The Decaying and Scattering Properties of the $d^*(2380)$ Hexaquark Bose–Einstein Condensate Dark Matter

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Abstract
Recently, a study has shown that the Bose–Einstein condensates (BECs) formed by the $d^*(2380)$ hexaquarks ($d^*(2380)$-BECs) can be thermally produced in the early universe and they are stable enough to be a competitive candidate for dark matter. Searching for the decaying signature of $d^*(2380)$-BECs is a possible way to verify this dark matter model. In this article, we discuss the scattering and decaying properties of the $d^*(2380)$-BECs and we show that the decay rate of the $d^*(2380)$-BECs is correlated with the TeV cosmic-ray flux. The predicted average decay rate in our Galaxy is several orders of magnitude larger than the current observed upper limit. Therefore, it would be very difficult for us to search for the decaying signature of the $d^*(2380)$-BEC dark matter model. Nevertheless, the size of the $d^*(2380)$-BECs may be large enough to have self-interaction so that we can possibly detect them in the future.

Unified Astronomy Thesaurus concepts: Dark matter (353); Particle physics (2088); Particle astrophysics (96)

1. Introduction
Observational data of galaxies, galaxy clusters, and the cosmic microwave background reveal that some unknown dark matter particles exist in our universe. However, all of the known fundamental particles in the Standard Model do not exhibit the properties of dark matter. Although many theoretical models have suggested some possible dark matter candidates such as weakly interacting massive particles (WIMPs) or sterile neutrinos, there is no promising observed signal of these hypothetical particles so far. Current observational data of direct detections (Tan et al. 2016; Aprile et al. 2017, 2018), indirect detections (gamma-ray, radio, or cosmic-ray detections; Bergström et al. 2013; Egorov & Pierpaoli 2013; Ackermann et al. 2015a; Boudaud et al. 2015; Calore et al. 2015; Abazajian & Keely 2016; Chan 2016, 2017; Daylan et al. 2016; Albert et al. 2017; Chan & Leung 2017; Chan et al. 2019; Cavasonza et al. 2019; Aguilar et al. 2019) and collider experiments (Abecerrribie et al. 2020) have ruled out a large parameter space of particle dark matter models, especially for WIMPs (Roszkowski et al. 2018).

Many previous models of particle dark matter assume that they are fermions (e.g., WIMP models). Nevertheless, many studies are now focusing on dark matter particles being bosons. One important feature of bosonic dark matter is that the bosonic dark matter particles can form a Bose–Einstein condensate (BEC) while femionic dark matter cannot (Chavanis 2011). For example, if the mass of the bosonic dark matter particles is $m \sim 10^{-22}$ eV, then they can form a very large BEC and behave like a large dark matter halo in a galaxy or galaxy cluster (Zhang et al. 2018).

Recently, a study has shown that a certain number of hexaquarks $d^*(2380)$ can be bound together to form a stable BEC (hereafter called $d^*(2380)$-BEC; Bashkanov & Watts 2020). The $d^*(2380)$-BECs can be thermally formed in the early universe (Bashkanov & Watts 2020). The hexaquark $d^*(2380)$ is formed by six quarks (three $u$ quarks and three $d$ quarks) and its existence was confirmed in collider experiments in the past decade (Adlarson et al. 2011, 2015; Li et al. 2019). The mass of an individual $d^*(2380)$ hexaquark is $m_d = 2.38$ GeV while the mass of a $d^*(2380)$-BEC can be larger than 1 TeV, which depends on the total number of bounded hexaquarks.

A $d^*(2380)$-BEC could break down and decay to emit gamma-rays with energy $\sim 100$–500 MeV (Bashkanov & Watts 2020). In this article, we theoretically discuss the scattering properties and the decay rate $\Gamma_d$ of the $d^*(2380)$-BECs. We show that the observed value of $\Gamma_d$ may not be a constant and it depends on the astrophysical environment. We also constrain the average $\Gamma_d$ in our Galaxy and compare it with our theoretical prediction.

2. Theoretical Prediction of the Scattering Rate and Decay Rate
A group of $d^*(2380)$ hexaquarks can form stable BECs. The binding energy depends on the number of hexaquarks bounded and the geometrical shapes (e.g., spherical shape) of the BECs. The binding energy $B$ of the $d^*(2380)$-BEC per number of hexaquarks $D$ is given by (Bashkanov & Watts 2020)

$$\frac{B}{D} = a_V(D - 1) - a_C \frac{D}{D^{1/3}},$$

where $a_V \sim 1$ MeV and $a_C \sim 0.1$ MeV are coefficients that determine the relative strengths of the attractive volume and the repulsive Coulomb terms. A stable $d^*(2380)$-BEC may consist of $\sim 10^3$–$10^6 d^*(2380)$ hexaquarks. The minimum $D$ for a stable $d^*(2380)$-BEC is $D \sim 10^3$ so that the binding energy threshold of a stable $d^*(2380)$-BEC is $\sim 1$ TeV (Bashkanov & Watts 2020). A large amount of stable $d^*(2380)$-BECs could be thermally formed in the early universe and we assume that the stable $d^*(2380)$-BECs constitute all of the dark matter in our universe.

As the universe expands, the matter temperature would decrease quickly to much less than 1 MeV. Therefore, after the $d^*(2380)$-BECs thermally formed in the early universe, they would cool down quickly and soon become very stable as the collisional kinetic energy is not enough to break down the $d^*(2380)$-BECs. However, after galaxies formed, some exotic
astrophysical phenomena (e.g., supernovae) would emit a large amount of high-energy photons and cosmic rays. The energies of these particles can be larger than the energy threshold (\(> 1\) TeV) such that they can break down the stable \(d^*\) B(2380)-BECs to free \(d^*(2380)\) hexaquarks. The free \(d^*(2380)\) hexaquarks are unstable and they will quickly decay to other elementary particles (e.g., gamma-ray photons) without forming back to a \(d^*(2380)\)-BEC. The energy spectra of the free \(d^*(2380)\) hexaquarks can be calculated numerically by considering several major decaying channels (e.g., via pion, proton, neutron, and deuterons; Bashkanov & Watts 2020).

Therefore, the decay rate of the \(d^*(2380)\)-BECs \(\Gamma_d\) would be dependent on the amount of the high-energy cosmic rays (including gamma-rays), which is proportional to the number density of the high-energy cosmic rays \(n_{CR}\). The interaction rate between high-energy cosmic rays and \(d^*(2380)\)-BECs in a particular volume is given by \(n_{CR} N_d \sigma_{CR,d} e\), where \(N_d\) is the total number of \(d^*(2380)\)-BECs inside the volume and \(\sigma_{CR,d}\) is the cross section of the interaction. Suppose that the energy of the cosmic rays is greater than the threshold break down energy of a \(d^*(2380)\)-BEC \(E \sim 1\) TeV. The \(d^*(2380)\)-BECs would break down to give a large amount of free \(d^*(2380)\) hexaquarks and they will decay in a very short time \((\approx 10^{-33}\) s\). Therefore, the number of decaying \(d^*(2380)\)-BECs per unit time \(N_d \Gamma_d\) is equal to the interaction rate:

\[
n_{CR} N_d \sigma_{CR,d} e = N_d \Gamma_d.
\] (2)

Following the above equation, we get the decay rate \(\Gamma_d = n_{CR} \sigma_{CR,d} e\).

On the other hand, the cosmic-ray flux \(\Phi_{CR}\) (in \(\text{cm}^{-2} \text{s}^{-1}\)) emitted from a volume is proportional to the number density of the cosmic rays \(n_{CR}\) by \(\Phi_{CR} = n_{CR}/4\) (like blackbody radiation emission). Therefore, we get \(\Gamma_d = 4 \sigma_{CR,d} \Phi_{CR}\). For thousands of \(d^*(2380)\) hexaquarks forming a \(d^*(2380)\)-BEC, the size of a \(d^*(2380)\)-BEC can be as large as \(R = n_{d} D^{1/3} \approx 10^{-12}\) cm (Bashkanov & Watts 2020), where we have assumed the self-interaction length \(a \approx 1\) fm and \(D = 10^{5}\). The cross section is approximately given by \(\sigma_{CR,d} = \pi R^2\). Hence, we have

\[
\Gamma_d = 4 \pi R^2 \Phi_{CR}.
\] (3)

It is worth noting that the size of a \(d^*(2380)\)-BEC is large enough to have nonnegligible interactions between the \(d^*(2380)\)-BECs. If they could have elastic collisions, the geometrical self-interaction cross section is given by \(\sigma_{dd} = 4 \pi R^2\). For \(D = 10^3\), the rest mass of a \(d^*(2380)\)-BEC is \(m_{BEC} \sim 1\) TeV. Therefore, the cross section per unit mass is \(\sigma_{dd}/m_{BEC} \sim 0.01\) cm\(^2\) g\(^{-1}\). This value is below the observed upper limits of the self-interacting dark matter model \((\sim 0.1 - 1\) cm\(^2\) g\(^{-1}\); Randall et al. 2008; Peter et al. 2013). Therefore, the proposed size and mass of the \(d^*(2380)\)-BEC dark matter is consistent with the observed limits. For \(D > 10^3\), the value of \(\sigma_{dd}/m_{BEC}\) would be less than 0.01 cm\(^2\) g\(^{-1}\). Although the value of \(\sigma_{dd}/m_{BEC}\) may not be large enough to form large density cores in galaxies (Chan 2013; Robles et al. 2019), the possible interactions between the \(d^*(2380)\)-BECs or the interactions between the \(d^*(2380)\)-BECs and baryons might have some other interesting implications that require further explorations. Nevertheless, the above geometrical approach does not include the possible quantum mechanical interactions between the \(d^*(2380)\)-BECs (e.g., tunneling effect) and between \(d^*(2380)\)-BECs and baryons. Some suppression or enhancement of interaction cross sections might appear so that the actual interaction cross sections would be quite different from our estimated value. If the enhancement is significant so that \(\sigma_{dd}/m_{BEC} \sim 0.1-1\) cm\(^2\) g\(^{-1}\), it may be able to account for the dark matter density cores observed in galaxies. Future experimental investigations on the \(d^*(2380)\) interactions can give better hints for this issue. On the other hand, since the cosmic rays we considered have a higher energy than the break down energy of a \(d^*(2380)\)-BEC, the geometrical argument applied in Equation (3) is still valid.

Consider the Milky Way as an example. The background diffuse TeV cosmic rays in our Galaxy would break down the \(d^*(2380)\)-BECs to give free \(d^*(2380)\) hexaquarks. Therefore, we can predict the average decay rate \(\Gamma_d\) in our Galaxy by using the background diffuse cosmic-ray data. The isotropic background TeV gamma-ray flux measured is \(< 10^{-15}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (Ackermann et al. 2015b; Harding 2019), which is much smaller than the isotropic background diffuse TeV electron and positron flux measured by the DAMPE (DAMPE Collaboration et al. 2017) and Fermi-LAT (Abdollahi et al. 2017) \((\approx 10^{-8}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)\). Therefore, the effect of the diffuse background TeV electrons and positrons would be much more dominant in breaking down the \(d^*(2380)\)-BECs. Using Equation (3), the predicted average decay rate of \(d^*(2380)\)-BECs in our Galaxy is \(\Gamma_d \approx 10^{-33}\) s\(^{-1}\). Compared with the age of our universe \(t \sim 10^{17}\) s, only a small amount of \(d^*(2380)\)-BECs have decayed. Based on this formulation, the \(d^*(2380)\)-BECs may be very stable in our universe. However, we expect that the decay rate would vary with different astrophysical environments and it is much larger in a volume surrounded by TeV gamma-ray or cosmic-ray sources.

### 3. Constraining the Decay Rate by Astronomical Data

The energy of photons emitted from the decay of a free \(d^*(2380)\) hexaquark is \(E = 100-500\) MeV (Bashkanov & Watts 2020). These photons would quickly contribute to the isotropic background gamma-ray spectrum. Therefore, the observational isotropic gamma-ray background (IGRB) data of energy 100–500 MeV might be able to constrain the decay rate \(\Gamma_d\). The IGRB was well-measured in the past decade (Ackermann et al. 2015b), which can give stringent constraints for \(\Gamma_d\).

The gamma-ray flux \(\phi\) (in \(\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\)) emitted by the decay of the \(d^*(2380)\) hexaquarks is given by

\[
\phi = \frac{J}{4 \pi m_{\text{d}}} \Gamma_d \left( \frac{E^2 dN}{dE} \right),
\] (4)

where \(dN/dE\) is the energy spectrum (in GeV\(^{-1}\)) of the decay per \(d^*(2380)\) hexaquark and \(J\) is the J-factor per unit solid angle, which is defined as

\[
J = \frac{1}{4 \pi \Delta \Omega} \int \rho ds \int d\Omega.
\] (5)

Here, \(\rho\) is the density of dark matter (i.e., \(d^*(2380)\)-BECs), \(s\) is the line-of-sight distance, and \(\Delta \Omega\) is the solid angle.

Recently, a comprehensive analysis considering different dark matter density profiles and different baryonic models has been done for the Milky Way (Lin & Li 2019). It shows that the Navarro–Frenk–White dark matter density profile with particular bulge and disk models (B7D1G1 and B6D1G1 models) can give the best fits for the rotation curve data out to \(\sim 100\) kpc obtained in Huang et al. (2016). Following this best-fit result...
with uncertainties and taking the distance to the Galactic center $D_L = 8 \text{kpc}$, we get $J = 0.064 - 0.073 \text{g cm}^{-2} \text{sr}^{-1}$ for the isotropic emission. The 1σ upper limit of the observed residual gamma-ray flux within $E = 140 - 200 \text{MeV}$ is $1.06 \times 10^{-6} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (Ackermann et al. 2015b). It gives $\Gamma_d = (7.5-8.6) \times 10^{-24} \text{s}^{-1}$, which is the upper limit of the average decay rate in our Galaxy. We can see that this upper limit is several orders of magnitude larger than our predicted value $\Gamma_d \sim 10^{-31} \text{s}^{-1}$. Therefore, it is very difficult for us to constrain the observed decay rate down to the predicted value based on the current observational data and techniques. In Figure 1, we show the calculated energy spectrum $\phi$ and compare it with the observational data. We can see that there are two peaks in the energy spectrum. However, the peak at a lower energy ($E \approx 180 \text{MeV}$) is much more dominant than the one at a higher energy ($E \approx 450 \text{MeV}$). Therefore, if one can constrain the decay rate upper limit down to the predicted value, the decaying feature of the $d^*(2380)$ hexaquarks can be best verified or falsified by the energy spectrum near $E = 180 \text{MeV}$.

**4. Discussion**

The $d^*(2380)$-BEC dark matter model is very attractive. This is because no extra elementary particle beyond the Standard Model or theory beyond general relativity is required to account for the dark matter. The existence of $d^*(2380)$ hexaquarks has been verified by experiments. Moreover, the $d^*(2380)$ hexaquarks can form stable BECs and these BECs can be thermally produced in the early universe (Bashkanov & Watts 2020). These properties make the $d^*(2380)$-BEC a very competitive candidate of dark matter and the entire model is very simple. Although the details of the strong interaction between $d^*(2380)$ are not well-understood, future particle experiments might be able to determine these details.

One important potential signature of this dark matter model is the decaying signal of the free $d^*(2380)$ hexaquarks. The stable $d^*(2380)$-BECs could be destroyed by the high-energy cosmic rays so that the free $d^*(2380)$ hexaquarks would spontaneously produce a large amount of $\sim 100 - 500 \text{MeV}$ gamma-rays. This process can be characterized by the decay rate $\Gamma_d$. In this article, we show that the value of $\Gamma_d$ is strongly correlated with the high-energy cosmic-ray flux. Generally speaking, the average decay rate $\Gamma_d$ within a volume is larger when there exists a larger flux of TeV cosmic rays. Therefore, the decay rate $\Gamma_d$ may not be a constant, which is different from the predictions of other decaying dark matter models (e.g., decaying sterile neutrinos (Boyarsky et al. 2014)). Nevertheless, one interesting feature of this nonconstant decay rate is that if there exist some extremely exotic high-energy astrophysical phenomena in a galaxy, the amount of cosmic rays may be large enough to destroy most of the $d^*(2380)$-BEC dark matter. Then, the galaxy would become a galaxy lacking dark matter, like NGC 1052-DF2 and NGC 1052-DF4 (van Dokkum et al. 2018, 2019).

Besides the theoretical prediction of $\Gamma_d$, we also constrain the $\Gamma_d$ by observational data. In fact, a recent study has performed a similar analysis to constrain the decay rate $\Gamma_d$ by astronomical data of different structures (Beck 2020). It shows that the Milky Way data can give the tightest constraint for the decay rate ($\Gamma \leq 3.9 \times 10^{-24} \text{s}^{-1}$). However, the J-factor obtained in that study using the CLUMPY code originates from the assumption of dark matter annihilation but not decay (Hütten et al. 2019), and the uncertainty of the J-factor is very large (approximately an order of magnitude; Beck 2020). In our analysis, the J-factor is calculated using the latest comprehensive study of our Galaxy, which has considered four different dark matter density profiles and 56 combinations of baryonic models. Therefore, our constraints would be more robust and contain fewer systematic uncertainties.

However, based on the observational data of the IGRB, we find that the predicted decay rate is much lower than our current observed upper limit. This suggests that verifying this dark matter model using a decaying signature is very difficult. Such a decaying signature might be stronger near the active galactic nuclei or the sources of some exotic astronomical phenomena (e.g., supernovae, black hole mergers). Future
observations focusing on $\sim$100–200 MeV gamma-rays might be possible to verify or falsify the $d^*(2380)$-BEC dark matter model, though it would not be an easy task.

Besides the decaying signature, the size of a $d^*(2380)$-BEC is not negligibly small so that the scattering between $d^*(2380)$-BECs or between $d^*(2380)$-BECs and baryons might be able to provide some observable signatures, such as the formation of small soft cores in dwarf galaxies (Fitts et al. 2019; Kahlhoefer et al. 2019) or the correlation between the dynamical mass and baryonic mass in galaxies and galaxy clusters (Chan 2019, 2020). We have applied a simple geometrical approach to estimate the self-interaction cross section between the $d^*(2380)$-BECs. However, due to our poor understanding of the $d^*(2380)$ interactions, the actual value of the cross section might be different from our estimated value. Therefore, it is still possible that the quantum-enhanced self-interaction cross section of $d^*(2380)$-BECs is large enough (e.g., $\sigma_{dd}/m_{\text{BEC}} \sim 1 \text{ cm}^2 \text{ g}^{-1}$) to form large core structures in galaxies. Extensive investigations in particle experiments, theoretical simulations, and astronomical observations are required to verify this interesting dark matter model.

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**References**

Abazajian, K. N., & Keeley, R. E. 2016, *PhRvD*, 93, 083514
Abdollahi, S., Ackermann, M., Ajello, M., et al. 2017, *PhRvD*, 95, 082007
Abecrombie, D., Akchurin, N., Akilli, E., et al. 2020, *PDU*, 27, 100371
Ackermann, M., Ajello, M., Albert, A., et al. 2015a, *PhRvL*, 115, 231301
Adlarson, P., Adolph, C., Augustyniak, W., et al. 2011, *PhRvL*, 106, 242302
Adlarson, P., Augustyniak, W., Bardan, W., et al. 2015, *PhLB*, 743, 325
Aguilar, M., Ali Cavasonza, L., Ambrosi, G., et al. 2019, *PhRvL*, 122, 041102
Albert, A., Anderson, B., Bechtol, K., et al. 2017, *ApJ*, 834, 110
Aprile, E., Aalbers, J., Agostini, F., et al. 2017, *PhRvL*, 119, 181301
Aprile, E., Aalbers, J., Agostini, F., et al. 2018, *PhRvL*, 121, 111302
Bashkanov, M., & Watts, D. P. 2020, *JPcG*, 47, 03LT01
Beck, G. 2020, arXiv:2003.09283
Bergström, L., Bringmann, T., Cholis, T., Hooper, D., & Weniger, C. 2013, *PhRvL*, 111, 171101
Boudaud, M., Aupetit, S., Caroff, S., et al. 2015, *A&A*, 575, A67
Boyarsky, A., Ruchayskiy, O., Iakubovskyi, D., & Frasse, J. 2014, *PhRvL*, 113, 251301
Calore, F., Cholis, I., McCabe, C., & Weniger, C. 2015, *PhRvD*, 91, 063003
Cavasonza, L. A., Gast, H., Krämer, M., Pellen, M., & Schael, S. 2017, *ApJ*, 839, 36
Chan, M. H. 2013, *MNRAS*, 433, 2310
Chan, M. H. 2016, *PhRvD*, 94, 023507
Chan, M. H. 2017, *PhRvD*, 96, 043009
Chan, M. H. 2019, *NatSR*, 9, 3570
Chan, M. H. 2020, *PDU*, 28, 100478
Chan, M. H., Cui, L., Liu, J., & Leung, C. S. 2019, *ApJ*, 872, 177
Chan, M. H., & Leung, C. H. 2017, *NatSR*, 7, 14895
Chavanis, P.-H. 2011, *PhRvD*, 84, 043531
DAMPE Collaboration, Ambrosi, G., An, Q., et al. 2017, *Natur*, 552, 63
Daylan, T., Finkbeiner, D. P., Hooper, D., et al. 2016, *PDU*, 12, 1
Egorov, A. E., & Pierpaoli, E. 2013, *PhRvD*, 88, 023504
Fitts, A., Boylan-Kolchin, M., Bozek, E., et al. 2019, *MNRAS*, 490, 962
Harding, J. P. 2019, ICRC (Madison, WI), 36, 691
Huang, Y., Liu, X.-W., Yuan, H.-B., et al. 2016, *MNRAS*, 463, 2623
Hütten, M., Combet, C., & Maurin, D. 2019, *CoPhC*, 235, 336
Kahlhoefer, F., Kaplinghat, M., Slatyer, T. R., & Wu, C.-L. 2019, *JCAP*, 12, 010
Lin, H.-N., & Li, X. 2019, *MNRAS*, 487, 5679
Lü, C.-Y., Wang, P., Dong, Y.-B., Shen, P.-N., & Zhang, Z.-Y. 2019, *PhRvD*, 99, 036015
Peter, A. H. G., Rocha, M., Bullock, J. S., & Kaplinghat, M. 2013, *MNRAS*, 430, 105
Randall, S. W., Markevitch, M., Clowe, D., Gonzalez, A. H., & Bardač, M. 2008, *ApJ*, 679, 1173
Robles, V. H., Kelley, T., Bullock, J. S., & Kaplinghat, M. 2019, *MNRAS*, 490, 2117
Roszkowski, L., Sessolo, E. M., & Trojanowski, S. 2018, *RPPh*, 81, 066201
Tan, A., Xiao, M., Cui, X., et al. 2016, *PhRvL*, 117, 121303
van Dokkum, P., Danieli, S., Abraham, R., Conroy, C., & Romanowsky, A. J. 2019, *ApJL*, 874, L5
van Dokkum, P., Danieli, S., Cohen, Y., et al. 2018, *Natur*, 555, 629
Zhang, X., Chan, M. H., Harko, T., Liang, S.-D., & Leung, C. S. 2018, *EPJC*, 78, 346