

Influence of the chemical potential on the Casimir-Polder interaction between an atom and gapped graphene or a graphene-coated substrate

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Abstract

© 2018 American Physical Society. We present a formalism based on first principles of quantum electrodynamics at nonzero temperature which permits us to calculate the Casimir-Polder interaction between an atom and a graphene sheet with arbitrary mass gap and chemical potential, including graphene-coated substrates. The free energy and force of the Casimir-Polder interaction are expressed via the polarization tensor of graphene in (2+1)-dimensional space-time in the framework of the Dirac model. The obtained expressions are used to investigate the influence of the chemical potential of graphene on the Casimir-Polder interaction. Computations are performed for an atom of metastable helium interacting with either a freestanding graphene sheet or a graphene-coated substrate made of amorphous silica. It is shown that the impacts of the nonzero chemical potential and the mass gap on the Casimir-Polder interaction are in opposite directions, by increasing and decreasing the magnitudes of the free energy and force, respectively. It turns out, however, that the temperature-dependent part of the Casimir-Polder interaction is decreased by a nonzero chemical potential, whereas the mass gap increases it compared to the case of undoped, gapless graphene. The physical explanation for these effects is provided. Numerical computations of the Casimir-Polder interaction are performed at various temperatures and atom-graphene separations.

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References

- [1] M. I. Katsnelson, *Graphene: Carbon in Two Dimensions* (Cambridge University Press, Cambridge, UK, 2012).
- [2] H. Aoki and M. S. Dresselhaus (eds.), *Physics of Graphene* (Springer, Cham, 2014).
- [3] V. A. Parsegian, *Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists* (Cambridge University Press, Cambridge, UK, 2005).
- [4] M. Bordag, G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, *Advances in the Casimir Effect* (Oxford University Press, Oxford, UK, 2015).
- [5] A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, *Rev. Mod. Phys.* **81**, 109 (2009). RMPHAT 0034-6861 10.1103/RevModPhys.81.109
- [6] J. F. Dobson, A. White, and A. Rubio, *Phys. Rev. Lett.* **96**, 073201 (2006). PRLTAO 0031-9007 10.1103/PhysRevLett.96.073201
- [7] G. Gómez-Santos, *Phys. Rev. B* **80**, 245424 (2009). PRBMDO 1098-0121 10.1103/PhysRevB.80.245424
- [8] D. Drosdoff and L. M. Woods, *Phys. Rev. B* **82**, 155459 (2010). PRBMDO 1098-0121 10.1103/PhysRevB.82.155459
- [9] D. Drosdoff and L. M. Woods, *Phys. Rev. A* **84**, 062501 (2011). PLRAAN 1050-2947 10.1103/PhysRevA.84.062501

- [10] B. E. Sernelius, *Europhys. Lett.* 95, 57003 (2011). EULEEJ 0295-5075 10.1209/0295-5075/95/57003
- [11] J. Sarabadani, A. Najj, R. Asgari, and R. Podgornik, *Phys. Rev. B* 84, 155407 (2011) PRBMDO 1098-0121 10.1103/PhysRevB.84.155407;
- [12] J. Sarabadani, A. Najj, R. Asgari, and R. Podgornik, *Phys. Rev. B* 87, 239905 (E) (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.239905
- [13] D. Drosdoff, A. D. Phan, L. M. Woods, I. V. Bondarev, and J. F. Dobson, *Eur. Phys. J. B* 85, 365 (2012). EPJBFY 1434-6028 10.1140/epjb/e2012-30741-6
- [14] B. E. Sernelius, *Phys. Rev. B* 85, 195427 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.85.195427
- [15] A. D. Phan, L. M. Woods, D. Drosdoff, I. V. Bondarev, and N. A. Viet, *Appl. Phys. Lett.* 101, 113118 (2012). APPLAB 0003-6951 10.1063/1.4752745
- [16] A. D. Phan, N. A. Viet, N. A. Poklonski, L. M. Woods, and C. H. Le, *Phys. Rev. B* 86, 155419 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.86.155419
- [17] W.-K. Tse and A. H. MacDonald, *Phys. Rev. Lett.* 109, 236806 (2012). PRLTAO 0031-9007 10.1103/PhysRevLett.109.236806
- [18] V. B. Svetovoy and G. Palasantzas, *Phys. Rev. Appl.* 2, 034006 (2014). 2331-7019 10.1103/PhysRevApplied.2.034006
- [19] L. M. Woods, D. A. R. Dalvit, A. Tkatchenko, P. Rodrigues-Lopez, A. W. Rodrigues, and R. Podgornik, *Rev. Mod. Phys.* 88, 045003 (2016). RMPHAT 0034-6861 10.1103/RevModPhys.88.045003
- [20] C. Abbas, B. Guizal, and M. Antezza, *Phys. Rev. Lett.* 118, 126101 (2017). PRLTAO 0031-9007 10.1103/PhysRevLett.118.126101
- [21] T. E. Judd, R. G. Scott, A. M. Martin, B. Kaczmarek, and T. M. Fromhold, *New J. Phys.* 13, 083020 (2011). NJOPFM 1367-2630 10.1088/1367-2630/13/8/083020
- [22] T. Cysne, W. J. M. Kort-Kamp, D. Oliver, F. A. Pinheiro, F. S. S. Rosa, and C. Farina, *Phys. Rev. A* 90, 052511 (2014). PLRAAN 1050-2947 10.1103/PhysRevA.90.052511
- [23] N. Khusnutdinov, R. Kashapov, and L. M. Woods, *Phys. Rev. A* 94, 012513 (2016). 2469-9926 10.1103/PhysRevA.94.012513
- [24] T. P. Cysne, T. G. Rappoport, A. Ferreira, J. M. V. P. Lopes, and N. R. M. Peres, *Phys. Rev. B* 94, 235405 (2016). 2469-9950 10.1103/PhysRevB.94.235405
- [25] N. S. Nichols, A. D. Maestro, C. Wexler, and V. N. Kotov, *Phys. Rev. B* 93, 205412 (2016). 2469-9950 10.1103/PhysRevB.93.205412
- [26] E. Eizner, B. Horovitz, and C. Henkel, *Eur. Phys. J. D* 66, 321 (2012). EPJDF6 1434-6060 10.1140/epjd/e2012-30294-x
- [27] E. M. Lifshitz and L. P. Pitaevskii, *Statistical Physics, Part II* (Pergamon, Oxford, UK, 1980).
- [28] M. Bordag, I. V. Fialkovsky, D. M. Gitman, and D. V. Vassilevich, *Phys. Rev. B* 80, 245406 (2009). PRBMDO 1098-0121 10.1103/PhysRevB.80.245406
- [29] I. V. Fialkovsky, V. N. Marachevsky, and D. V. Vassilevich, *Phys. Rev. B* 84, 035446 (2011). PRBMDO 1098-0121 10.1103/PhysRevB.84.035446
- [30] M. Bordag, G. L. Klimchitskaya, and V. M. Mostepanenko, *Phys. Rev. B* 86, 165429 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.86.165429
- [31] G. L. Klimchitskaya and V. M. Mostepanenko, *Phys. Rev. B* 87, 075439 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.075439
- [32] G. L. Klimchitskaya and V. M. Mostepanenko, *Phys. Rev. B* 89, 035407 (2014). PRBMDO 1098-0121 10.1103/PhysRevB.89.035407
- [33] G. L. Klimchitskaya, V. M. Mostepanenko, and B. E. Sernelius, *Phys. Rev. B* 89, 125407 (2014). PRBMDO 1098-0121 10.1103/PhysRevB.89.125407
- [34] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, *Phys. Rev. B* 89, 115419 (2014). PRBMDO 1098-0121 10.1103/PhysRevB.89.115419
- [35] G. L. Klimchitskaya and V. M. Mostepanenko, *Phys. Rev. A* 89, 052512 (2014). PLRAAN 1050-2947 10.1103/PhysRevA.89.052512
- [36] A. A. Banishev, H. Wen, J. Xu, R. K. Kawakami, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, *Phys. Rev. B* 87, 205433 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.205433
- [37] M. Chaichian, G. L. Klimchitskaya, V. M. Mostepanenko, and A. Tureanu, *Phys. Rev. A* 86, 012515 (2012). PLRAAN 1050-2947 10.1103/PhysRevA.86.012515
- [38] B. Arora, H. Kaur, and B. K. Sahoo, *J. Phys. B* 47, 155002 (2014). JPAPFH 0953-4075 10.1088/0953-4075/47/15/155002
- [39] K. Kaur, J. Kaur, B. Arora, and B. K. Sahoo, *Phys. Rev. B* 90, 245405 (2014). PRBMDO 1098-0121 10.1103/PhysRevB.90.245405

- [40] K. Kaur, B. Arora, and B. K. Sahoo, Phys. Rev. A 92, 032704 (2015). PLRAAN 1050-2947 10.1103/PhysRevA.92.032704
- [41] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. A 89, 062508 (2014). PLRAAN 1050-2947 10.1103/PhysRevA.89.062508
- [42] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. A 89, 012516 (2014). PLRAAN 1050-2947 10.1103/PhysRevA.89.012516
- [43] M. Bordag, G. L. Klimchitskaya, V. M. Mostepanenko, and V. M. Petrov, Phys. Rev. D 91, 045037 (2015) PRVDAQ 1550-7998 10.1103/PhysRevD.91.045037;
- [44] M. Bordag, G. L. Klimchitskaya, V. M. Mostepanenko, and V. M. Petrov, Phys. Rev. D 93, 089907 (E) (2016). 2470-0010 10.1103/PhysRevD.93.089907
- [45] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. B 91, 174501 (2015). PRBMDO 1098-0121 10.1103/PhysRevB.91.174501
- [46] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. A 94, 042501 (2016). 2469-9926 10.1103/PhysRevA.94.042501
- [47] G. L. Klimchitskaya, Int. J. Mod. Phys. A 31, 1641026 (2016). IMPAEF 0217-751X 10.1142/S0217751X16410268
- [48] G. Bimonte, G. L. Klimchitskaya, and V. M. Mostepanenko, Phys. Rev. A 96, 012517 (2017). 2469-9926 10.1103/PhysRevA.96.012517
- [49] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. B 93, 245419 (2016). 2469-9950 10.1103/PhysRevB.93.245419
- [50] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. B 94, 195405 (2016). 2469-9950 10.1103/PhysRevB.94.195405
- [51] G. L. Klimchitskaya, C. C. Korikov, and V. M. Petrov, Phys. Rev. B 92, 125419 (2015) PRBMDO 1098-0121 10.1103/PhysRevB.92.125419;
- [52] G. L. Klimchitskaya, C. C. Korikov, and V. M. Petrov, Phys. Rev. B 93, 159906 (E) (2016). 2469-9950 10.1103/PhysRevB.93.159906
- [53] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. A 93, 052106 (2016). 2469-9926 10.1103/PhysRevA.93.052106
- [54] G. L. Klimchitskaya and V. M. Mostepanenko, Phys. Rev. B 95, 035425 (2017). 2469-9950 10.1103/PhysRevB.95.035425
- [55] M. Bordag, I. Fialkovskiy, and D. Vassilevich, Phys. Rev. B 93, 075414 (2016) 2469-9950 10.1103/PhysRevB.93.075414;
- [56] M. Bordag, I. Fialkovskiy, and D. Vassilevich, Phys. Rev. B 95, 119905 (E) (2017). 2469-9950 10.1103/PhysRevB.95.119905
- [57] G. Bimonte, G. L. Klimchitskaya, and V. M. Mostepanenko, Phys. Rev. B 96, 115430 (2017). 2469-9950 10.1103/PhysRevB.96.115430
- [58] T. Stauber, N. M. R. Peres, and A. K. Geim, Phys. Rev. B 78, 085432 (2008). PRBMDO 1098-0121 10.1103/PhysRevB.78.085432
- [59] V. Druzhinina and M. DeKieviet, Phys. Rev. Lett. 91, 193202 (2003). PRLTAO 0031-9007 10.1103/PhysRevLett.91.193202
- [60] H. Oberst, Y. Tashiro, K. Shimizu, and F. Shimizu, Phys. Rev. A 71, 052901 (2005). PLRAAN 1050-2947 10.1103/PhysRevA.71.052901
- [61] V. N. Marachevsky, J. Phys. A: Math. Theor. 45, 374021 (2012). 1751-8113 10.1088/1751-8113/45/37/374021
- [62] Z.-C. Yan and J. F. Babb, Phys. Rev. A 58, 1247 (1998). PLRAAN 1050-2947 10.1103/PhysRevA.58.1247
- [63] J. F. Babb, G. L. Klimchitskaya, and V. M. Mostepanenko, Phys. Rev. A 70, 042901 (2004). PLRAAN 1050-2947 10.1103/PhysRevA.70.042901
- [64] R. Brühl, P. Fouquet, R. E. Grisenti, J. P. Toennies, G. C. Hegerfeldt, T. Köhler, M. Stoll, and C. Walter, Europhys. Lett. 59, 357 (2002). EULEEJ 0295-5075 10.1209/epl/i2002-00202-4
- [65] G. Vidali and M. W. Cole, Surface Sci. 110, 10 (1981). SUSCAS 0039-6028 10.1016/0039-6028(81)90584-7
- [66] A. O. Caride, G. L. Klimchitskaya, V. M. Mostepanenko, and S. I. Zanette, Phys. Rev. A 71, 042901 (2005). PLRAAN 1050-2947 10.1103/PhysRevA.71.042901
- [67] L. A. Falkovsky, J. Phys.: Conf. Ser. 129, 012004 (2008). 1742-6596 10.1088/1742-6596/129/1/012004
- [68] P. K. Pyatkovskiy, J. Phys.: Condens. Matter 21, 025506 (2009). JCOMEL 0953-8984 10.1088/0953-8984/21/2/025506
- [69] V. P. Gusynin, S. G. Sharapov, and J. P. Carbotte, New J. Phys. 11, 095013 (2009). NJOPFM 1367-2630 10.1088/1367-2630/11/9/095013
- [70] S. A. Jafari, J. Phys.: Condens. Matter 24, 205802 (2012). JCOMEL 0953-8984 10.1088/0953-8984/24/20/205802

- [71] K. F. Mak, M. Y. Sfeir, Y. Wu, C. H. Lui, J. A. Misewich, and T. F. Heinz, Phys. Rev. Lett. 101, 196405 (2008). PRLTAO 0031-9007 10.1103/PhysRevLett.101.196405
- [72] D. B. Hough and L. R. White, Adv. Colloid Interface Sci. 14, 3 (1980). ACISB9 0001-8686 10.1016/0001-8686(80)80006-6
- [73] L. Bergström, Adv. Colloid Interface Sci. 70, 125 (1997). ACISB9 0001-8686 10.1016/S0001-8686(97)00003-1
- [74] J. M. Obrecht, R. J. Wild, M. Antezza, L. P. Pitaevskii, S. Stringari, and E. A. Cornell, Phys. Rev. Lett. 98, 063201 (2007). PRLTAO 0031-9007 10.1103/PhysRevLett.98.063201
- [75] H. Haakh, F. Intravaia, C. Henkel, S. Spagnolo, R. Passante, B. Power, and F. Sols, Phys. Rev. A 80, 062905 (2009). PLRAAN 1050-2947 10.1103/PhysRevA.80.062905
- [76] J. Schiefele and C. Henkel, Phys. Rev. A 82, 023605 (2010). PLRAAN 1050-2947 10.1103/PhysRevA.82.023605
- [77] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. D 81, 055003 (2010). PRVDAQ 1550-7998 10.1103/PhysRevD.81.055003
- [78] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, Phys. Rev. D 89, 035010 (2014). PRVDAQ 1550-7998 10.1103/PhysRevD.89.035010
- [79] H. R. Haakh, C. Henkel, S. Spagnolo, L. Rizzuto, and R. Passante, Phys. Rev. A 89, 022509 (2014). PLRAAN 1050-2947 10.1103/PhysRevA.89.022509
- [80] D. E. Chang, K. Sinha, J. M. Taylor, and H. J. Kimble, Nat. Commun. 5, 4343 (2014). 10.1038/ncomms5343
- [81] H. Bender, C. Stehle, C. Zimmermann, S. Slama, J. Fiedler, S. Scheel, S. Y. Buhmann, and V. N. Marachevsky, Phys. Rev. X 4, 011029 (2014). 2160-3308 10.1103/PhysRevX.4.011029
- [82] M. Köhne, R. Bennett, T. Reisinger, and S. Y. Buhmann, Phys. Rev. A 96, 013626 (2017). 2469-9926 10.1103/PhysRevA.96.013626