A fine-tuned Higgs potential with two degenerate minima for a dark QCD matter scenario

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We consider the Higgs potential in generalizations of the Standard Model. The possibility of the potential to develop two almost degenerate minima is explored. This would imply that QCD matter at two distinct sets of quark masses is relevant for astrophysics and cosmology. If in the exotic minimum the QCD matter ground state is electromagnetically neutral, dark matter may consist of QCD matter and antimatter in bubbles of the Higgs field.

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INTRODUCTION

Dark matter studies receive considerable attention in fundamental research (see e.g. [1–16]). Various scenarios proposed require new particles in extensions of the Standard Model (SM) (see e.g. [1, 6]).

The purpose of our short note is to discuss a possible alternative of such scenarios based on exotic QCD matter. In a recent work the authors presented a detailed study suggesting that QCD matter depends decisively on the Higgs field [17–19]. Within the SM the quark masses in QCD are proportional to the Higgs field. In turn, changing its ground state value does change the quark masses in QCD, however, in a manner that keeps all quark-mass ratios fixed. In [19] a possible first order transition along the Higgs field trajectory was discussed. It is compatible with current QCD lattice simulations of the baryon ground state masses, but should be scrutinized by further dedicated QCD lattice studies.

In Fig. 1 we show our prediction of the baryon masses along the Higgs trajectory [17–19]. The bands in the plot provide an estimate of uncertainties based on our Fit 1 and Fit 2 scenarios as discussed in [19]. At fixed ratio $m_s/m = 26$ the masses are plotted as a function of the strange quark mass. The key observation is that within a critical region of the Higgs, field baryonic matter and antimatter is composed from Λ and ¯Λ particles rather than from nucleons and anti-nucleons. This follows from the relation $M_{\Lambda} < M_N$, which holds at a specific range of the strange quark mass. Since Λ particles are electromagnetically neutral such matter does not radiate and therefore appears dark. Since the Higgs sector of the SM drives a possible electroweak phase transition and baryogenesis models (see e.g. [20–23]) it is important to explore exotic Higgs sector extensions of the SM in more detail.

THE HIGGS POTENTIAL

We consider the Higgs sector of the SM [20, 23–33]. At tree-level the Higgs potential in the SM can be expressed in terms of two parameters only

$$V(H) = \frac{M_h^2}{2 v^2} \left(H^\dagger H - \frac{v^2}{2}\right)^2,$$

with the complex doublet Higgs field $H$, the Higgs mass parameter $M_h \approx 125.2$ GeV and the vacuum expectation value $v \approx 246.2$ GeV of the Higgs field in its physical vacuum state [34]. In this work we are interested in the Higgs potential at $H^\dagger H \leq v^2$, where it is known that even loop corrections in the SM are sizeable (see e.g. [24, 26, 28–30, 35, 36]). Since the Higgs potential will be affected in most generalizations of the SM we follow here a phenomenological path where we explore the consequence of a fine-tuned potential with two degenerate minima. An effective field theory approach would require $(H^\dagger H)^3$ and...
(H^\dagger H)^4 operators of the form

\[ V(H) = \frac{2M_h^2}{v^6 (1 - r^2)^2} \left( H^\dagger H - \frac{v^2}{2} \right)^2 \left( H^\dagger H - \frac{v^2}{2} \right)^2, \]

and \[ r = v_a/v = m_s/m_s^{\text{phys}}, \]

with \( v_a \) the vacuum expectation value of the Higgs field at the exotic minimum. By construction, the model potential (2) has two degenerate minima. At its physical one it recovers the empirical mass of the Higgs. The ratio \( r = v_a/v \) determines the strange quark mass in the exotic minimum.

The puzzle with (2) is that it may be unnatural in the size of its dimension-full operators. However, we may recast the problem by considering loop corrections (see e.g. [24, 26, 29]). In the presence of multi-loop effects we may use the ansatz

\[ V(H) = \frac{M_h^2}{2v^2} \left[ \log((\gamma + r^2) - \log(\gamma + 1))^2 \right] \left( H^\dagger H - \frac{v^2}{2} \right)^2 \times \left[ \log [\gamma + 2H^\dagger H/v^2] - \log(\gamma + r^2) \right]^2, \]

where the particular form of the log term in terms of the parameter \( \gamma \) is taken from [30]. There the value \( \gamma = 0.1 \) is used.

According to Fit 1 and Fit 2 we expect dark QCD matter in the range 0.39 < \( r < 0.57 \) and 0.39 < \( r < 0.54 \) respectively. The critical values are close to those as derived in [19] on the unphysical trajectory where \( m_s + m_d \) is kept constant. In Fig. 2 we plot the effective potentials of (1-3) as a function of \( h = \sqrt{2H^\dagger H}/v \) at the particular choice \( r = 0.45 \). The two degenerate minima are clearly visible for any of the three choices \( \gamma = 0.1, \gamma = 0.2 \) and \( \gamma = 0.3 \). With the parameter \( \gamma \) we can efficiently dial the magnitude of the Higgs potential close to the origin. In the vicinity of the two local minima we find a rather mild dependence on the form of our parametrization. The polynomial ansatz (2) or the double-log form (3) lead to almost indistinguishable results.

One may object to such a fine-tuned Higgs potential. However, we wish to recall that there are ample cases in physics in which a system is driven by fine-tuned dynamical assumptions. So, at this stage of the development we would not write too much. Rather, it is more enlightening to discuss in more detail the consequences of a possible dark QCD matter scenario.

Whether massive dark matter clusters form depends on the equation of state of the \( \Lambda \) particles in the Higgs bubble. In a conventional meson-exchange phenomenology, the repulsive omega-meson exchange process is expected to dominate the short-range interaction. Due to approximate isospin conservation, pion- and rho-meson exchange processes are suppressed. It remains the eta-meson exchange and the two-pion exchange contributions, which may bring in some weak intermediate-range attractive force [42–44]. While there appears to be a rather weak net attraction at the physical point [44–47] available studies suggest a sizeable quark-mass dependence thereof [42, 46–48]. We conclude that at the exotic Higgs minimum, that comes at much smaller quark masses, there is little evidence to expect this weak attraction to survive. In turn there would be no significant clustering of dark matter inside the Higgs bubbles to massive objects. This is compatible with empirical constraints on the dark matter distributions, which do not suggest large-scale clustering effects (see e.g. [8, 37, 49, 50]).

If the exotic minimum in the Higgs potential is slightly metastable, we expect a scenario where the vacuum shows bubbles with dark QCD matter inside, but normal QCD matter outside. Since the two minima are separated by a huge barrier tunneling effects should not dominate here. Inside the bubbles the matter or antimatter ground states consists of \( \Lambda \) or \( \bar{\Lambda} \) particles, however with exotic properties as demonstrated in [19].
SUMMARY AND CONCLUSIONS

We constructed a phenomenological Higgs potential with two degenerate local minima. It was argued that such an extension of the SM may lead to dark QCD matter that lives in bubbles of the Higgs field, with normal QCD matter outside and dark QCD matter inside. Within the bubbles we expect exotic Λ and ¯Λ particles, that are formed by QCD at unphysically small strange quark masses. It would be interesting to further scrutinize the dark QCD matter scenario proposed here. With current QCD lattice techniques it is possible to substantiate or rule out such a scenario. It would be important to establish a more fundamental framework in which such an exotic Higgs potential is implied.

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[1] G. Bertone, D. Hooper, and J. Silk, Phys. Rept. 405, 279 (2005), hep-ph/0404175.
[2] M. Rocha, A. H. G. Peter, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, J. Onorbe, and L. A. Moustakas, Mon. Not. Roy. Astron. Soc. 430, 81 (2013), 1208.3025.
[3] S. Tulin, H.-B. Yu, and K. M. Zurek, Phys. Rev. D87, 115007 (2013), 1302.3898.
[4] K. Petraki and R. R. Volkas, Int. J. Mod. Phys. A28, 1330028 (2013), 1305.4939.
[5] C. Jarlskog, Phys. Rev. Lett. 55, 1039 (1985).
[6] J. Braathen and S. Kanemura (2019), 1903.05417.
[7] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018).
[8] C. Tamarit, Phys. Rev. D90, 055024 (2014), 1404.7673.
[9] Y. Hamada, Ph.D. thesis, Kyoto U. (2016).
[10] J. de Swart, G. Bertone, and J. van Dongen (2017), Nature Astron.1,0059(2017), 1703.00013.
[11] C. Jarlskog, Phys. Rev. Lett. 55, 1039 (1985).
[12] M. E. Shaposhnikov, JETP Lett. 44, 465 (1986), [Pisma Zh. Eksp. Teor. Fiz.44,36(1986)].
[13] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pene, Mod. Phys. Lett. A9, 795 (1994), hep-ph/9312215.
[14] G. W. S. Hou, Int. J. Mod. Phys. D20, 1521 (2011), 1101.2161.
[15] K. Sasaki, E. Oset, and M. J. Vicente Vacas, Phys. Rev. C74, 064002 (2006), nucl-th/0607068.
[16] H. Polinder, J. Haidenbauer, and U.-G. Meißner, Phys. Lett. B653, 29 (2007), 0705.3753.
[17] E. Bauer, G. Garbarino, and C. A. Rodríguez Pea, Phys. Rev. C92, 014301 (2015).
[18] J. Haidenbauer, U.-G. Meißner, and S. Poves, Nucl. Phys. A954, 273 (2016), 1511.05859.
[19] K. Sasaki, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, T. Inoue, N. Ishii, and K. Murano (HAL QCD), PTEP 2015, 113B01 (2015), 1504.01717.
[20] K. Sasaki, S. Aoki, T. Doi, S. Gongyo, T. Hatsuda, Y. Ikeda, T. Inoue, T. Iritani, N. Ishii, and T. Miyamoto (HAL QCD), EPJ Web Conf. 175, 05010 (2018).
[21] S. R. Beane et al., Mod. Phys. Lett. A26, 2587 (2011), 1103.2821.
[22] A. B. Newman, T. Treu, R. S. Ellis, D. J. Sand, J. Richard, P. J. Marshall, P. Capak, and S. Miyazaki,
[50] N. C. Relatores, A. B. Newman, J. D. Simon, R. Ellis, P. Truong, L. Blitz, A. Bolatto, C. Martin, and P. Morrissey, Astrophys. J. 873, 5 (2019), 1902.09629.