $Y = n_X/s$ of $X \equiv N_1, \eta, B-L$ (s being the entropy density) have to be solved numerically. While we consider self-annihilation of η into account in the Boltzmann equations, the (co)annihilation rates for N_1 remain much suppressed compared to decay rate of N_1 due to small couplings and phase-space suppression. The small Dirac Yukawa couplings of sub-TeV scale N_1 are required to satisfy light neutrino masses. The dominant decay and inverse decay rates of N_1 are sufficient to keep N_1 almost in equilibrium till $T = T_n$. In addition to considering the finite-temperature masses of N_1, η, and L, we also consider the modified CP asymmetry parameter ϵ_1 by appropriately considering such corrections. The lepton asymmetry at the sphaleron decoupling epoch $T_{\rm sph} \sim 130$ GeV gets converted into baryon asymmetry. The final baryon asymmetry η_B can be analytically estimated to be [89]

$$\eta_B = \frac{a_{\rm sph}}{f}\epsilon_1 \kappa, \tag{2}$$

where the factor f accounts for the change in the relativistic degrees of freedom from the scale of leptogenesis until recombination and comes out to be $f = \frac{106.75}{3.91} \simeq 27.3$. κ is known as the efficiency factor which incorporates the effects of washout processes, while $a_{\rm sph}$ is the sphaleron conversion factor. The lepton asymmetry at the sphaleron

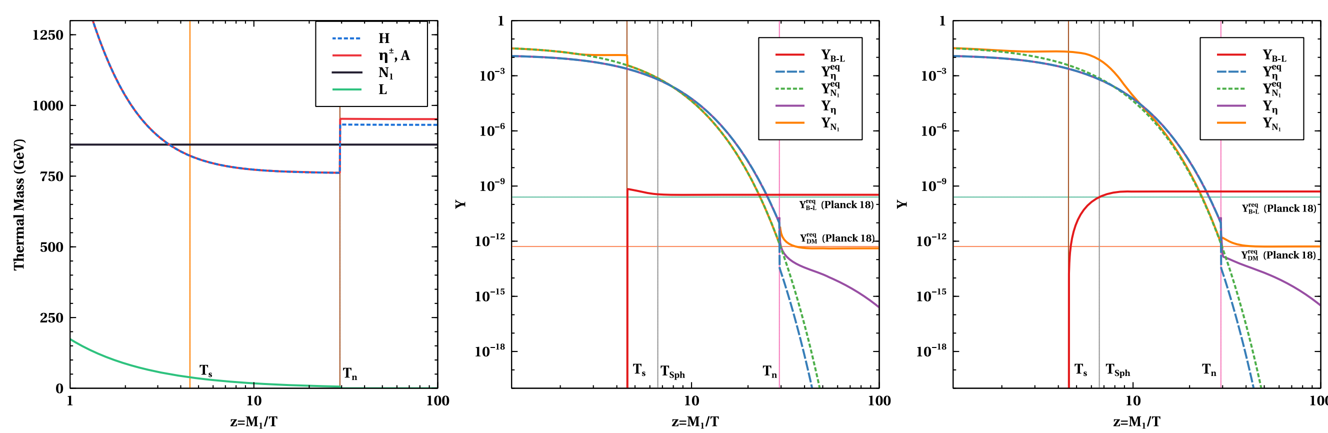

FIG. 1. Left panel: finite-temperature masses of L and N_1 and components of η for BP1 shown in Table I. Middle panel: evolution of comoving number densities for η, N_1, and $B-L$ for BP1 shown in Table I (the lightest neutrino mass is 10^{-1} eV in normal ordering and $z_{23} = 10.34i$). Right panel: the same as in the left panel but for the lightest neutrino mass 10^{-5} eV. The vertical line labeled as T_s (T_n) denotes the temperature below which $N_1 \to L\eta$ decay is kinematically allowed (disallowed). The vertical line labeled as $T_{\rm sph}$ indicates the sphaleron decoupling temperature of ~130 GeV.

decoupling epoch $T_{\mathrm{sph}} \sim 130$ GeV gets converted into baryon asymmetry as [90]

$$Y_B \simeq a_{\mathrm{sph}} Y_{B-L} = \frac{8N_F + 4N_H}{22N_F + 13N_H} Y_{B-L}, \tag{3}$$

which, for our model, with $N_F = 3$ and $N_H = 2$ gives $a_{\mathrm{sph}} = 8/23$.

Instead of considering any approximate analytical expressions, we solve the explicit coupled Boltzmann equations involving N_1, η, and $B-L$ number densities numerically for the same benchmark points shown in Table I. The middle and right panels in Fig. 1 show the corresponding evolution of N_1, η, and $B-L$ for BP1 considering two different values of lightest neutrino mass m_1 assuming normal ordering (NO). The heavier RHN masses are fixed at $M_2 = 2M_1$ and $M_3 = 3M_1$, while the nonzero complex angle in the orthogonal matrix R (which appears in Casas-Ibarra parametrization [91]) is chosen to be $z_{23} = 10.34i$. The quasidegenerate nature of RHN spectrum is motivated from the fact that the temperature-corrected CP asymmetry parameter is derived only for the interference of tree-level and self-energy diagrams. For the choices of masses and Casas-Ibarra parameters, Dirac Yukawa couplings of N_1 remain at $\lesssim \mathcal{O}(10^{-5})$, while for $N_{2,3}$ they can be as large as $\mathcal{O}(10^{-1})$. Depending upon the lightest neutrino mass $m_1 = 10^{-1}$ eV and $m_1 = 10^{-5}$ eV, leptogenesis can be in strong and weak washout regimes as seen from the middle and right panels in Fig. 1, respectively. As clearly seen from both these panels, Y_{B-L} remains zero at $T > T_s$ when $N_1 \to \eta L$ is kinematically forbidden. Soon after this threshold, lepton asymmetry freezes in and saturates to the asymptotic value at large z. After the initial rise in Y_{B-L}, the middle panel shows a slight decrease before saturation, typical of a strong washout regime due to larger values of m_1 and, hence, larger Dirac Yukawa couplings associated with N_1. For the chosen benchmark satisfying $T_s > T_{\mathrm{sph}} > T_n$, the comoving abundance of RHN N_1 saturates at $T < T_n$, giving rise to the required DM relic. While η can decay at $T < T_n$, it cannot affect baryon asymmetry as $T_n < T_{\mathrm{sph}}$ for BP1. Even for $T_n > T_{\mathrm{sph}}$, η decay need not change lepton asymmetry if $\eta \to \eta^\dagger$ type of processes via the scalar portal remain efficient. The late decay of η can, however, change the abundance of N_1. However, for the chosen benchmark point BP1, such late decay contribution to DM abundance is negligible. As seen from the middle and right panels in Fig. 1, the DM final abundance is consistent with the observed DM relic $\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$ [2]. Both the strong and weak washout regimes can produce the required lepton asymmetry by T_{sph} needed to generate observed baryon-to-photon ratio $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}$ [2]. Similar results are also obtained for inverted ordering of light neutrino masses as well as other choices of benchmark parameters. While we have assumed RHN to be in the bath initially, the generic conclusions do not change even if we consider RHNs to freeze in from the bath.

Detection prospects. In the left panel in Fig. 2, we show the GW spectrum for the benchmark points given in Table I. The same table also contains the details of the GW-related parameters used for calculating the spectrum. Clearly, the peak frequencies as well as a sizable part of the spectrum for three benchmark points remain within the sensitivity of planned future experiment like the Laser Interferometer Space Antenna (LISA) [92], keeping the discovery prospect of the model very promising. Sensitivities of other future

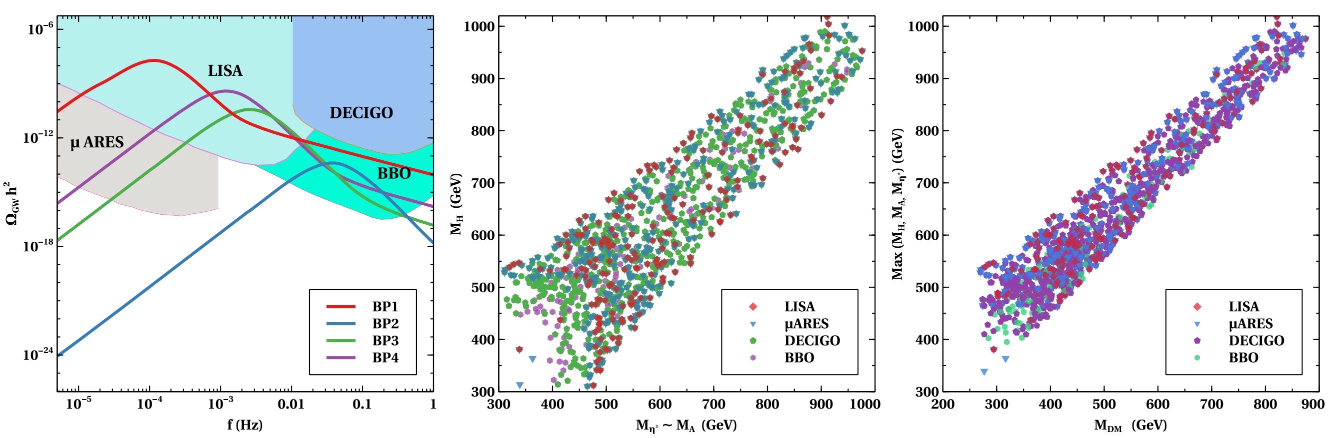

FIG. 2. Left panel: GW spectrum corresponding to the benchmark points given in Table I. The future sensitivity of LISA, μARES, BBO, and DECIGO are shown as shaded regions. Middle panel: parameter space in $M_{\eta^\pm} \sim M_A$ versus M_H plane with the color code showing sensitivity of different GW experiments. Right panel: the parameter space in heaviest scalar-M_{DM} parameter space with the color code showing sensitivity of different GW experiments. In this scan, $\mu_\eta \in (200\text{–}800)$ GeV, $\lambda_2 \in (1, 2)$ the lightest neutrino mass is 10^{-3} eV in NO, $z_{23} = 8i$, and the heavier RHN masses are fixed at $M_2 = 2M_1$ and $M_3 = 3M_1$. The points shown in the scan plots are consistent with DM relic criteria.

experiments like μARES [93], the Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) [94], and the Big Bang Observer (BBO) [95] are also shown as shaded regions, covering most of the GW spectrum for our benchmark points. In order to project the parameter space of the model against GW sensitivities of these experiments, we perform a numerical scan to find the region consistent with a FOPT and DM relic criteria. The parameter space is shown in the middle and right panel plots in Fig. 2 with the variations in inert doublet scalar and DM masses. In the color code, we show the reach of different future GW detectors in terms of respective signal-to-noise ratio (SNR) more than 10. The SNR is defined as [96]

$$\rho = \sqrt{\tau \int_{f_{\min}}^{f_{\max}} df \left[\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm expt}(f)h^2}\right]^2}, \tag{4}$$

with τ being the observation time for a particular detector, which we consider to be 1 yr. Clearly, all four experiments mentioned above can probe the parameter space. It should be noted that the allowed parameter space for inert doublet scalars remains within the TeV ballpark in order to have a first-order EWPT. This also restricts DM mass in the same ballpark in order to realize the forbidden decay scenario. Note that all the points in the scan plots shown in Fig. 2 do not fulfill the criteria for the observed baryon asymmetry. They can, however, be made to satisfy the required BAU by suitably varying the CI parameter z_{23} without affecting rest of the phenomenology significantly.

Because of the sub-TeV particle spectrum, the model can also have interesting collider prospects due to the inert scalar doublet η. The model can give rise to same-sign dilepton plus missing energy [97,98], dijet plus missing energy [99], trilepton plus missing energy [100], or even monojet signatures [101,102] in colliders. The model can also have interesting prospects of charged lepton flavor-violating decays like $\mu \to e\gamma$ and $\mu \to 3e$ due to light N_1 and η going inside the loop mediating such rare processes. Particularly for fermion singlet DM, such rare decay rates can saturate present experimental bounds [91].

Conclusion. We have studied a novel way of generating baryon asymmetry and dark matter in the Universe from a common source, namely, forbidden decay of dark matter felicitated by a first-order electroweak phase transition. We adopt the minimal scotogenic model to illustrate the idea where a Z_2-odd scalar doublet η assists in realizing a first-order EWPT while also leading to the origin of light neutrino mass at one-loop level with the help of three copies of Z_2-odd right-handed neutrinos. The lightest RHN is the DM candidate and stable at zero temperature. However, finite-temperature effects and dynamics of the FOPT give rise to a small temperature window $T_s > T > T_n$, prior to the nucleation temperature when DM or N_1 can decay into η and L generating a nonzero lepton asymmetry which can get converted into baryon asymmetry by electroweak sphalerons provided $T_s > T_{\rm sph}$, the sphaleron decoupling temperature. The DM becomes stable at $T < T_n$, leading to saturation of its comoving abundance at late epochs. The requirement of a first-order EWPT, successful cogenesis leading to observed baryon asymmetry and DM relic in this setup forces the mass spectrum of newly introduced particles to lie in the sub-TeV range to be probed at collider experiments. On the other hand, the specific predictions for stochastic gravitational wave spectrum can be probed at planned experiments like LISA. Such complementary detection prospects keep this novel cogenesis setup verifiable in the near future. While we considered a single-step FOPT in our work, two-step FOPT can lead to interesting results for cogenesis along with new detection prospects. On the other hand, implementation of this idea to achieve direct baryogenesis at a scale much lower than the sphaleron decoupling temperature can lead to GW with much lower frequencies which can be observed at pulsar timing array (PTA) experiments and could, in fact, be a possible explanation for the recent PTA data [103–106]. We leave such tantalizing possibilities to future works.

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