Rotational Effects of Nanoparticles for Cooling down Ultracold Neutrons

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a detailed example. Nesvizhevsky et al. first calculated the neutron scattering cross section quantum mechanically. During that process, the neutron energy can be transferred to the translational movement of the nanoparticles. The energy loss of the neutron to the nanoparticle was obtained by using the principle of energy-momentum conservation. It was found that under some specific experimental conditions, this method might increase the ultracold neutron density by several orders of magnitude\(^{19,20}\). In comparison with other methods in which UCN are obtained by selecting neutrons within a very narrow fraction of the whole energy spectrum, this new method can increase the phase space density of UCN.

However, rotational effects are neglected in the previous study\(^{19}\). Intuitively, rotational degrees of freedom of nanoparticles could play a non-negligible role. In this paper, we try to further this interesting idea by including rotational effects, and the same conditions assumed in ref. 19 are followed, i.e., free nanoparticles are in thermal equilibrium with superfluid helium at 0 K, no internal degrees of freedom of nanoparticles are excited for the neutron energy under consideration, etc. Thus the limitations of applicability in the previous study in ref. 19 are also the same in our work. The remainder of this article is organized as follows. We first illustrate quantum coherence effect for neutron scattering by a simple example. Then we present our methods and results in which the rotational effects of nanoparticles are included. Other possible applications are also discussed, such as neutron scattering with nano shells and magnetized nanoparticles, and reducing the geometric phase effect which is one of the most important systematics of the nEDM experiment. Finally, we present the conclusion of this work.

**Quantum Coherence**

Due to the similarity between the neutron wavelength and the nanoparticle size, cold neutrons and UCN interact strongly with nanoparticles because of quantum coherence. Simple cases are illustrated here. First, we suppose the slow neutrons described by a plane wave are scattered by a single nucleus fixed at the origin. Then the scattered neutron wave can be expressed as follows during this low energy process\(^{18,21–24}\):

\[
\psi = -\frac{a}{r} \exp\left(\frac{2\pi i}{\lambda} r\right),
\]

(1)

where \(a\) is the scattering length of neutrons in the nucleus, \(\lambda\) denotes the de Broglie wavelength of the incident neutron, and \(r\) is the distance from the origin. It is easy to obtain the total scattering cross section:

\[
\sigma_{\text{tot}} = 4\pi a^2.
\]

(2)

Then we come to another situation, in which two nucleus of the same type fixed at different positions \(\vec{r}_1\) and \(\vec{r}_2\) are scattered by neutrons. The scattered wave is:

\[
\psi = -\frac{a}{r_1} \exp\left(\frac{2\pi i}{\lambda} r_1\right) - \frac{a}{r_2} \exp\left(\frac{2\pi i}{\lambda} r_2\right).
\]

(3)

Since the wavelength of UCN is much larger than the distance between the nucleus, i.e., \(\lambda \gg |\vec{r}_1 - \vec{r}_2|\), the scattered wave can be approximated as:

\[
\psi = -\frac{a}{\bar{r}} \exp\left(\frac{2\pi i}{\lambda} \bar{r}\right) \approx -\frac{2a}{\bar{r}} \exp\left(\frac{2\pi i}{\lambda} \bar{r}\right)
\]

(4)

where \(\bar{r}\) is the average of \(r_1\) and \(r_2\). The total scattering cross section in this case is given by:

\[
\sigma_{\text{tot}} = 4\pi (2a)^2 = 16\pi a^2,
\]

(5)

which is four times of that associated with single nucleus. In short, due to the very large wavelength of UCN compared with nano-sized particles, quantum coherence plays a crucial role. It produces a quadric increment for which is four times of that associated with single nucleus. In short, due to the very large wavelength of UCN compared with nano-sized particles, quantum coherence plays a crucial role. It produces a quadric increment for which is four times of that associated with single nucleus. In short, due to the very large wavelength of UCN compared with nano-sized particles, quantum coherence plays a crucial role. It produces a quadric increment for which is four times of that associated with single nucleus. In short, due to the very large wavelength of UCN compared with nano-sized particles, quantum coherence plays a crucial role. It produces a quadric increment for which is four times of that associated with single nucleus. 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According to the law of angular momentum conservation,

\[ J \omega = m v_0 b (1 - \cos \theta) \]  

(6)

where \( J \) is the momentum of inertia, \( m \) the neutron mass, \( v_0 \) the incident neutron velocity, \( \omega \) the angular velocity of the nano sphere, and \( \theta \) the scattering angle. Applying the law of energy conservation, the rotational energy carried by the sphere is expressed as:

\[ \frac{1}{2} J \omega^2 = \frac{5 b^2 v_0^2 \sin^2 \theta}{2 A R^2} \]  

(7)

where \( A \) is the nano sphere mass in units of neutron mass. The ratio of rotational energy transfer is easily obtained:

\[ \frac{\Delta E_{R}}{E} = -\frac{10}{A} \left( \frac{b}{R} \right)^2 \frac{x^4}{(2kR)^4} \]  

(8)

where \( x = qR = 2kR \sin \frac{\theta}{2} \) is the incident wave vector, \( \bar{q} = \bar{k} - \bar{k}' \) is the scattering wave vector, \( \bar{k} \) is the incident wave vector, and \( \bar{k}' \) is the final wave vector. The collision is elastic in the center-of-mass frame, so we have \( \bar{k} = \bar{k}' \).

Substituting the scattering amplitude into Eqn. (8), the mean energy loss due to rotational degrees can be derived as:

\[ \xi_{r} = \frac{\{\Delta E_{R}\}}{E} = \int \frac{\Delta E_{R}}{E} \frac{d\sigma}{d\Omega} \frac{d\Omega}{d\Omega} \]  

\[ = -\frac{10}{A} \left( \frac{b}{R} \right)^2 \frac{1}{(2kR)^4} \int_{0}^{2kR} \frac{1}{2} j_1^2 (x) dx \]  

(9)

where \( j_1(x) \) is the first order spherical Bessel function. We calculate the above integrals numerically by using the Simpson’s method26. When calculating the rotational-degree-caused energy transfer, the problem is considered classically, in which the neutron is considered as a point-like particle. Only if the impact parameter is within the radius of the nanoparticle, will a collision happen. In this classical situation, the average impact parameter is obviously \( \bar{b} = R/2 \) for incident neutrons when collisions occur. The total energy loss is the sum of the energy loss due to the translation and rotation movements. We present the behavior of the energy loss ratio due to rotational effects in Fig. 2 for a diamond nanoparticle with radius of 1 nm.

When the incident neutron wave vector is much smaller than the nanoparticle size, i.e., \( kR \ll 1 \):

\[ \xi_{r} = -\frac{5}{6A} \]  

(10)

while in this case the translational energy transfer rate is:

\[ \xi_{t} = -\frac{2}{A} \]  

(11)

It is easy to see that under long wavelength limit, rotational degrees of freedom of the nanoparticles carry as much as 5/12, i.e., ~40% amount of energy as the translational degrees of freedom. As we can see from Fig. 3, when the rotational effects are taken into account, the energy transfer efficiency is increased by as much as 40%. To slow down neutrons as much as possible, it is important to increase the energy transfer efficiency for each collision between neutrons and the moderator. Typically, hundreds or even thousands of collisions are required for neutrons to be in thermal equilibrium with the moderator, so a 40% increase of the efficiency per collision can be significant.
Neutrons Scattered by a Nano Shell

The average relative energy loss is inversely proportional to the mass of nanoparticles. Higher moderating efficiency is expected when the mass of the scatterer becomes smaller. Therefore, we turn to consider the nano shell, of which the mass is much smaller than that of the nanoparticle in the same volume. Here we calculate the associated moderating efficiency. For simplicity, we only consider single layer shells. The phenomenological potential for the interaction of a neutron with a nano shell can be express as:

$$V(r) = \frac{h}{m} n \delta(r - R)$$  \hspace{1cm} (12)

where $h$ is the Planck's constant, $n$ the neutron surface density of the shell and $R$ the shell radius.

Using the first order Born approximation, the total scattering cross section is found to be:

$$\sigma_{\text{tot}} = 2\pi \frac{1}{(kr)^2} \left[ \pi R^2 \int_0^{2kR} \frac{1}{x} \sin^2 x dx \right]$$  \hspace{1cm} (13)

The total mean relative energy loss per collision is derived as

$$\xi = \xi_r + \xi_t = -\frac{1}{A(kR)^2} \int_0^{2kR} \frac{1}{x} \sin^2 x dx = \frac{3}{2A} \int_0^{2kR} \frac{1}{x} \sin^2 x dx$$  \hspace{1cm} (14)

where $A$ is the mass of nano shell, again in units of the neutron mass. As a shell has a relatively larger initial momentum than a sphere since the former concentrates its mass on surface, we expect that rotational effects are less efficient. In fact, if we take long wavelength limit, the ratio is

---

Figure 2. Translation, rotation, and total relative mean energy loss per collision, as a function of neutron wave vector, for the diamond nanoparticle with radius of 1 nm.

Figure 3. The ratio of energy loss due to rotation degrees of freedom to translation of the 1 nm diamond nano sphere.
\[ \frac{\xi_r}{\xi_t} = \frac{1}{4} \] (15)

which is ~17% less than the sphere case.

For practical purposes, we consider using C_{60}, of which the radius is 0.71 nm, to moderate UCN. By applying Eqn. (13), we found that the total scattering cross section of C_{60} is 3600 times of a single carbon nucleus. The derived energy loss per collision of C_{60} is shown in Fig. 4.

Though mean energy loss per collision is proportional to $1/A$, i.e., inversely proportional to the total nucleus number in the nanoparticle, the neutron scattering cross section is in quadratic relation to the nucleus number. If we only take the scattering effects into consideration, higher neutron cooling efficiency is expected for larger nanoparticles. However, the neutron absorption cross section increases linearly with the nucleus number. It will be an optimization problem to balance all these factors.

**Neutrons Scattered by a Magnetized nanoparticle**

It is known that neutrons can interact with magnetic particles since they have a magnetic moment. Hence it is natural to consider the magnetic effects for some specific nanoparticles. According to ref. 21, magnetic scattering has no interference with the nuclear scattering. The magnetic scattering cross section includes spin states transitions and for the elastic case it can be expressed as:

\[ \frac{d\sigma}{d\Omega} = (\gamma r_0)\gamma |\langle \sigma'|\sigma \cdot \vec{Q}_{\perp}\rangle|^2 \] (16)

where $r_0$ is the classical radius of electrons, and $\gamma$ is the gyromagnetic ratio of neutrons, $\sigma'(\sigma')$ refers to the spin state, $\sigma^\prime$ are the Pauli matrices and:

\[ \vec{Q}_{\perp} = -\frac{\gamma r_0}{2\mu_B} \hat{q} \times \left[ \overrightarrow{M}(\hat{q}) \times \hat{q} \right] \] (17)

where $\mu_B$ the magnetic moment of electrons, $\overrightarrow{M}(\hat{q})$ is the Fourier transformation of the nano sphere magnetization $\overrightarrow{M}(r)$.

Using Eqn. (16), the total cross section of a neutron scattered by a magnetized nanoparticle is found to be:

\[ \sigma_{tot} = \sigma_N + 2\pi^2 |\overrightarrow{M}|^2 R^6 \sin^2 \phi \left[ \frac{\gamma r_0}{\mu_B} \right]^2 \frac{1}{(2kR)^2} - \frac{1}{(2kR)^3} + \frac{\sin (4kR)}{(2kR)^4} - \frac{\sin^2 (2kR)}{(2kR)^4} \] (18)

where $\sigma_N$ is the nuclear scattering cross section of the nanoparticle, $\phi$ the angle between the scattering wave vector and the magnetization. For atoms with strong magnetism, we expect that the magnetic scattering might be important. For example, the magnetic scattering length of the Co atom is even larger than its nuclear scattering length, then its magnetism may also serve to slow down neutrons. The magnetic, nuclear and total cross sections are shown in Fig. 5.

**Possible Application in the nEDM Experiments**

There are other possible applications of nanoparticles in fundamental neutron physics. In the nEDM experiment, the geometric phase effect is considered to be a major systematic error\(^{27}\), which is due to the correlation between the velocity and the position time series of the UCN\(^{23}\). When using \(^3\)He atoms as the co-magnetometer, it was
found that this geometric phase effect get suppressed due to randomizations caused by collisions between $^3$He atoms and liquid $^4$He. It was also noticed that the diffusive reflections of UCN by the wall can reduce this effect\(^2\). However, this effect can not bring great benefits here since the neutron has a negligible cross section when scattering with $^4$He. If we introduce nanoparticles into the liquid $^4$He, not only the neutrons can be further slowed down, but also the geometric phase effect caused by scattering neutrons is reduced.

**Conclusion and Discussion**

Due to quantum coherence, nano-sized particles have very large cross sections when scattered with very cold and ultracold neutrons. Neutrons with large wavelength will strongly interact with the nanoparticles immersed in the superfluid helium, which consequently take away energy of the incident neutrons. Based on this fact, neutrons could be slowed down if the temperature of nanoparticles is lower than that of neutrons. Previously, only translational energy is considered within this new moderating mechanism. By taking into account of the rotational effects, we find that neutron-moderating efficiency might be increased by as much as 40% accordingly. One of the most important advantages of this moderator scheme is its simplicity. For the superthermal liquid helium UCN moderator used by several nEDM experiments\(^29\)–\(^31\), if their operating temperature can be lowered down to ~mK, the moderator scheme discussed in this paper could be realized simply by adding some nanoparticles. Since many tests and experiments have been done for the superthermal UCN sources operating at temperatures of a few hundreds mK, we would expect the main technology difficulty might be cooling the liquid helium inside the moderator down to ~mK. The temperature required is just the practical lower limit of the commercially available dilution refrigerators. Practically, it would be difficult to realize the new moderator scheme but it is not impossible. We further derive the scattering cross section and moderating efficiency of neutrons scattered by a nano shell made by $^{60}$Co as an example. We also consider using the magnetic nanoparticles to slow down neutrons, and give the associated scattering cross section. We find that nanoparticles could be applied to the nEDM experiment not only to slow down neutrons but also reduce a systematic error.

**References**

1. Nesvizhevsky, V. V. et al. Quantum states of neutrons in the Earth’s gravitational field. Nature 415, 297–299 (2002).
2. Schmiedmayer, J. & Abele, H. Probing the dark side. Science 349, 786–787 (2015).
3. Jenke, T. et al. Gravity resonance spectroscopy constrains dark energy and dark matter scenarios. Phys. Rev. Lett. 112, 151105 (2014).
4. Yue, A. T. et al. Improved determination of the neutron lifetime. Phys. Rev. Lett. 111(22), 222501 (2013).
5. Wietfeld, F. E. & Greene, G. L. Colloquium: The neutron lifetime. Rev. Mod. Phys. 83(4), 1173–1192 (2011).
6. Alarcon, R. Fundamental physics with cold and ultracold neutrons. Revista Mexicana De Fisica 53, 125–127 (2007).
7. Arzumanov, S. et al. A new project to measure the neutron lifetime using storage of ultracold neutrons and detection of inelastically scattered neutrons. Nuclear Instruments and Methods in Physics Research A 611(2-3), 186–188 (2009).
8. Serebrov, A. P. Solid deuterium and UCN factory: application to the neutron electric dipole moment measurement. Nuclear Instruments and methods in Physics Research A. 440(3), 653–657 (2000).
9. Liu, J. et al. Determination of the axial-vector weak coupling constant with ultracold neutrons. Phys. Rev. Lett. 105(18), e107708 (2010).
10. Altaev, I. et al. Test of Lorentz invariance with spin precession of ultracold neutrons. Phys. Rev. Lett. 103(8), 081602–081605 (2009).
11. Nesvizhevsky, V. V. et al. Neutron whispering gallery. Nature Physics 6(2), 114–117 (2010).
12. Dubbers, D. & Schmidt, M. G. The neutron and its role in cosmology and particle physics. Rev. Mod. Phys. 83(4), 1111–1171 (2011).
13. Trkov, A. Nuclear reactions and physical models for neutron activation analysis. Journal of Radioanalytical and Nuclear Chemistry 304(2), 763–778 (2015).
14. Nesvizhevsky, V. V. Experiments with ultracold neutrons. Physics Letters B 34(4), 293–295 (2011).
15. Pokotilovskii, Yu. N. & Gareeva, G. F. A method for high-resolution and high-efficiency spectroscopy of ultracold neutrons at a small energy transfer and low scattering probabilities. Instruments and Experimental Techniques 46(1), 13–18 (2003).
16. Nesvizhevsky, V. V. et al. Study of levitating nanoparticles using ultracold neutrons. New J. Phys. 14(9), 1–5 (2012).
17. Thomsen, K. Conceptual proposal for compound moderators with preferential emission directions. Physics Procedia 60, 278–293 (2014).
18. Golub, R., Richardson, D. & Lamoreaux, S. K. Ultra-Cold Neutrons, (Adam Hilger. 1991).
19. Nesvizhevsky, V. V., Pignol, G. & Protasovb, K. V. Nanoparticles as a possible moderator for an ultracold neutron source, International Journal of Nanoscience 6(06), 485–499, (2007).
20. Nesvizhevskya, V. V., Pignola, G. & Protasovb, K. V. Thermalization of neutrons by ultracold nanoparticles 24th International Conference on Low Temperature Physics 1679–1681 (2006).
21. Squires, G. L. Introduction to the theory of thermal neutron scattering. (Dover Publications, Inc. 1996).
22. Sakurai, J. J. Modern Quantum Mechanics. (Addison-Wesley Publishing Company, Inc. 1994).
23. Messiah, A. Quantum Mechanics (Dover Publications, INC. 2013).
24. Lefmann, K. Neutron Scattering: Theory, Instrumentation and Simulation 83, 023402 (2011).
25. Artemiev, V. A., Nezvano, A. Yu. & Nesvizhevsky, V. V. Precise calculations in simulations of the interaction of low energy neutrons with nano-dispersed media. Crystallography Reports. 61(1), 84–88 (2016).
26. Press, W. H. et al. Numerical Recipes (Cambridge University Press, 1989).
27. Golub, R. & Lamoreaux, S. K. Neutron electric-dipole moment, ultracold neutrons and polarized 3He. Phys. Rep. 237(1), 1–62 (1994).
28. Yan, H. & Plaster, B. Impact of motion along the field direction on geometric-phase-induced false electric dipole moment signals. NIMA 642, 84 (2011).
29. Ito, T. M. et al. An apparatus for studying electrical breakdown in liquid helium at 0.4 K and testing electrode materials for the neutron electric dipole moment experiment at the spallation neutron source. Rev. Sci. Instrum. 87, 045113 (2016).
30. Masuda, Y. et al. Spallation UCN production for nEDM. Physics Procedia 51, 89–92 (2013).
31. Schmidt-Wellenburg, P. A. Development and Tests of a Superthermal Helium-4 Source for the Production of Ultra Cold Neutrons (Technische Universität München, 2005)

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Author Contributions
H.Y. proposed the idea. X.T. and H.Y. performed the calculations, G.S., J.G., Y.R., checked the results. All authors reviewed the manuscript.

Additional Information
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