Diamond nano-powders: a new type of neutron reflectors. Will it lead to a new generation of slow-neutron sources?

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Abstract

This report is based on a talk with the same title given at QUARKS-2014 Workshop in Suzdal. It describes very efficient reflectors of a new type for slow neutrons with parameters largely exceeding those for alternative reflectors, which had been known prior to this research. The new reflectors are powders of nanoparticles with particle sizes comparable to neutron wavelengths. The best material for such nanoparticles is diamond. The new development can potentially result to emerging of a new generation of advanced sources of slow neutrons.

1 Introduction

Slow neutrons are subdivided into several groups as a function of their velocity/energy: 1. Cold Neutrons (CNs) with the typical velocity of 500 m/s. A lot of CNs are produced in typical thermal neutron sources (nuclear reactors and spallation neutron sources) if they are equipped with liquid-deuterium or liquid-hydrogen cryogenic sources of CNs. CNs are available for neutron experiments in a form of neutron beams with typical cross sections of up to several tens of centimeters and the angular divergence of a few degrees; 2. Ultra Cold Neutrons (UCNs) with the typical velocity of 5 m/s. In spite of impressive worldwide efforts to improve UCN sources, extremely low densities are currently available for experiments. However a unique property of the total reflection of UCNs from material and magnetic walls provides their long storage and accumulation in traps and thus makes them highly demanded. UCNs could also be used in a form of beams but usually rather as gas with isotropic angular distribution enclosed in traps with typical sizes of many liters; 3. Very Cold Neutrons (VCNs) with the typical velocity of 50 m/s. They are presently characterized by limited fluxes (compared to CNs) and no efficient reflection and storage (compared to UCNs).

The situation with VCNs is going to change due to the invention of efficient nano-diamond powder reflectors for slow neutrons, in particular for VCNs. Related results were published in refs. (1), (2), (3), (4), (5), (6), and obtained at the Institut Max von Laue Paul Langevin, Grenoble, France (7) in the collaboration of co-authors of these publications. Here we describe briefly main results in the field, and refer the reader to original articles given in the reference list for any further details. The described phenomenon is dominant in the process of neutron scattering on nanoparticles provided that neutron wavelengths are comparable to particle sizes. The characteristic scale of the problem is illustrated in Figure 1, which presents the size distribution of diamond nanoparticles used in our first experiments.

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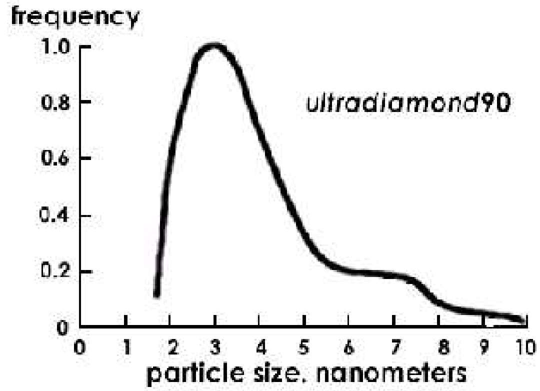

Figure 1: The distribution of sizes of diamond nanoparticles ''Ultradiamond90'' used in first neutron experiments (2).

The reflectivity of slow neutrons from powder of diamond nanoparticles is illustrated in Figure 2 in comparison with the reflectivity of alternative reflectors, and it will be analyzed in more detail below.

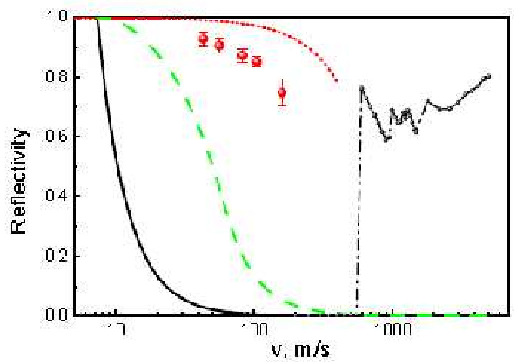

Figure 2: Elastic reflectivity of slow neutrons is illustrated as a function of neutron velocity for reflectors of various types. Black solid line stands for neutron-nuclei optical potential of bulk diamond (the highest known optical potential). Green dashed line shows reflectivity of neutrons from the best super-mirror. Black dashed-dotted line corresponds to graphite reactor reflectors. And finally red points indicate the measured reflectivity of slow neutrons from a 3-cm-thick layer of powder of Ultradiamond90 nanoparticles; dotted red line illustrates a potential gain in reflectivity, which could be obtained with improved parameters of the nano-powder reflector. More details are given in ref. (3)

In first section we present basic general features concerning scattering of slow neutrons on nanoparticles. These features are essential for efficiently reflecting VCNs from powders of nanoparticles as described in second section. This reflection allows for storage of VCNs in traps as analyzed in third section. As shown in fourth section, neutrons of even higher energy, so-called CNs, are quasi-specularly reflected from powders at small grazing incidence angles. Fifth section lists some applications of these phenomena. Behavior of nanoparticles in high radiation fluxes is important for some applications as mentioned in sixth section. Finally we overview further developments and give a conclusion.

2 Neutron scattering on nanoparticles

While analyzing the interaction of slow neutrons with atoms, one should note that the neutron-electron interaction is typically only a minor correction compared to the neutron-nucleus interaction (except for the case of strongly magnetized materials) and thus it could be neglected. As the wavelength of a slow neutron is much larger than the size of a nucleus, we always deal with isotropic s-scattering of a neutron on a nucleus and can characterize it with a single parameter: a scattering length. As the wavelength of a slow neutron is also larger than a typical interatomic distance, we deal with coherent scattering of neutrons at many nuclei simultaneously. As a result, any medium can be represented as a uniform effective neutron-nuclei optical potential. A typical value of the optical potential is 10-7 eV (it could be thought of as a typical nuclear potential of 10 MeV diluted over volume).

At even larger scale of a scattering center, of the order of a few nanometers, the neutron wavelength starts to be comparable to the scatter size. This fact justifies our choice of the term ''nano-powder reflectors''. For a given neutron wavelength and a variable nanoparticle size, two tendencies should be noted: 1. the cross-section of interaction of the neutron with a nanoparticle increases rapidly as a function of the nanoparticle size as long as the size is relatively small; 2. the angular divergence of scattered neutrons and the cross-section of large-angle scattering drops down rapidly as soon as the size becomes relatively large. The ''optimum'' wavelength, at which these two tendencies overlap, corresponds to the neutron wavelength approximately equal to the nanoparticle size.

Provided this ''optimum'' condition is met, the cross-section of coherent elastic scattering of a neutron on a nanoparticle is that large that it could reach square nanometers!

We would like to enhance scattering on one hand, and to decrease neutron absorption on another hand. What is the best choice for the nanoparticle material?

Concerning the value of optical neutron-nuclei potential, it is diamond, beryllium oxide, beryllium, 58Ni isotope or more exotic cases. Beryllium and beryllium oxide are not very practical because of their toxicity. The cross section of absorption in nickel (isotope) is too high. So we are left with diamond. Fortunately the techniques of production of diamond nanoparticles with about the optimum size of a few nanometers are available on the market.

Would it be possible to ''replace'' atoms in standard reflectors of nuclear reactors with diamond nanoparticles in order to improve the reflectors in some range of parameters? If yes, in what range?

3 Reflection of VCNs from powders of nanoparticles

At first stage we neglected the relatively complex internal structure of a diamond nanoparticle and its shell, choosing to modulate it as a uniform sphere with some mean neutron-nuclei optical potential. The neutron-nanoparticle elementary interaction is calculated using the first Born approximation. The approximate validity of this approximation as well as all explicit formulas are justified and derived in refs. (8), (9).

This simplified approach allowed us to understand all principal tendencies and estimate characteristic parameters of the problem. Within this approach we designed experiments on reflection of slow neutrons from layers of powders of diamond nanoparticles (2), and thus proved experimentally the existence of the phenomenon of exceptionally large albedo of slow neutrons from such layers. Slow neutrons are reflected from layers of nanoparticles essentially in the same way as thermal neutrons are reflected from heavy water in nuclear reactors: due to their diffusion caused by multiple scattering events.

One important feature is that most neutrons are reflected elastically, with no change in their energy, as expected from the hypothesis that coherent elastic scattering is the dominant process.

Another important feature is that albedo is large only for neutrons with velocities of up to about 100 m/s that is only as long as neutron wavelengths are close to nanoparticle sizes. For smaller particles, scattering cross sections are too low. For larger particles, scattering is not isotropic but straightforwardly directed.

4 Storage of VCNs in traps

Any precision comparison of theoretical predictions to experimental results required, however, two additional steps:

- Instead of approximately estimating the neutron reflectivity in a ''one-reflection'' experiment one should use multiple consequent reflections and thus storage of slow neutrons in a closed trap with the walls consisting of powder of diamond nanoparticles kept together using some construction materials;
- A theoretical analysis of the process should take into account more features involved (in particular, precise solution of the scattering problem, chemical impurities in nanoparticles, structure of the cross-section of neutron scattering on bound hydrogen, size and shape distributions of nanoparticles, their clusterization, interference effects etc) these points are under study.

A closed trap with the walls consisting of powder of diamond nanoparticles enclosed in thin-wall aluminum envelopes is shown in Figure 3, and the results obtained using this trap (3) are shown in Figure 2 in the introduction to this article.

Figure 3: A nano-powder trap for slow neutrons.

As you can conclude from the data shown in Figure 2, powder nano-diamond reflectors provide by far the best reflectivity in a very broad velocity/energy range. For comparison, you can see in this figure the best data for all existing alternative neutron reflectors.

5 Quasi-specular reflection of CNs from powders

These reflectors are much less efficient for neutrons with velocities of a few hundred meters per second. Although this limitation is of principal character, as mentioned above, it is of interest to extend the range of operation of our reflectors at least for some particular cases.

One such case is so-called quasi-specular reflection of CNs from powders at small grazing incidence angles (4). CNs scatter at a nanoparticle so that their longitudinal velocity changes slightly and their tangential velocity changes significantly. With a certain simplification, the behavior of CNs arriving to a layer of nanoparticles at a small grazing angle could be described as a sum of two nearly independent motions: longitudinal velocity stays unchanged, while for a relatively small tangential velocity we get reflection like that in previous sections. The net effect is that CNs are reflected with relatively high probability to quasi-specular direction (with additional angular dispersion equal about to the incidence angle) as shown in Figure 4.

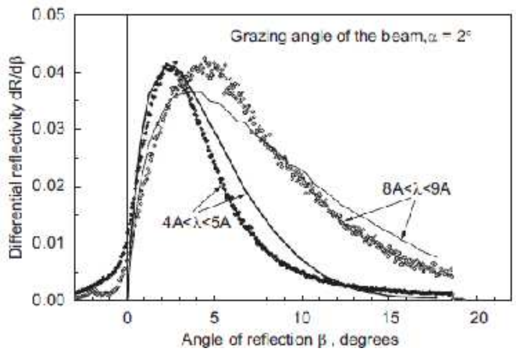

Figure 4: Angular distributions of reflected cold neutrons. The incidence angle is equal to 2 degrees. The neutron wavelength is shown in the figure.

6 Possible applications

Neutrons of all mentioned energy ranges (CNs, VCNs, UCNs) are used in numerous experiments in the field of fundamental particle physics as evident, for instance, from proceedings of dedicated workshops (10), (11), (12).

To mention some examples:

- experiments searching for the electric dipole moment (EDM) of the neutron using the method of storage of UCNs in traps and passage of CNs through non-centrosymmetric crystals;
- precision studies of the neutron beta-decay: measurements of asymmetry coefficients using CNs and UCNs as well as measurements of the neutron lifetime using UCNs and CNs;
- search for neutron-antineutron oscillations (CNs) and the neutron electric charge (VCNs and UCNs);
- search for fundamental short-range interactions using gravitational and centrifugal quantum states of UCNs and CNs, as well as scattering of CNs on noble gases.

On one hand, all these studies would gain if experiments are done with high fluxes/densities of VCNs using both the ‘’standard‘‘ beam techniques and storage of VCNs in traps. On another hand, new types of experiments would emerge. As a manifestation of broad interest to nanodiamond powder reflectors, one could mention that all major neutron facilities and projects, including Institut Max von Laue Paul Langevin in Grenoble, European Spallation Source in Lund, PIK reactor in Gatchina and others, explore implementations of such reflectors; within IAE there is a dedicated project studying various options.

7 Behavior of nanoparticles in high radiation fluxes

An important parameter, which has to be further explored in order to validate the possibility of using diamond nano-powder reflectors in the vicinity of intense neutron sources (nuclear reactors, spallation sources) consists of their resistance to high radiation fluxes (of fast neutrons and gamma quanta). A potential danger consists of conversion of diamond nanoparticles to carbon. Nevertheless first experimental results and theoretical estimations are promising.

8 Conclusion

To summarize results: Powders of diamond nanoparticles provide the first efficient reflectors for VCNs (1), (2), (3) as well as quasi-specular reflection of CNs (4). Such reflectors could provide a major gain in fluxes and densities of slow neutrons in various configurations (6). High resistance of diamond nanoparticles in moderate radiation fluxes has been proven. Absorption of neutrons in diamond nanoparticles is dominated by hydrogen admixtures (5); the amount of hydrogen could be significantly reduced by means of proper powder treatment and conditioning. Alternative materials (with even lower absorption) and nanoparticle parameters (nanorods) (13) could be studied in order to improve even further the reflective properties of nano-powders. Side benefits from the present development are potential for equilibrium cooling of VCNs in gels of ultracold weakly bound nanoparticles (1), (9), (14), and observation of a new phenomenon of ''levitation'' of nanoparticles in the vicinity of surface (1), (15).

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