

Comment on Dark Matter Capture in Neutron Stars with Exotic Phases¹

Motoi Tachibana^{†2} and Marco Ruggieri^{‡3}

[†]Department of Physics, Saga University, Saga 840-8502, Japan

[‡]Department of Physics and Astronomy, University of Catania,
Via S. Sofia 64, I-95125 Catania, Italy

Abstract

In this short paper, we argue the issue on dark matter capture in neutron stars. After summarizing the whole scenario and the introduction of previous studies along this line, we propose some potentially important effects due to the appearance of exotic phases such as neutron superfluidity, meson condensation and quark superconductivity. Those effects might be sizable and alter the previous results.

¹Based on the talk in the International Conference "Baryons13" held at Glasgow in June 2013.

²motoi@cc.saga-u.ac.jp

³marco.ruggieri@lns.infn.it

One of the modern physics perspectives is unity of matters and universe, as shown by UROBOROS. Study of the early universe is such an example, where particle physics and cosmology are mutually intertwined. In this short paper, we would like to present a connection between astrophysics and particle physics as another example.

Dark matter (DM) was originally proposed by Zwicky as "missing mass" in 1933 [1]. Since then, there are enormous indirect evidences of its existence such as the galaxy rotation curve and the cosmic microwave background (CMB). So many people have no doubt for the existence of DM, while the properties are little known and mysterious. One candidate for the DM is weakly-interacting massive particle (WIMP), which interacts with nucleons through the weak interaction. DM is one of the most interesting subjects in modern physics.

On the other hand, neutron star (NS) was proposed by Baade and Zwicky in 1934, as a remnant after the supernova explosion [2]. Landau called the star "a gigantic nucleus" since it is literally made by neutrons [3]. From the properties such as density, magnetic field and rotation period, we see that NS provides a good market selling ultimate environments, which leads us to the concept of dense nuclear matter and even denser object, i.e., deconfined quark matter.

In spite of many indirect evidences, we need direct measurements of DM to comprehend its properties. To this end, there are on-ground experiments, such as XENON and CDMS [4]. Those experiments try to constrain the WIMP DM-nucleon cross section as well as the WIMP DM mass.

Here is an interesting observation. If dark matter really exists, it should be everywhere, even around neutron stars. When a DM comes inside NS, it interacts with neutrons. Since the cross section $\sigma_{N\chi}$ is given by the mean free path as well as the number density of medium, one can roughly estimate $\sigma_{N\chi}$ in the case of typical neutron star mass and radius, $M_{NS} = 1.4M_{SUN}$ and $R = 10\text{km}$, where M_{SUN} is the solar mass. The result is $\sigma_{N\chi} \approx 5 \times 10^{-46} \text{ cm}^2$, which is the way below the limit through the direct measurements. From this naive observation, we are encouraged to pursue the connection between dark matter and neutron stars in more detail.

There have already been various studies along this line [5]. Among them, we consider here the issue on dark matter capture in neutron stars and propose some new ideas from the viewpoint of many-body physics. Note here that the idea of DM capture by the stellar objects itself is not so new. For instance, people have considered the DM capture by Sun as a solution to the solar neutrino puzzle [6] and applied the idea into the case of NS [7].

In considering this issue, there are three important stages. I. Capture, II. Thermalization and III. Black-hole formation. Here we summarize the previous studies, especially based on [8].

The stage I is described by the following equation:

$$\frac{dN_\chi}{dt} = C_{N\chi} + C_{\chi\chi}N_\chi - C_{\chi a}N_\chi^2,$$

where N_χ is the number of captured DMs. $C_{N\chi}$, $C_{\chi\chi}$ and $C_{\chi a}$ are the DM-neutron capture rate, the DM self-capture rate and the DM pair annihilation rate, respectively.

In the stage II, DM loses its energy through the collision with neutrons, and then gets into the thermal equilibrium. The process is described by the following equation:

$$\frac{dE}{dt} = -\xi n_B \sigma_{N\chi} v \delta E,$$

where E is the energy of DM, δE the energy loss per one collision, $\sigma_{N\chi}$ the DM-neutron cross section, n_B the baryon number density, and v the DM velocity, respectively. Remark here on the parameter ξ , which is called the capture efficiency factor. In neutron star, neutrons are highly degenerate so that there is the Pauli-blocking effect. ξ exactly parametrizes how much the system is degenerate.

Lastly in the stage III, thermalized DMs drift into the core of NS and form the isothermal sphere, whose radius r_{th} is fixed by the balance between kinetic and gravitational potential energy. As time goes by, the number of captured DMs increases. If the DM density gets larger than the baryon density ρ_B within the radius r_{th} , namely,

$$\frac{3N_\chi m_\chi}{4\pi r_{th}^3} \geq \rho_B$$

then DMs become self-gravitating. This is the on-set of gravitational collapse and black-hole formation. From the above inequality, one can estimate the critical number of DMs, N_{self} , beyond which the host neutron star can be destructed. This is an essential point because relatively old neutron stars with the age around 10^{10} years have been found observationally. This means that the following inequality should hold:

$$N_\chi \leq N_{self},$$

which gives the constraint between the DM parameters, m_χ and $\sigma_{N\chi}$.

In [8], as concrete examples, the astrophysical observations such as the pulsar B1620-26 and the nearby pulsars J0437-4715 and J2124-3358 have been investigated. Consequently the constraints on DM parameters obtained there are well below the limit from the direct measurements.

The above is a brief summary of the scenario for the DM capture in NS. So far, people have been studying the issue mainly from particle physics side. As was mentioned before, however, NS is literally a star made by highly degenerate neutrons so that many-body effects, which have been neglected in the preceding works², should be important and may alter the previous results.

²The only exception is the treatment performed by Bertoni et al. [9].

According to the many-body calculations, depending on temperature and chemical potential of the system, the existence of exotic phases such as neutron superfluidity, proton superconductivity, meson condensation and quark superconductivity/superfluidity have been predicted. Those phases can be characterized by the energy gap of quasiparticles and the appearance of some new low-energy degrees of freedom associated with symmetry breaking.

Here are examples to show what could happen if the exotic phases appear in NS [10]:

(1) Neutron superfluid phase

In this phase, the superfluid (SF) phonon mode appears as a new degrees of freedom at low energy. The dominant process which affects the capture rate and thermalizaion of DM stems from the scattering between DM and SF phonons. This can be described by the effective Lagrangian, for instance, such as that in [11].

(2) Color-flavor locked (CFL) phase

This phase is expected to occur at asymptotically high baryon density. In the phase, all the quarks gain the energy gap Δ_{CFL} and the low-energy degrees of freedom are the Nambu-Goldstone modes associated with $U(1)_B$ symmetry breaking as well as chiral symmetry breaking. Δ_{CFL} affects the structure of the Fermi surface, which leads us to the modification of the capture efficiency factor ξ . Since Δ_{CFL} is estimated around several tenth of MeV, compared with the Fermi momentum p_F , the effect could be sizable. This point will be addressed in the future .

In summary, stellar constraints on DM properties, together with the direct measurements and the collider experiments, are important. In this manuscript, we specially considered the issue on the DM capture in NS. Since the existence of exotic phases due to the many-body effects have not been so much cared in the previous studies, we proposed here what could happen if the exotic phases are taken into account. More detailed study will be the future issue.

Acknowledgements

The authors thank the Yukawa Institute for Theoretical Physics, Kyoto University. Discussions during the YITP workshop YITP-T-13-05 on "New Frontiers in QCD" were useful to complete this work. The work of M.T. is supported in part by the JSPS Grant-in-Aid for Scientific Research, Grant No. 24540280.

References

- [1] F. Zwicky, *Helv. Phys. Acta* 6 (1933) 110-127.
- [2] W. Baade and F. Zwicky, *Phys. Rev.* 46 (1934) 76-77.
- [3] D. G. Yakovlev et al., *Phys. Usp.* 56 (2013) 289-295.
- [4] For the XENON project, see <http://xenon.astro.columbia.edu/>.
For the CDMS project, see <http://cdms.berkeley.edu/>.
- [5] For the review, see K. Petraki and R. R. Volkas, *Int. J. Mod. Phys. A*28 (2013) 1330028; K. Zurek, arXiv:1308.0338 [hep-ph] and references therein.
- [6] W. H. Press and D. N. Spergel, *Astrophys. J.* 296 (1985) 679-684.
A. Gould, *Astrophys. J.* 321 (1987) 571.
- [7] I. Goldman and S. Nussinov, *Phys. Rev. D*40 (1989) 3221-3230.
- [8] S. D. McDermott, H-B. Yu and K. Zurek, *Phys. Rev. D*85 (2012) 023519..
- [9] B. Bertoni, A. E. Nelson and S. Reddy, *Phys. Rev. D*88 (2013) 123505.
- [10] M. Tachibana, the presentation in the International Conference "Baryons13", June 2013, Glasgow. <http://nuclear.gla.ac.uk/Baryons2013/>.
- [11] V. Cirigliano, S. Reddy and R. Sharma, *Phys. Rev. C*84 (2011) 045809.