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Production of ultracold neutrons in a decelerating trap

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Abstract. This note proposes a new concept for the production of ultracold neutrons (UCNs) in a decelerating trap. UCNs are widely used in the physics of elementary particles and fundamental interactions, and can potentially be used in studies of condensed matter. However, most of these studies are limited by the available UCN densities and fluxes. One of the ways to increase them is to extract more neutrons from the full phase space of a source and better exploit peak fluxes in pulsed neutron sources, orders of magnitude larger than the mean values. For instance, at ESS, the pulsed flux will be a factor of ∼25 larger than the mean flux of ILL at nominal power. Here, a concept of UCN sources is proposed, which allows to implement this idea. We propose to produce very cold neutrons (VCNs) in converters located in a neutron source, extract and slow them down to UCNs by a decelerating magnetic or material trap. As shown in this paper, for both pulsed and continuous neutron sources, this method could provide a high conversion efficiency of VCNs to UCNs with low losses of density in the phase space. More detailed calculations and the proposals for concrete technical designs are going to be developed in future publications.

Keywords: Ultracold neutrons, very cold neutrons, phase space, pulsed magnetic fields

1. Introduction

Ultracold neutrons (UCNs) with an energy E_{UCN} lower than the critical energy $E_{\lim}(A)$ of a substance A, determined by the coherent scattering length of neutrons, are reflected from its surface. A typical critical velocity of the substance is $v_{\lim} = \sqrt{2E_{\lim}/m_{\mathrm{n}}} \sim 6$ m/s, where m_{n} is the neutron mass. As a result, UCNs with a velocity lower than the critical velocity of the walls can be stored for a long time in the trap, thus becoming a sensitive probe in the physics of elementary particles and fundamental interactions, and, in cases mentioned below, in neutron scattering.

In particular, the discovery of UCNs [26,47] aroused from the necessity to increase the sensitivity of experiments to search for the neutron electric dipole moment d_{n}; the best current result is $d_{\mathrm{n}} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}) \cdot 10^{-26}$ e $\cdot$ cm [1]. Its nonzero value would violate the symmetry with respect to time reversal. UCNs were also used for the observation of quantum states of matter in a gravitational field [33] and for the constraints on additional fundamental interactions that might appear when light weakly interacting particles or additional dimensions of space are introduced [5], in certain hypotheses for explaining dark matter and dark energy [22]. The sensitivity of all these experiments is limited by statistics, although they used the most intense UCN sources [2,24,49]. Neutron lifetime measurements are apparently limited by systematics, because the results of the two methods (in trap and in beams) diverge [39,43,51]. However, larger statistics would allow to simplify the experimental design of both methods types, and to reveal the systematic effects. Precision measurements of neutron β-decay provide information on the weak interaction parameters and are sensitive to exotic decay modes. A discovery potential is

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associated to searches for neutron-antineutron oscillations (present day experimental limit $\tau_{n-\bar{n}} > 0.86 \cdot 10^8$ s [8]), which would violate the conservation of the baryon number B, in particular, using a new approach based on coherent reflection of neutron and antineutrons [32,37]. One can add a long list of other fundamental problems, the solutions of which require an increase in the UCN density: these include, for example, the search for mirror neutrons, the violation of the Lorentz invariance, the verification of the electrical neutrality of the neutron.

High UCN densities are critical in studies of the dynamics of nano-objects on the surface [10,35], and might become important in a number of neutron scattering methods similar to those that use cold and thermal neutrons, including spin-echo spectrometers, reflectometers, small-angle scattering diffractometers, time-of-flight spectrometers, and others. These methods, however, have yet to be adapted to the velocities of very cold neutrons (VCNs), and even more so to the UCN velocities.

As it is clear from the comparison of statistical and systematic uncertainties in these experiments and from the general trends, an important limitation of UCN applications is the smallness of the available densities and fluxes. This is a consequence of their low energy, thus, a small fraction of the flux in the thermal spectrum of the neutron source, which is $\sim 10^{-11}$. However, in spite of this smallness factor, they were discovered by the method of separating UCNs from the broad thermal spectrum [26,47]. Equilibrium cooling in a cryogenic moderator increases the phase-space density of neutrons, thus the fraction of UCNs in the spectrum [2,49]. Also nonequilibrium methods for producing UCNs from thermal and cold neutrons are well developed [17]. Thus, solid-deuterium UCN converters have been implemented, for example, at the Los Alamos National Laboratory [42] and at the Paul Scherrer Institute [4], and projects of UCN converters based on ^{4}He are at different stages of development [3,28,40,44].

The actual UCN densities obtained are usually orders of magnitude lower than the initial expectations. The reason lies in the difficulty of extracting more neutrons from the full phase-space and transporting UCNs from the cryogenic environment to the experimental setup at room temperature, without a major loss in the phase-space density. The need for separating windows, valves, long transport lines, intermediate volumes etc, adds complications. A typical efficiency of a UCN extraction could be estimated as follows. A mean neutron flux in an intense neutron source, a reactor or a spallation source, can reach up to $\sim 10^{15}$ n/(cm^{2}s). In a typical source of cold neutrons, like the liquid deuterium source at ILL [2], the corresponding fraction of UCN flux in the tail of the thermal source is $F_{\mathrm{UCN}} \sim 3 \cdot 10^3$ UCN/(cm^{2}s). A loss-free extraction of these neutrons would provide an unprecedented UCN density, without the need to construct a dedicated UCN source. In the cases of solid-deuterium UCN converters in the vicinity of the neutron source or liquid-helium converters at an external neutron beam, the projected UCN densities are at least a few times larger than that. However, in spite of major long-term efforts, the extracted UCN densities are always at least a hundred times lower, below 10^2 UCN/(cm^{2}s) [9]. Therefore, of interest are methods exploiting the full phase-space or at least a much larger volume of it, i.e., in which the extraction and transportation of UCNs are not required. The proposed method involves the production of VCNs in a converter located in a neutron source, their extraction, transportation in a neutron guide with specular reflection from the walls, their deceleration to UCN energies and the subsequent addition of UCN bunches from different pulses of the source.

2. Description of the method, scheme of the installation

First, we present the principle of the proposed method, and then explain point by point the components of the method. In the installation that implements the proposed method, the VCN converter (pos. 1 in Fig. 1) is located close to center of the neutron source and in front of the specularly reflecting neutron guide (pos. 2) needed to transport VCNs outside the biological shielding where the other components are placed. Behind the biological shielding (pos. 3) of the neutron source, a device for focusing the VCNs in time is placed (pos. 4) to recover the phase-space density diluted when neutrons exit the shielding. Then the VCNs are trapped and decelerated to UCNs in a decelerating (material or magnetic) trap (pos. 5). This relatively small bunch of UCNs then enters a much larger accumulation volume (pos. 7) separated from the guide by a fast valve (pos. 6). The synchronization of the valve opening/closing allows to fill in the accumulation volume with a phase-space density close to that in the bunch of UCNs in the guide. The main part of the VCNs that are not captured in the trap is extracted from the

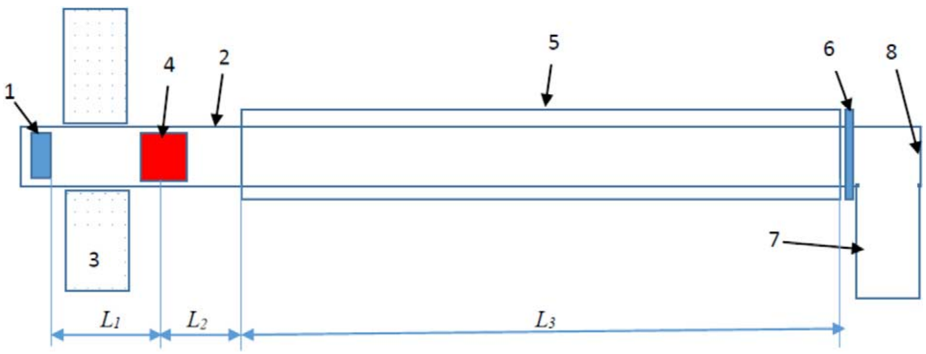

Fig. 1. A scheme of the installation to produce and accumulate UCNs: 1 – VCN converter, 2 – specular guide, 3 – biological shielding of the neutron source, 4 – time focusing device, 5 – segment of deceleration of VCNs to UCNs, 6 – fast valve, 7 – UCN accumulation volume, 8 – thin separating foil.

guide exit, which ends is a thin separating foil (pos. 8), so that they can be exploited by other instruments placed downstream the proposed experimental setup.

The specular neutron guide consists of a segment "1" of length L_1, along which VCNs freely propagate, a segment "2" of length L_2, in which they are focused in time, and a segment "3" of length L_3, in which they are decelerated. The first segment "1" allows us to avoid placing devices in strong radiation fields. However, in it, the initial length of the neutron bunch increases due to the neutron velocity spread, therefore, the length L_1 should be reasonably reduced. Radiation decreases at a distance of $\sim$1 m from the neutron source, but to test the method feasibility, we consider a conservative value $L_1 \sim 5$ m equal to the thickness of a typical biological shielding. To compensate for the increase in the length of the neutron bunch in in segment "1", i.e., to avoid a dilution of the phase-space density of VCNs proportional to the increase of the length of the bunch, we use the focusing device and the second segment "2" ($L_2 \sim L_1$). The length L_3 is determined by the technically achievable deceleration value and can be 10–15 m. Ideally, this decelerating trap does not change the phase-space density substantially. The total guide length can be 20–25 m, and so that such a guide can be easily placed in a standard experimental hall. For a continuous neutron source, the segment "2" is absent.

The accumulation volume (pos. 7) is located at the end of the guide. If one lets the UCN bunch enter the last small segment of the guide and the accumulation volume and then quickly closes it inside with the valve (pos. 6), the bunch is trapped. The UCN valve is opened only for the moment of arrival of the UCN bunches. It can be magnetic or mechanical, but transparent to VNCs to allow other downstream instruments to use them.

The main processes used in this method have been considered, some of them have already been implemented. For a pulsed source, this method can provide UCN densities approaching half of the peak phase-space density in the converter, as was proposed by F.L. Shapiro [45]. The choice of optimal phase-space range and the efficient extraction of VCNs are the basis of the "Steyerl turbine" [48]. Time focusing of neutrons was proposed in [14]. The motion of neutrons together with a material trap has been demonstrated [7,19]. The slowing down of neutrons by an inhomogeneous magnetic field has been repeatedly shown [38], and the slowing down of neutral atoms and molecules by an inhomogeneous magnetic field is used in experiments [11–13,21,25,50]. The novelty of the proposed concept lies in the combination of several methods developed in different fields of physics, so that the method of obtaining near-peak UCN densities can be implemented in practice.

3. Formation of UCN bunches

3.1. VCN converter

In the following, we show feasibility of the method on an example of a solid-deuterium converter by analogy with UCN converters [17]. It is placed into the maximum neutron flux in the vicinity of the neutron source and is surrounded by a nanodiamond reflector [27,36] in combination with a liquid-deuterium or hydrogen premoderator from all sides, except for the direction of the VCNs extraction. The purpose of the VCN converter is to increase the VCN phase-space density compared to that in the pre-moderator (the cold neutron source). The reflector is rather transparent for thermal and cold neutrons, but reflects efficiently VCNs. It is used to accumulate the VCN density in the converter and increase the fraction of VCNs directed along the guide axis. In the absence of the reflector, the converter size would have to be increased. Let the diameter of the converter disk be equal to the characteristic VCN guide diameter, $d \sim 7$ cm. The converter thickness can be $\Delta l \sim 10$ cm; the thickness is limited by the mass of solid-deuterium which could be cooled down in the conditions of high thermal load in the vicinity of the neutron source. In the case of a too large heat load in the position of UCN converter (for instance at the ESS), one should reduce the converter thickness to an acceptable level or just use the VCN flux from the tail of the thermal spectral distribution produced in the liquid deuterium cold neutron source.

3.2. Neutron bunch

During a neutron source burst of duration $\Delta\tau_{\text{n.s.}}$, a neutron bunch of length $l_b \sim \Delta\tau_{\text{n.s.}} \cdot V_{S0} + \Delta l$ enters the guide, where v_{S0} is the neutron velocity along the direction of the bunch movement. The choice of the v_{S0} value is important. For the low-velocity fraction of neutrons in the VCN converter (cold neutron source), any element of the phase-space has the same phase-space density. Therefore, any process which conserves the phase-space density should lead to the same final UCN density in the accumulation volume. However, the slowest neutrons are difficult to extract without major losses and too fast neutrons are difficult to decelerate using the proposed method. The v_{S0} value is chosen to correspond to the lower limit of the range of maximum phase-space density. For a relatively thick converter and separating windows, its conservative estimate is $\sim$50 m/s [2,49], but it can be reduced to $\sim$30 m/s or even $\sim$15 m/s in the case of beryllium windows. If $\Delta l \sim 10$ cm, $v_{S0} \sim 50$ m/s and $\Delta\tau_{\text{n.s.}} \sim 2$ ms (ESS, Lund), the contribution of both terms in the expression above is about the same, and $l_{\text{b}} \sim 20$ cm. If $\Delta\tau_{\text{n.s.}} \ll 2$ ms (for instance, JINR, Dubna), one could also consider converters with a higher VCN production rate and a smaller extraction depth [18,31]. Extracting, focusing and decelerating a small bunch is a more difficult task, but its solution might lead to a higher phase-space density.

For matching the downstream devices, the intensity distribution within the bunch is important. For the solid-deuterium converter and both long and short source pulses, the phase-space density is fairly uniform in its central part $l_{\text{b}} \sim 10$ cm and falls towards the periphery. To maximise the density, the peripheral zones of the phase-space element can be cut off, and only this central uniform part can be used.

In the segment "1" of the specular neutron guide, the VCN bunch freely propagates and its length S increases in accordance with the formula known from the optics of beams: $S^2 = l_{\text{b}}^2 + (s\Delta v_0/v_{S0})^2$, where s is distance from the initial point and Δv_0 is the spread of velocities in the bunch; the value of Δv_0 is chosen from the condition that all these neutrons can be trapped when cooled down to the UCN range. At a distance $L_1 = 5$ m it exceeds 0.6 m (the total bunch length > 1.2 m).

3.3. Time focusing device

The focusing device can be considered as a "thin lens" – in which the neutron coordinates with respect to the center of the bunch change slightly, and the deviation of the velocity from the central value changes in the proportion to the distance to the center of the bunch. In the second drift segment, the bunch length decreases, and at a certain distance L_2 the bunch length reaches the initial value $\sim$10 cm.

The principle of operation of a magnetic lens is as follows. In a certain segment of the neutron guide, a magnetic field is produced that is uniform in space, but with its gradient directed along the neutron guide axis. When a neutron enters the magnetic field region, its kinetic energy changes by the value $U(\boldsymbol{r}, \boldsymbol{t}) = -\mu_n B(\boldsymbol{r}, \boldsymbol{t})$, where $\boldsymbol{r}$ is the neutron coordinate, μ_n is the neutron magnetic moment, $B(\boldsymbol{r})$ is the magnetic field at point r, and r is time. Neutrons of one polarization state are accelerated, while neutrons of the other polarization state are decelerated. Thus, only one spin component is used and the initial phase-space density is recovered for half of neutrons. We will see in Section 3.4. and Appendix A how to recover the initial phase-space density if needed. During the flight through the region of a spatially uniform field, the neutron moves at a constant velocity, and at the second boundary of the field, its energy changes again, but this time in accordance with the new value of the field, which has changed during the flight time. The difference between these two effects leads to the modulation of neutron velocity in accordance with the instance of time when it crosses the center of lens. The total action to the center of the bunch is equal to zero. The particles in the rear of the bunch experience acceleration, and those in the front slow down. Strong enough magnetic fields are hard to produce, therefore, note that if the magnetic field strength changes its value to the opposite during the neutron flight through the magnetic field zone, the required value of the magnetic field strength is minimal.

An alternative focusing upon the interaction with a moving material wall (grating) is studied, for example, in a series of works [15,16], or with a neutron spin-flip in the intense magnetic field [6,20]. Other methods of focusing can also be proposed, for example, using the reflection of VCNs from a moving wall.

3.4. VCN decelerator

The resulting VCN bunch must be quickly trapped non-adiabatically into a magnetic or material trap and adiabatically decelerated together with the trap. The fast trapping is important for decreasing losses in the phase-space density and an adiabatic deceleration of the trap does not affect the phase-space density. By the time the bunch reaches the beginning of the deceleration segment, a neutron-reflecting "wall" has already been formed and it moves with a velocity v_{S0}.

The material trap can be imagined in the form of an empty cola can without a lid on the side of the converter. Alternatively, it is sufficient to have only a flat bottom and the walls of the VCN specular guide would play the role of side walls of the trap. Note that an immobile material trap could only hold UCNs. To trap VCNs, one needs to move it with the bunch velocity and slow it down (for example, using a magnetic drive).

The principle of the magnetic wall is similar. It is not possible to provide a constant magnetic field strength high enough to decelerate VCNs. However, the use of a runaway magnetic wall, firstly, reduces the required field many times, and secondly, allows using a significantly larger pulsed magnetic field [23]. These gain factors are illustrated in Fig. 2 and explained below. The trap field is produced by a sequence of annular segments with length ΔL ($\Delta L \ll d$) adjusted to each other. Each segment is a conductor wound on the neutron guide and is powered from its own source of pulsed current with a duration of $\sim$1 ms. For a pulsed neutron source, the repetition rates of the current pulses and the source, $\nu_{\text{n.s.}} \sim 5$–15 Hz, coincide. For a continuous source, it can be selected from considerations of the energy efficiency of the magnetic system. The displacement of the magnetic trap along the guide axis is achieved thanks to a corresponding delay of the current pulses in successive segments. Let the magnetic field gradient acting on the neutron with the velocity v_{S0} be $\partial B/\partial z \sim 0.17$ T/cm, and the corresponding trapping maximum magnetic field $\sim(1.7+2.6)$ T. This field value accounts for both the potential and kinetic energy of neutrons in the trap that slows down a neutron bunch with the initial size of $\sim$10 cm at a constant deceleration $-10g$. The indicated magnetic field is somewhat redundant and is selected from the condition that the magnetic trap is capable of trapping all neutrons with any initial velocity and initial coordinate from the selected neutron bunch. The optimal value might be calculated from the condition of overlap of the phase space elements in the bunch before deceleration and in the bunch in the trap.

Moving a light material wall with a magnetic drive is not energy-intensive, but building a reliable mechanical system with a large number of rapidly moving parts is a difficult task. In the case of a magnetic trap, it is easier to build a system that works reliably for a long time, however, it is energy intensive and more expensive to operate. Note that the simultaneous use of material and magnetic traps can significantly reduce the requirements for the magnetic system. On the other hand, it could significantly increase the deceleration rate or/and increase the range of longitudinal velocities of trapped neutrons.

The dynamics of neutron motion during deceleration is easier to describe in the case of a material trap, the wall of which is "infinitely sharp". In this case, the boundaries of the region of stable motion are determined analytically. A neutron striking the wall at a velocity of Δv abruptly decreases it by $2\Delta v$. After that, the neutron begins to lag

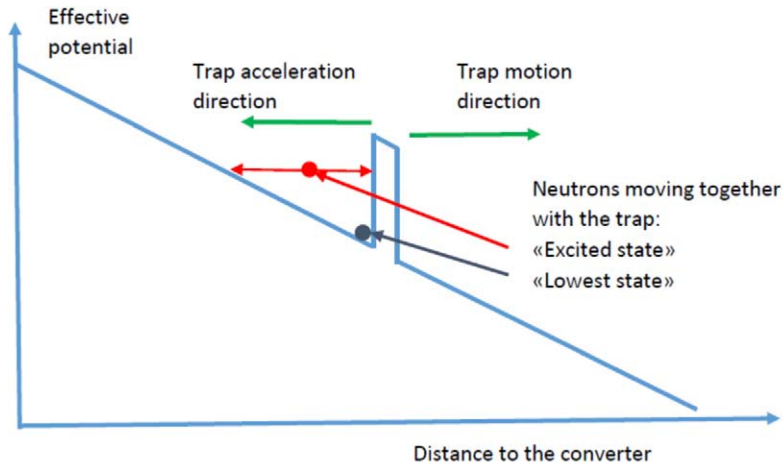

Fig. 2. Effective potential that traps the neutron bunch in the reference system associated with the runaway decelerating trap.

behind the wall, but due to the wall deceleration a, at some moment it starts to overtake the wall again. In the reference frame associated with the wall, the neutron motion is represented by oscillations in the potential well, schematically shown in Fig. 2. The effective ramp-down potential arises from the reference frame deceleration. The rectangular positive potential corresponds to the material wall with a critical velocity v_{lim}. The zero-energy neutron in the potential well, shown with a blue circle, does not move relative to the well. A neutron with some energy relative to the bottom of the potential well indicated by a red circle makes oscillatory movements in the potential well, indicated by the red arrows. The trapping potential is similar to that in the case of neutron whispering gallery [34].

From the analysis of Fig. 2, two important conclusions can be drawn. With a sufficiently long neutron guide: 1) a running away and decelerating trap can, in principle, decelerate neutrons of any initial velocity, 2) the trap height can be arbitrary lower than the initial VCN energy; it is determined only by the energy range of the trapped UCNs.

4. Accumulation of UCN bunches from different pulses of the pulsed neutron source

With the parameters of our numerical example, the neutron bunch length is $\Delta l \sim 10$ cm, and the velocity spread is $\pm v_{\text{lim}}$. At the guide diameter of $\sim$7 cm, the bunch volume $V_{\text{b}} \sim 3.6 \cdot 10^{-4}$ m^3 is insufficient for most experiments. To increase it, one needs to add sequentially UCN bunches coming from the guide. The method of adding the bunches is similar to pumping a volley ball with a hand pump. Its complete physical analogy is the method of accumulation of radioactive ions, considered in [30]. If we quickly remove the trap and close the UCN bunch, neutrons will be trapped in the accumulation volume and in the neighboring small segment of the guide. For this purpose, a magnetic or mechanical valve can be used. The fast valve is open during the arrival of an UCN bunch and closed the rest of the time. The valve actuation time constant should be noticeably shorter than the time of UCN transport with a characteristic velocity of $\sim$5 m/s over a distance equal to the size of the UCN bunch, which is $\sim$80 ms. Since the entire mechanism is located in an easily accessible area far from the neutron source and the time constants of its operation are relatively large, it is realizable.

Let new portions of neutrons N_{b} enter the accumulation volume for a long time. The number of accumulated neutrons N_{st} reaches saturation when, over the same period, the same number of neutrons is lost in the accumulation volume as arrived. Neutron losses are determined by two reasons: the finite storage time of neutrons τ_{st} in the accumulation volume, which leads to a relative decrease in the intensity $\Delta N/N_{\text{st}} = 1/\nu_{\text{n.s.}}\tau_{\text{st}}$ and neutrons escape from the accumulation volume towards the source when the valve is open, losses at which are $\Delta N/N_{\text{st}} = V_{\text{b}}/2V_{\text{st}}$; the factor 2 reflects the fact that only half of the neutrons in the volume V_{b} have velocities directed towards the neutron source. From the balance equation we get $N_{\mathrm{st}} = N_{\mathrm{b}}/(1/\nu_{\mathrm{n.s.}}\tau_{\mathrm{st}} + V_{\mathrm{b}}/2V_{\mathrm{st}})$. With conservative values $\tau_{\mathrm{st}} \sim 100$ s, $\nu_{\mathrm{n.s.}} \sim 10$ Hz and $V_{\mathrm{st}} \sim 0.36\ \mathrm{m}^3$, the number of accumulated neutrons in saturation will be approximately 700 times greater than the number of neutrons in one bunch.

In the case of a magnetic trap used for slowing down neutrons, the UCN density could be doubled by adding bunches of neutrons with opposite spin orientations in one volume in analogy to the process of adding cold neutrons in one volume considered in [52]. This does not contradict Liouville's theorem but has not yet been implemented with UCNs. The method of magnetized foils [41] could be used in principle to do this by adiabatically displacing UCNs of one polarization without affecting the UCNs with the other polarization. More details are given in Appendix A. Note that in the case of a material trap, both neutron polarizations are trapped simultaneously and adding bunches of neutrons with opposite spin orientations in one volume is not needed.

5. Parameters of the installation

The total guide length required to implement this method is about $L = L_1 + L_2 + (V_{S0})^2/2a + L_{\mathrm{ad}} \sim 25$ m, so that it can be placed in a standard experimental hall; L_{ad} is the length of the guide required for the bunch adiabatic capture into deceleration. The total time of flight of the bunch through the guide is $T = (L_1 + L_2)/(V_{S0} - V_{\mathrm{lim}}) + V_{S0}/a \sim 0.67$ s. At a frequency $\upsilon_{\mathrm{n.s.}} \sim 10$ Hz, 6–7 traps and, correspondingly, 6–7 neutron bunches are simultaneously found in the guide. The distance between the bunches changes from $\sim$5 m at the entrance to $\sim$0.5 m at the exit. The characteristic parameters of a UCN source with a magnetic trap from the considered numerical example are collected for convenience in the Table 1. They should be optimized for each project, taking into account the individual designs. The power released from the magnetic traps operation at room temperature is rather high, typically $\sim$10 kW per trap, and, therefore requires careful optimization and the search for the least energy-intensive solutions. One can use only each second, third or fourth burst of the neutron source and so on. This method conserves the same UCN density but allows to fill in only a proportionally smaller volume, which is acceptable for a fraction of typical UCN experiments.

6. Additional possibilities of the method

One can use a broader initial VCN spectrum employing a stronger magnetic field of the decelerating trap. This increases the bunch size, the number and volume of accumulated UCNs. After trapping such a broad neutron spectrum, the trap size increases adiabatically, its volume increases, and the velocities decrease in order to get the standard UCN spectrum. Note, however, that increasing the strength of magnetic fields can be associated with significant technical difficulties.

An alternative option is to convert UCNs (for instance, produced in a standing alone inexpensive UCN source of high phase-space density) to monochromatic VCNs or even cold neutrons by their acceleration in the analogous trap. The feasibility of building such a UCN source is becoming a hot topic; the first published example we are aware of is [46]; a few more configurations are discussed. In the long term this method may become an alternative to the construction of expensive standard neutron sources. In principle, the UCN density in a standing-alone dedicated UCN source can be significantly larger than the equilibrium UCN densities in cold sources of the most powerful modern neutron sources. Provided the acceleration of UCNs is not associated with significant losses in the phase-space density, one could obtain cold neutron pulses with record densities/fluxes without the need to build an expensive thermal neutron source. Note, however, that high neutron velocities require either an increase in the length of the accelerating segment in proportion to the square of the velocity, or an increase in the rate of acceleration. Both of these methods are resource-intensive, so the maximum achievable velocity is determined by a reasonable velocity/cost trade-off. At the acceleration rate considered above of $10g$, an accelerating system $\sim$1.25 km long is required to achieve a characteristic cold neutron velocity of $\sim$500 m/s. More details are given in Appendix B.

Table 1

The parameters of the UCN source are given only for the purpose of demonstrating its feasibility and should be optimized for each specific project involving precise parameters of the neutron source, precise technical arrangement of the proposed focusing/decelerating system, and the optimization of the two simultaneously. In particular, several parameters can be changed to facilitate the practical implementation of the proposed method, which, however, will lead to a decrease in performance of the UCN source. These parameters include: the magnitude of the magnetic field strength of the trap, the diameter of the neutron guide, and the fraction of neutron source pulses used. This analysis goes far beyond the scope of this conference contribution. Note that the considered parameters are close to those of the ESS spallation source ($\Delta\tau_{\text{n.s.}} = 2.86$ ms, $\nu_{\text{n.s.}} = 14$ Hz)

Source pulse duration, $\Delta\tau_{\text{n.s.}}$ (VCN)	ms	2
Converter thickness (solid ortho-deuterium), Δl	m	0.1
Converter diameter, d	m	0.07
Initial velocity of the bunch, V_{S0}	m/s	50
Length of the neutron bunch at the converter, l_{b}	m	0.1
Maximum velocity spread in the bunch, ΔV_0	m/s	± 6
Deceleration, a	m/s^2	10^2
Frequency of bunches, $\nu_{\text{n.s.}}$	Hz	10
Initial/final distance between bunches	m	5/0.5
Number of bunches in the deceleration segment		6–7
Magnetic field strength in the deceleration segment	T	4.3
Length of the deceleration segment, $(V_{S0})^2/2a$	m	12.5
Total length of the neutron guide, L	m	25
Time of flight of the bunch through the guide, T	s	0.67
UCN bunch volume, V_{st}	dm^3	0.36
Number of accumulated bunches		700

The method of increasing the UCN velocity to produce faster neutrons has already been studied in [29]. In contrast, the method for increasing the UCN energy proposed in this work preserves the density in the phase-space and can be considered as a logical continuation of this idea. Note that an increase in the velocity of all neutrons from some phase-space element and an increase in the energy of all neutrons from that element lead to different transformations in the phase-space. If an increase in velocity leads to an increase in the size of the bunch in space and, accordingly, to a decrease in the density in the phase-space (proportional to the ratio of the velocities), the method proposed here preserves the density in the phase-space.

7. Conclusion

We propose the method for producing UCNs based on the VCN deceleration by a decelerating trap. A high conversion efficiency of VCNs into UCNs can be achieved.

For pulsed neutron sources, the UCN density in the phase-space can approach the initial peak density (the idea of F.L. Shapiro); the maximum gain factor in the UCN density compared to the (otherwise used) mean UCN density is equal to the reciprocal duty cycle of the neutron source. Long pulses (as, for instance, at ESS) provide a simpler implementation due to larger neutron bunches and slower manipulations with them. On the other hand, short pulses (as, for example at IBR2 and projected IBR3) might provide a larger gain provided the efficient manipulation with short UCN pulses. Accumulation of different UCN bunches produced from different pulses of the neutron source allows to increase the total volume, which can be filled in with UCNs with this density by a factor of $\sim 10^3$ compared to the single bunch volume; this gain factor can nearly approach the UCN storage time divided by the frequency of the pulsed neutron source.

The proposed method is also of interest for continuous neutron sources, in particular, for the PF2 facility [49] at ILL, due to the most efficient conversion of VCNs into UCNs. The neutron phase-space density, even in the existing liquid-deuterium source of cold neutrons [2] ($>10^3$ UCN/cm^3), is an order of magnitude higher than the best worldwide achieved today. The use of an optimized (solid-deuterium) converter and an efficient (nanodiamond) VCN reflector would significantly increase this estimation. A loss-free extraction and deceleration of VCNs would provide an UCN source with a much higher performance than it is currently.

By analogy with the proposed VCN deceleration method, an accelerating trap converts UCNs to faster neutrons of an arbitrary velocity while preserving the initial high phase-space density produced in a standing alone inexpensive high-density UCN source.

Some of the methods for manipulating the elements of the phase-space occupied by neutrons have not yet been implemented; therefore, their analysis, modeling, implementation and optimization are important tasks that should be solved before starting any implementation of the proposed method as a whole. In particular, a prototype of the entire system can be built using a beam of hydrogen atoms with the same initial velocity: since their magnetic moment is three orders of magnitude higher, that is, the required magnetic field strengths are three orders of magnitude lower.

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Appendix A. A possibility of increasing the density by adding UCNs with opposite polarizations

Some experiments, such as searching for a non-zero electric dipole moment of the neutron and spin-dependent extra fundamental interactions, spin-echo spectrometry, storing polarized neutrons in magnetic traps, studying the interaction of UCNs with magnetized surfaces, etc, use polarized neutrons. In this case, no additional transformation of the phase-space is required because the UCNs are already polarized.

Other types of experiments, such as measuring the lifetime of a neutron in material traps, studying the interaction of UCNs with a surface, neutron optics, using gravitational quantum states, (n,γ)-surface spectroscopy, etc, would benefit from doubling the UCN density due to the addition of UCNs with opposite polarizations in one volume, provided that the key parameter is the density, and not the total number of UCNs.

The Liouville theorem does not prohibit the addition of UCN densities with opposite polarization directions in one spatial volume. Neutron of the opposite polarizations occupy different phase-space volumes, corresponding to different polarizations. Indeed, the overlap of these volumes on one spatial coordinate does not result in the compression of the resulting phase-space volume as the total phase-space volume didn't change. We illustrate this statement with the following example.

Imagine a volume separated by magnetized foils as shown in Fig. 3. Volume "1" is filled with UCNs of one polarization. Volume "2" is filled with UCNs of opposite polarization. The foils are magnetized in such a way that they transmit UCNs of one polarization, but block UCNs of the opposite polarization. If the arrows of UCN polarization and foil magnetization are parallel in Fig. 3, then the foil is transparent, and if they are antiparallel, then it is reflecting.

If we now adiabatically and simultaneously move the two foils to the right, as shown in Fig. 3, most of the UCNs will be in one half of the volume, and the density in it will almost double. At the initial moment of time, UCNs with "up" polarization (red circle with an arrow pointing up) fill volume "1", and UCNs with "down" polarization (green circle with arrow pointing down) fill volume "2". The foil indicated by green line with an arrow reflects UCNs with "down" polarization, but is transparent to UCNs with "up" polarization. The foils indicated by red lines with arrows reflect UCNs with "up" polarization, but are transparent to UCNs with "down" polarization. Now, adiabatically and parallel to each other, move the two red foils to the right, as shown by the black dotted arrows. UCNs from volume "1" move to volume "2", and UCNs, which were in volume "2" initially, remain there.

This example is just an illustration of the principle possibility. Such a scheme for adding densities has never been implemented before, so its effectiveness is still difficult to assess. The main concern is the losses associated

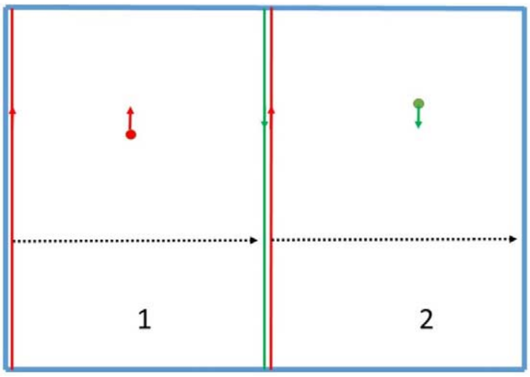

Fig. 3. A simplified illustration of the principal possibility of doubling the UCN density by adding UCNs with opposite polarization directions in one volume. The storage volume is shown with thick blue line. Magnetized foils can slide along the inner walls, shown by red and green lines with arrows.

with the UCN absorption and up-scattering in the magnetized foils. To minimize this effect, one should carefully design the foils and decrease the number of subsequent penetration by optimizing the geometry of the traps and the foils. To ensure the adiabaticity condition, the number of UCN passages through the (green) magnetized foil must be "much greater than unity", say 10. If its thickness is, say, 10 μm, the total UCN losses will be on the order of 20–30% percent of the UCN of one polarization, or 10–15% from the total density. Still there is a serious problem of designing the magnetic coating in such a way that magnetic potential compensates precisely nuclear potential (for the corresponding neutron polarization), so the method would not work for the fraction of slowest UCNs.

This method has never been discussed for neutrons, but has many well-known analogies in fields as diverse as electronics, chemistry, transmission of cell membranes, transmission of filters, and so on. A magnetized foil is a "semiconductor" for UCNs.

Appendix B. A possibility of producing monochromatic neutrons with a high density in phase-space

An obvious logical continuation of the VCN deceleration method is the reverse process of UCN acceleration by an oncoming accelerating trap, as shown in Fig. 4. The effective linear growing potential arises due to the acceleration of the coordinate system. A rectangular positive potential corresponds to a magnetic or material wall. For simplicity, edge effects, which are necessarily present in the case of a magnetic potential, are not indicated. A neutron with zero energy in a potential well shown as blue circle does not move relative to the well. A neutron with some energy relative to the potential well indicated by red circle oscillates in the potential well, as indicated by red arrows. For clarity, the height of the wall potential is disproportionally increased.

In principle, it is possible to obtain neutrons of any energy with the same high density in the phase-space as the initial UCN density in the phase-space. High velocities require either an increase in the length of the neutron guide in proportion to the square of the velocity, or an increase in the acceleration rate. Both of these methods are resource-intensive, so the maximum achievable velocity is determined by a reasonable velocity/cost trade-off. At the above acceleration rate of $10g$, to achieve a characteristic cold neutron velocity of 500 m/s, an accelerating system 1.25 km long is required. Under certain conditions, this may be justified. In particular, the use of ultrahigh densities of UCNs obtained in a specialized and relatively inexpensive low-power UCN source to produce faster neutrons of the same density in the phase-space can become in long term an alternative to the construction of expensive standard neutron sources.

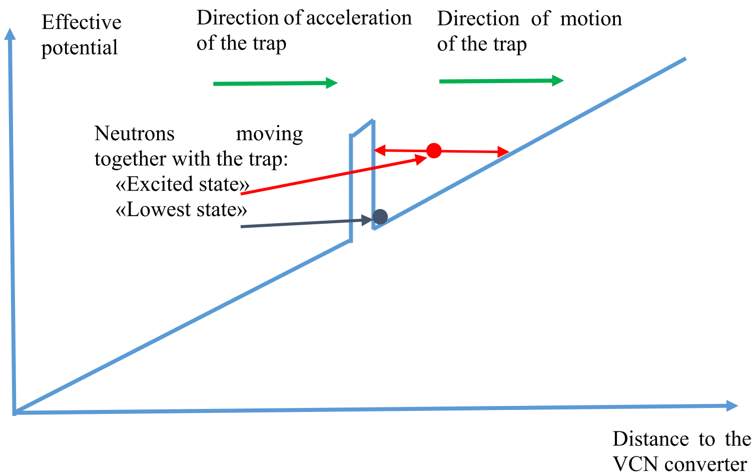

Fig. 4. Effective potential locking the neutron bunch in the coordinate system associated with the running-away accelerating trap.

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