Annals of Physics 354 (2015) 213–243

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Holes localized on a Skyrmion in a doped antiferromagnet on the honeycomb lattice: Symmetry analysis

N.D. Vlasii [a,d], C.P. Hofmann [b], F.-J. Jiang [c,*], U.-J. Wiese [d]

[a] *Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, 14-b Metrologichna Str., Kyiv, 03680, Ukraine*

[b] *Facultad de Ciencias, Universidad de Colima, Colima C.P. 28045, Mexico*

[c] *Department of Physics, National Taiwan Normal University, 88, Sec. 4, Ting-Chou Rd., Taipei 116, Taiwan*

[d] *Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, Bern University, Sidlerstrasse 5, CH-3012 Bern, Switzerland*

ARTICLE INFO

Article history:
Received 19 November 2014
Accepted 17 December 2014
Available online 26 December 2014

Keywords:
Skyrmion
Hole-doped antiferromagnet
Honeycomb lattice
Effective field theory

ABSTRACT

Using the low-energy effective field theory for hole-doped antiferromagnets on the honeycomb lattice, we study the localization of holes on Skyrmions, as a potential mechanism for the preformation of Cooper pairs. In contrast to the square lattice case, for the standard radial profile of the Skyrmion on the honeycomb lattice, only holes residing in one of the two hole pockets can get localized. This differs qualitatively from hole pairs bound by magnon exchange, which is most attractive between holes residing in different momentum space pockets. On the honeycomb lattice, magnon exchange unambiguously leads to f-wave pairing, which is also observed experimentally. Using the collective-mode quantization of the Skyrmion, we determine the quantum numbers of the localized hole pairs. Again, f-wave symmetry is possible, but other competing pairing symmetries cannot be ruled out.

1. Introduction

Understanding the mechanism underlying high-temperature superconductivity has remained a major challenge in condensed matter physics. Since high-temperature cuprate superconductors are

* Corresponding author.
E-mail address: fjjiang@ntnu.edu.tw (F.-J. Jiang).

http://dx.doi.org/10.1016/j.aop.2014.12.012

insulating antiferromagnets before doping, it is natural to also investigate their antiferromagnetic precursors. In particular, one may hope to identify potential mechanisms for Cooper pair preformation in the antiferromagnetic phase. While we do not necessarily expect to unravel the relevant mechanism in this way, it motivates a careful systematic study. In previous work we have investigated the interactions between holes in lightly doped antiferromagnets, using a systematic low-energy effective field theory approach, both on the square [1] and on the honeycomb lattice [2].

The effective theory is formulated in terms of the staggered magnetization order parameter field, whose fluctuations correspond to spinwaves (magnons), and in terms of fermionic hole fields. This is in complete analogy to baryon chiral perturbation theory in particle physics, where the fluctuations in the chiral order parameter manifest themselves as pions, while baryons (protons and neutrons) are analogous to the doped holes [3–6]. Based on microscopic Hubbard and t-J models, and using a systematic low-energy expansion, we have constructed effective field theories for magnons and holes, both on the square and on the honeycomb lattice [1,2,7–11]. In both cases, one-magnon exchange mediates weak attractive forces between doped holes. As doping is increased, antiferromagnetism is weakened, and ultimately disappears as a long-range order phenomenon, when one enters the superconducting phase. Still, intermediate-range antiferromagnetic correlations persist even in the superconductor, and it is interesting to ask which objects form when one is about to leave the antiferromagnetic phase. At the edge of this phase, the spin stiffness ρ_s decreases and the energy $4\pi\rho_s$ of Skyrmion excitations in the staggered magnetization order parameter is thus reduced. In addition, doped holes can gain energy when they localize on a topological Skyrmion defect. We have systematically investigated this phenomenon as a potential mechanism for Cooper pair preformation for antiferromagnets on the square lattice [12]. Interestingly, in this case, both one-magnon exchange and Skyrmion localization lead to bound states in the same symmetry channel. The role of Skyrmions in quantum antiferromagnets has been investigated in [13–31].

The main purpose of the present paper is to extend the study of hole localization on a Skyrmion to antiferromagnets on the honeycomb lattice, which underlies certain high-temperature superconductors, including the dehydrated version of $Na_2CoO_2 \times yH_2O$. In this case, experiments suggest that the pairing symmetry is f-wave [32]. F-wave pairing has also been found for other strongly correlated systems on the honeycomb lattice [33–35]. As we studied earlier [2], in contrast to the square lattice case, on the honeycomb lattice, leading order one-magnon exchange gives rise to long-range attraction only between holes residing in different hole pockets (characterized by the "flavors" α and β). As an unambiguous prediction of the effective theory, the binding occurs in the f-wave channel, and is thus indeed consistent with experiment [32]. As we will show here, unlike in the square lattice case, on the honeycomb lattice the symmetry channels favored by hole localization on Skyrmions are not in one-to-one correspondence with the symmetry channels resulting from one-magnon exchange. In particular, a Skyrmion with the standard radial profile can only localize holes residing in the α-pocket, while an anti-Skyrmion can only localize β-holes. While f-wave symmetry still arises, other competing pairing symmetries are possible as well. Only detailed energetic considerations, which we leave for future work, can unambiguously decide which pairing mechanism is favored by Skyrmion localization. In this paper, we concentrate entirely on the systematic symmetry analysis of the various hole states localized on a Skyrmion.

It should be pointed out that the underlying microscopic model, where our systematic effective field theory is based upon, is the Hubbard model on the honeycomb lattice in the strong coupling limit. Hence our analysis is not directly applicable to graphene which refers to the Hubbard model in the weak coupling limit, and presents a semi-metal phase. However, as pointed out in Ref. [36], graphene is not comprehensively captured in the (strict) weak coupling limit—rather an intermediate coupling perspective has to be adopted. In particular, the intricate competition between chiral d-wave and f-wave has been subject to intense research from the perspective of intermediate coupling (for details see the review [37] and references therein).

The rest of the paper is organized as follows. In Section 2 we review the effective field theory formulation of antiferromagnetic magnons on the honeycomb lattice and discuss Skyrmions as classical solutions. We also comment on the Hopf term and on the collective modes of a rotating Skyrmion which we then quantize. In Section 3, the effective field theory description is extended by introducing holes doped into the system. Section 4 is devoted to the symmetry analysis of states of single holes