# Reflectors for VCN and applications of VCN

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Present contribution is based on the talk given at the VI International Symposium on Radiation Physics in Zacatecas (Mexico). It summarizes recent developments on nanoparticle reflectors for very cold neutrons (VCN). Particular attention is devoted to powders of detonation nanodiamonds, possessing exceptional properties for such reflectors. Examples of VCN applications in particle and nuclear physics are given.

*Keywords:* Nanoparticle powders; very cold neutrons; neutron albedo.

Este trabajo está basado en la conferencia ofrecida en el VI Simposio Internacional de Física de Radiaciones en Zacatecas (México). Resume los avances recientes en reflectores de nano-partículas para neutrones muy fríos (VCN). En particular en lo relativo al uso de polvos de nano-diamantes, que poseen propiedades excepcionales como reflectores. Se ofrecen ejemplos de aplicaciones de VCN en Física Nuclear y de Partículas.

*Descriptores:* Polvos de nanopartículas; neutrones muy fríos; albedo de neutrones.

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## 1. Introduction

We present new developments on reflectors for slow neutrons; in particular, for so-called very cold neutrons (VCN) with energies in the range of $\sim 4\times 10^{-7}$-$2\times 10^{-4}$ eV, or velocities in the range of $\sim$8-200 m/s. The lower bound for this range corresponds to the largest nuclear optical potential (velocity) available. Neutrons with even smaller energy are called ultracold neutrons (UCN). They are reflected from nuclear optical potential of surface material at any incidence angle; therefore they could be stored in closed traps for extended period of time. UCN are widely used in precision particle physics experiments [1-10]. Applications of UCN are emerging in surface and nanoparticle physics [11-14]. The upper bound for the VCN energy (velocity) range corresponds to minimum energy (velocity) of neutrons present in typical beams of cold neutrons (CN). CN (also VCN) are totally reflected from flat surface only if the incidence angle is sufficiently small; so that the perpendicular-to-surface component of the neutron velocity is lower than the material critical velocity. CN have found extremely broad applications in various domains of science such as solid state, soft matter, surface physics, magnetism, chemistry, biology and many others, pursued at various reactor and spallation neutron sources all over the world [15-18] etc. Besides, CN is the best tool for precision studies of the neutron $\beta$-decay [19-20]. They are intensively used in studies of fundamental symmetries [21-23].

Applications of the intermediate VCN energy range have not yet been explored, except for a few examples [24]. On the other hand, some experiments in particle physics ([25-26], in-flight measurements of the neutron lifetime) require this energy. Besides, "standard" neutron-scattering applications of slow neutrons in solid state, soft matter, surface physics, chemistry, biology, magnetism etc would profit from extending the range of available energies to even lower values. As any progress in all the mentioned above areas followed from preceding methodical and technological developments, we hope for a break-through in the use of VCN due to recent developments of VCN reflectors. Such reflectors would allow significant increase in VCN fluxes; also they provide unique tool for shaping and analyzing beams of VCN and storage of VCN in traps.

## 2. Reflectors for VCN

The reason explaining why VCN have been neglected consists probably in our ignorance of physical phenomena that would allow us to shape and analyze VCN spectra as well as produce high VCN fluxes. It is well known that neutrons on both sides of the VCN energy range are very convenient for manipulations. Thus, UCN are totally reflected from surfaces and can be trapped. Trapped neutrons present an extremely sensitive probe for fundamental neutron physics. Therefore they are intensively used in spite of ridiculously low their densities (even lower than those of residual atoms in interstellar space!). Thermal and faster neutrons are efficiently reflected from matter due to multiple billiard-ball their collisions with nuclei in matter. This process is not that efficient for CN as typical CN wavelength is comparable or even larger than inter-atomic distances. In simple terms, soft CN do not resolve separate nuclei; they pass through matter with no

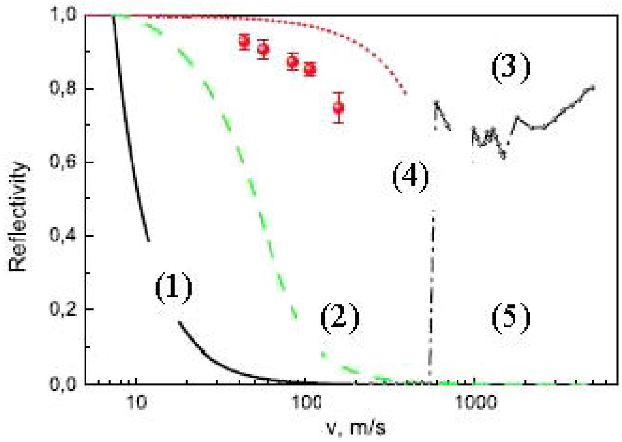


FIGURE 1. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror (dashed line), (3) Hydrogen-free ultradiamond powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination. Experiment. (5) MCNP calculation for reactor graphite reflector with the infinite thickness at ambient temperature (dashed-dotted line).

interaction. Some scattering of CN in matter occurs at collective excitations, for example phonons. The spectrum of collective excitations is poorly populated at CN energies, therefore scattering cross-sections are small; such neutrons do not scatter. Essentially, the last effect defines the boarder-line between CN and VCN.

Consider in general terms the condition providing efficient scattering of VCN in matter. An evident straightforward solution of the problem consists in increasing characteristic distance between scatterers and increasing scattering cross-sections, thus providing effective billiard-ball collisions of VCN with such a specially prepared matter consisting of nanoparticles or nanostructures [12]. Powder of detonation diamond nanoparticles is an evident candidate for such VCN reflector, due to exceptionally high optical nuclear potential, low absorption cross-section of diamond, and availability of the nanoparticles in optimum sizes (approximately equal to the neutron wavelength of $\sim$5 nm). Formation of diamond nanoparticles by explosive shock was observed nearly 50 years ago [27]. Since then very intensive studies of their production and various applications have been performed worldwide. These particles measure a few nanometers. They consist of a diamond nucleus (with a typical diamond density and optical nuclear potential) within an onion-like shell of a complex chemical composition [28] (with significantly lower optical potential). A recent review of the synthesis, structure, properties and applications of diamond nanoparticles can be found, for instance, in Ref. 29. The critical velocity of diamond, 8 m/s, is the highest available, thus providing the highest scattering efficiency for VCN and CN. The absorption cross-section of carbon is exceptionally low $\sim$3.5 mb, thus providing a huge number of consecutive scattering events. In fact, neutron losses are dominated by impurities on surface of nanoparticles, in particular by small impurity of hydrogen with its huge inelastic cross-section (up to $\sim 10^2$b), and significant absorption cross-section (0.3 b) even at zero temperature. That is why proper control/elimination/substitution of hydrogen is a major issue in any neutron application of nano-diamonds; on the other hand, neutrons provide an extraordinary probe to study hydrogen in the powders.

A theoretical description of the scattering of VCN on a single nanoparticle in the first Born approximation is straightforward; it could be found, for instance, in Ref. 30. The scattering amplitude on a single round particle with uniform optical potential equals

$$f(\theta) = -\frac{2mU_0}{\hbar^2}\gamma^3\left(\frac{\sin(qr)}{(qr)^3} - \frac{\cos(qr)}{(qr)^2}\right),$$
$$q = 2k\sin\left(\frac{\theta}{2}\right) \tag{1}$$

where $\theta$ is the scattering angle, $m$ is the neutron mass, $U_0$ is the real part of the nanoparticle optical potential, $\hbar$ is the Planck constant, $r$ is the nanoparticle radius, $k = 2\pi/\lambda$ is the neutron wave vector, and $\lambda$ is the neutron wavelength. The scattering cross-section equals

$$\sigma_s = \int |f|^2 d\Omega = 2\pi\left|\frac{2m}{\hbar^2}U_o\right|^2 r^6 \frac{1}{4(kr)^2} \times \left(1 - \frac{1}{(kr)^2} + \frac{\sin(2kr)}{(kr)^3} - \frac{\sin^2(kr)}{(kr)^4}\right) \tag{2}$$

the cross-section of absorption of neutrons in a nanoparticle with the imaginary part of the neutron-nuclei optical potential $U_1$, equals

$$\sigma_a = \frac{4\pi}{3}\frac{2m}{\hbar^2}U_1 r^4 \frac{1}{kr} \tag{3}$$

These simple formulas are usually sufficiently precise to describe qualitatively all phenomena of interest. Interference between scatterings at neighbor nanoparticles could be neglected if the neutron velocity is not too low. Mie scattering [26] of neutrons by single nanoparticles to very large angles could be neglected for not too narrow distributions of neutron velocities and nanoparticle sizes.

When VCN arrives to macroscopically thick layer of such diamond nanoparticles, it could be reflected from this layer after multiple scattering events, in analogy to albedo of thermal (and faster) neutrons from nuclear reactor reflectors (water, heavy water, carbon, beryllium etc) [31]. The first experiments on scattering of VCN from nano-structured materials as well as on VCN storage were carried out in the seventies [32] and continued in Ref. 33. However, until recently, albedo of VCN from disordered medium had not been intensively studied and used because the effects observed were not significant. Things did change since one started using diamond nanoparticles [34], which allowed us to bridge the complete energy gap between efficient reactor reflectors [35] for thermal and cold neutrons and optical neutron-matter potential for UCN. In order to measure precisely the VCN reflection probability from powder of diamond nanoparticles and to explore feasibility of VCN storage in traps with nanostructured walls, we carried out a dedicated VCN storage experiment [36]. The measured probability of neutron isotropic flux reflection from powder of diamond nanoparticles is compared with other known reflectors in Fig. 1. The maximum energy of reflected VCN and the reflection probability exceed the corresponding values for the best supermirror available [37]. One should note also that VCN reflection from powder is mainly elastic as the neutron mass is much smaller than the nanoparticle mass (an effective mass of a scatterer in powder is even much larger than a single nanoparticle mass due to strong inter-particle bonding). Further improvement of VCN storage times could be achieved by removing a part of hydrogen from powder, by isotopic substitution of hydrogen by deuterium, or/and by cooling a trap to a temperature, at which the inelastic up-scattering of VCN at hydrogen is strongly suppressed.

In case of CN, the angle of neutron scattering on each nanoparticle is small. Therefore neutrons arriving at a large incidence angle to the powder surface penetrate deep into the powder and do not return to the surface before they are absorbed (see Fig. 1). Nevertheless, neutrons arriving at a small incidence angle $\alpha$ to the powder surface could return to surface after several small-angle scattering events. Such a neutron albedo is analogous to the process considered in a general form in Ref. 38, where an analytic expression describing the probability and angular spectrum of reflected radiation is found for various laws of single scattering of ions, electrons, protons and photons from a medium consisting of scattering centers with sizes significantly larger than the radiation wavelength. As the typical number of scattering events is small, the exit angle $\beta$ is approximately equal to $\alpha$; with a diffusive halo around it $\pm\alpha$. The penetration depth of neutrons into the powder is small; therefore the absorption affects reflectivity much less than that in the previous case of large incidence angles. We call such a process quasi-specular reflection [39]. The observed probability of quasi-specular reflection of CN reached up to $\sim$50%; it could be slightly improved by removing some hydrogen from powder. The wavelength range of effective quasi-specular reflection is limited to below $\sim$4Å by Bragg scattering of neutrons in the bulk of a diamond nanoparticle. In contrast to standard sub-critical reflection of neutrons from optical potential of uniform medium, the quasi-specular reflection might be observed also at highly above-critical angles. Powders of diamond nanoparticles used here reflect neutrons with perpendicular velocity components larger than 40 m/s.

As shown in Ref. 40, such nanoparticle reflectors would not be very efficient for thermal neutrons as the difference of the thermal neutron wavelength and nanoparticle size is too large. Besides, Bragg scattering is dominant in this energy range.

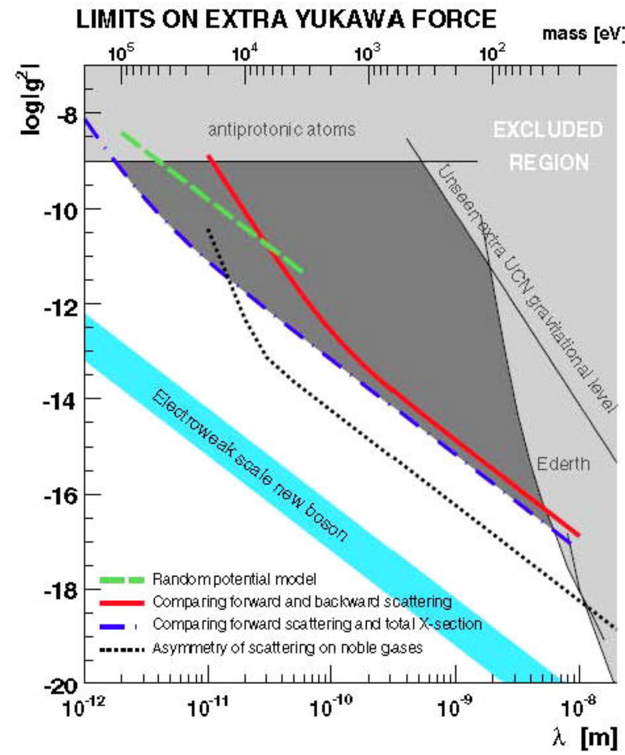


FIGURE 2. Strength of extra Yukawa interaction (normalized to the nuclear interaction) is shown as a function of the characteristic range of the extra force. The shaded regions correspond to current experimental constrains at 95% C.L. (dashed, dot-dashed, and bold lines) [25,51].The dotted line is an estimation of sensitivity of an experiment with VCN proposed in Ref. 25.

## 3. Applications of VCN

Reflectors presented here are of particular interest in view of their application for improving performance of UCN and VCN sources, for instance combining solid-deuterium source similar to that presented in Ref. 41 and the reflector accumulation of VCN. Besides, VCN storage allows us to accumulate significant number (density) of VCN in a closed trap (much larger than that typical for UCN). Quasi-specular reflection of CN could be used for neutron reflectors in zones close to reactor core, where other reflectors would not survive radiation damage. These reflectors would increase CN fluxes available for external experiments.

Keeping in mind limited length of this contribution, let's just list some examples, in which VCN would be useful, leaving careful analysis for future.

We analyzed recently [25] various experiments that could be used for phenomenological constrain for extra short range forces, motivated by new light weakly-interacting bosons [42] and particularly by theories with large extra dimensions [43-48]. As pointed in Refs. 49 to 50 and in other references, neutrons could provide a particularly good probe for such searches. In fact, we confirm that the existing neutron experiments provide already the best constrains. Moreover, they could be easily improved using precision measurement of the (forward-backward) asymmetry of scattering of VCN at atoms in diluted noble gases. The best existing constrain in the distance range of 1 pm-10 nm was obtained from the analysis of the energy dependence of the neutron scattering lengths in the $b_{ne}$ measurements; the precision is limited by the correction for the $b_{ne}$ value itself. An obvious proposal for improving this constraint is to set up experimental conditions free of the $b_{ne}$ contribution. This is indeed possible, because neutron-electron scattering is essential for fast neutron only, and is absent for slow neutrons. One could measure forward-backward asymmetry of the scattering of neutrons at atoms in noble gases in the following way: the initial velocity of the neutrons should correspond to the energy range of VCN; the double-differential measurement of neutron velocity before/after scattering should be used to calculate the transferred momentum for every collision. The asymmetry of neutron scattering at an atom in the center-of-mass reference system would experience a characteristic step as a function of neutron velocity in presence of extra forces. As VCN velocity is compatible to atom thermal velocity, the neutron scattering in the laboratory system is quite anisotropic; therefore the kinematics of scattering has to be calculated. Conservative estimation of the experiment accuracy at the level of $10^{-3}$ brings possible constrains shown in Fig. 2 with dotted line.

Another experiment strongly profiting from high VCN fluxes is the precision measurement of the neutron whispering gallery quantum states [26]. The advantage compared to using CN consists in possibility of selective populating low deeply-bound quantum states with low tangential momentum. Such quantum states would be particularly sensitive to extra short-range interactions. The advantage compared to using UCN consists in significantly larger statistics. At smaller characteristic distances, dedicated experiments on neutron interference in crystals [50] might provide sensitive constrains; at larger characteristic distances, the best neutron constrain might come from GRANIT experiment [52].

Precision studies of the neutron $\beta$-decay (in-flight measurements of the neutron lifetime and the asymmetry coefficients in the neutron $\beta$-decay) would profit from larger probability of $\beta$-decay inside the experimental setup due to using slower neutrons [53]. Simultaneously the ratio signal/background would improve at least proportionally to decrease in the mean neutron velocity.

Measurements of nuclear reactions induced by polarized slow neutrons ([54], for example), typical for instruments as PF1B at the ILL [55], could profit from accumulation of VCN in a closed trap, thus from increase in the total flux.

Of cause, every such experiment should be analyzed in detail prior to its realization both from the point of view of its statistical power and eventual systematic effects.

## 4. Conclusions

Powders of nanoparticles with a size of $\sim$5 nm reflect efficiently VCN and CN due to approximate equality of their size and the neutron wavelength. Diamond, with its exceptionally high optical nuclear potential and low absorption cross-section, is a unique material for such VCN and CN reflectors. Powder of diamond nanoparticles provided the best reflectors for neutrons in the complete VCN energy range, and allowed the first observation of quasi-specular reflection of cold neutrons from disordered medium.

We discuss potential increase of VCN and CN fluxes related to use of the nano-powder reflectors, and present examples of experiments using VCN: phenomenological constrains for short-range forces in scattering of VCN on nuclei or in precision measurements using neutron whispering gallery, as well as precision in-flight measurement of the neutron lifetime.

It looks interesting to increase available VCN fluxes, also to consider experiments profiting from large VCN fluxes.

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