We propose a new concept for ultracold neutron (UCN) production using a compact neutron source. The essential idea is to surround a volume of superfluid helium with a “supercold” moderator in the vicinity of a low-radiation neutron production target from (p,n) reactions. The supercold moderator should possess a peak brightness near the single-phonon excitation band of the superfluid helium for UCN at 1 meV. This would maximize UCN production in the UCN converter with the limited flux available from a compact neutron source. We report the conceptual design of a compact UCN source system to demonstrate that such a small UCN source can be operated at a compact pulsed neutron source facility. The estimated UCN production rate is as high as ~ 80 UCN/cc/s when the brightness of the supercold moderator peaks at 1 meV. The main advantages of this compact UCN source include the competitive rate of UCN production, the very low radiative and thermal loads on the UCN source, the relatively low cost of operation, and easy accessibility to the experimental area. Although no such supercold moderator has yet been demonstrated, promising materials for the supercold moderation medium exist.
INTRODUCTION

Neutrons with kinetic energy of less than 250neV are normally referred to ultracold neutrons (UCNs). These ultra low-energy neutrons are totally reflected from the surfaces of certain materials with high optical potential energy ($V_F$) at any incident angle. This allows one to store UCNs in a material container for times which are virtually limited only by the neutron lifetime of about 880 seconds\textsuperscript{[1]}. UCNs can also be highly polarized by passing them through magnetic fields and can be trapped by strong magnetic field gradients. Due to these favorable properties, UCNs have been employed as a sensitive probe in many physics experiments involving the testing of fundamental theories such as searching for a neutron electric dipole moment (nEDM)\textsuperscript{[2, 3]}, measuring the neutron lifetime\textsuperscript{[4–6]} and neutron decay correlation coefficients, searching for axions and axion-like particles\textsuperscript{[7–9]}, and searching for certain forms of dark matter\textsuperscript{[10]}.

The brightest UCN sources operate in what is termed the “superthermal” mode, in which neutrons do not come into thermal equilibrium with a moderator\textsuperscript{[11]}. In this case, cold neutrons are incident on a medium held at a low temperature (a UCN converter) and lose their energy in one step by exciting the collective modes of the medium, conserving energy and momentum, and coming nearly to rest in the medium. Thereby they become UCNs. The upscattering of UCNs to higher energy states can be suppressed by lowering the temperature of the converter medium such that no elementary excitations are present, and the loss of UCNs from nuclear absorption mainly limits the increase of the UCN density in the converter. Superfluid $^4$He\textsuperscript{[12]}, solid D$_2$\textsuperscript{[13]}, and solid O$_2$\textsuperscript{[14]} are the most commonly tested moderating media for use as UCN converters thus far due to their zero or very low nuclear absorption cross-sections and the existence of elementary excitations (phonons, magnons) whose dispersion relation intersects that of the free neutron.

A neutron moderator can increase the phase space density starting from an initial state without forcing the neutrons to come into thermal equilibrium with the moderator. Thermal equilibrium of the moderating medium allows one to use a detailed balance to establish the relationship between the scattering kernels for the forward and reverse directions as $v w(i)\sigma_s(i, i_0) = v_0 w(0)\sigma_s(0, 0)$ or, in terms of the initial and final energies,

$$\left(E_i + \Delta\right)\sigma(E_i + \Delta \rightarrow E_i) =$$

$$\exp\frac{\Delta}{kT} E_i\sigma(E_i \rightarrow E_i + \Delta).$$

If we consider the extreme case of a cold moderating medium at a temperature of $T \rightarrow 0$ with only two energy states separated by $\Delta \gg kT \rightarrow 0$, the scattering kernel for the second (upscattering) term in the integral equation for the phase space density becomes negligible and disappears at $T = 0$ due to the conservation of energy. If the initial phase space distribution is characterized by a Maxwellian neutron flux at a temperature $T_n \gg \Delta$, the phase space density will increase to a value proportional to $(E_i/\Delta)\exp(\Delta/kBT)$, thereby increasing exponentially as a function of the temperature. This mechanism is known as the “superthermal” principle in the field of ultracold neutron moderation\textsuperscript{[15]}, which concentrates on that subset of the neutron phase space distribution with final energies $E_i$ near zero. It emphasizes especially those scattering events in which the neutron loses essentially all of its energy in one collision. These events are often dominated by coherent elementary excitations in the medium, whose dispersion relations define which subclasses of neutrons from the initial distribution can conserve energy and momentum during the collision and be brought to rest. Liouville’s theorem is violated in this case by the avoidance of thermal equilibrium: the creation of entropy in the moderating medium during the neutron moderation process is removed by the refrigerator that maintains the $\Delta \gg T$ condition.

For superfluid $^4$He, only a certain energy range of cold neutrons play an important role in UCN production due to the well-known, sharply-defined phonon-roton dispersion curve in superfluid $^4$He\textsuperscript{[16]}\textsuperscript{[10]}. The production mechanism for UCN in superfluid $^4$He can be decomposed into two distinct processes: single-phonon excitation and multi-phonon excitation. The multi-phonon process involves a broad range of neutron dynamic structure factor $S(Q, \omega)$ in the energy-momentum space. The neutron dynamic structure factor for single-phonon excitation is sharply defined and forms nearly a delta function in the dispersion curve\textsuperscript{[16, 17]}. Owing to this characteristic of superfluid $^4$He as a UCN conveter, only a very narrow energy range of cold neutrons near 1meV can be downscattered into the UCN energy regime through single-phonon excitation. The single-phonon process is more than one order of magnitude more probable than the multi-phonon process at the $T \rightarrow 0$ limit\textsuperscript{[17]}. The upscattering of UCN is a major source of UCN loss after their production in a superthermal moderating medium. In this process, UCNs absorb energy from the thermally-excited elementary excitations of the medium and escape. The UCN loss from this process in $^4$He was calculated long ago by Golub\textsuperscript{[18, 19]}. This loss mechanism is proportional to the temperature via $\frac{1}{T_{ph}} \sim T^7$ in the temperature regime 0.5K $\leq T \leq 1.5$K. The temperature of superfluid helium should therefore be kept as low and as stable as possible to minimize the UCN loss. There are other
FIG. 1: Schematic of the compact UCN source. A proton beam is incident on a Be target. A heavy water reflector surrounds the target and solid methane cold moderator. The cold moderator surrounds the UCN production volume filled with superfluid $^4$He.

less important loss mechanisms from the UCN moderator due to absorption by any residual $^3$He in the liquid, wall losses, or inelastic scattering by He gas molecules, as well as two-phonon excitation processes. The last two factors can also be reduced with a lower and stable temperature of the superfluid $^4$He.

One, therefore, wants more cold neutrons near 1meV feeding the UCN moderator and stable low temperature operation for a superfluid $^4$He superthermal source. For UCN sources cited at spallation or reactor-based cold neutron facilities, however, it is quite challenging to meet these conditions simultaneously. Neutron spectra from liquid H$_2$ or D$_2$ cold moderators at these neutron facilities normally have peak energy which are far higher than 1meV and therefore do not optimally match the single-phonon excitation band of superfluid $^4$He. Neutrons away from this energy introduce an additional thermal heat load on the moderator vessel and medium through neutron capture reactions. If one is too close to the neutron source, the heat load from fast neutrons and gammas emitted from the reactor core or spallation target becomes prohibitive.

In this paper, we present the concept of a superfluid $^4$He UCN moderator fed by a compact neutron source. The much less intense radiation coming from the production target of a compact neutron source presents a sufficiently low heat load on the cold moderator feeding the UCN moderator to imagine the operation of a new type of “supercold” moderator to cause the peak energy of the cold neutron flux to approach 1meV. As shown later, if a supercold neutron moderating medium can be developed, the UCN source proposed here can produce enough UCN to be useful for research work without imposing prohibitive cryogenic or radiation safety requirements.

COMPACT NEUTRON SOURCE

The compact neutron sources in this paper are small accelerator-based pulsed cold neutron sources. The basic concept of a compact neutron source is to produce neutrons from (p,n) reactions in targets such as Li or Be and to moderate them to the $\sim$1meV energy range with cold moderator materials[20]. Such compact neutron sources are realized with pulsed proton accelerators with low beam energy at $\sim$MeV and currents of tens of $\sim$mA. The neutrons produced from MeV (p, n) reactions in Li and Be targets are less energetic than those at spallation or reactor sources, and the energies of these neutrons are below the threshold of many secondary nuclear reactions. The compact neutron source can, therefore, be operated with much less onerous shielding requirements.

Given that the activation from the reaction in the neutron production target is very low, the compact source has the capability to accommodate new materials for slow neutron moderation which may not survive intact in environments with higher levels of radiation. For example, the Low Energy Neutron Source (LENS) at Indiana University has been successfully operating a solid methane cold moderator, which is the brightest slow neutron moderator medium known thus far, well into the solid phase at 4K $\sim$20K[20, 21]. We can operate a solid methane moderator at LENS in spite of the well-known fact that radiation damage in solid methane can cause the moderator to explode. The radiation field produced in LENS is below the threshold of the catastrophic recombination process of radiation defects which occurs in methane.

The key idea behind efficient UCN production in a compact neutron source is to maximize the advantage one can gain from a “supercold” moderator medium. Because the moderating power of certain new materials under consideration can be greater than those used in a spallation source such as liquid D$_2$, H$_2$, or D$_2$O, they can shift more neutrons down into the energy regime close to the relevant energies of elementary excitations in the UCN converter material.
A conceptual schematic of the compact UCN source is shown in Fig. 1. The configuration of the target, moderator and reflector (TMR) for the LENS neutron source, similar to the source we have in mind for neutron generation in this case, can be found in the literature [20]. The TMR configuration has been slightly modified from this design for UCN production.

![Cold Neutron Flux in UCN volume](chart1)

(a) Cold neutron flux at the UCN converter volume at the maximum UCN production rate

![Cold neutron flux and S(λ) of superfluid 4He as a function of the neutron wavelength](chart2)

(b) Cold neutron flux and S(λ) of superfluid 4He as a function of the neutron wavelength

**FIG. 2:** Cold neutron spectra accumulated in the UCN converter volume from solid CH₄ and methane clathrate hydrate cold moderators

In this study, we assume a 13MeV proton beam with 25mA beam current incident on a Be target with a 0.6 msc pulse-width and at a frequency of 20Hz. Recently, there are a number of projects being considered to improve the power levels of proton beams to 50 kW or more in the energy range of 2 – 50MeV for compact neutron sources around the World [22, 23]. Metallic Be was chosen as the target material due to its high neutron yield, high melting point, good mechanical strength, and simplicity of handling. The selected thickness of the Be target is 1.1mm. The target thickness must be less than the range of the protons, which is around 1.3mm for a 13MeV proton beam in Be, in order to avoid the problems of hydrogen embrittlement of the Be. The neutron yields have been empirically measured as 7.6 × 10⁻³n/p up to 23MeV. The estimated total neutron from the Be target is \( \sim \) 1.43 × 10¹³n [20]. D₂O at room temperature is chosen for the reflector, as it preserves more neutrons to be feed into the supercold moderator volume mainly due to the very small neutron absorption cross-section of deuterium.

We simulate two choices for the slow neutron moderator to feed the superfluid ⁴He UCN converter. One choice is solid methane in phase II (4K ~ 20K), which is well known as one of the brightest cold moderator materials discovered thus far [24]. Methane molecules possess rotational excitation modes which are free to rotate even at very low temperatures below the solidification temperature of 20K [25]. The neutron dynamic structure factor \( S(Q, \omega) \) of solid methane in this temperature regime was developed and tested for the LENS source [21, 26]. The neutron energy spectra calculated from a MCNPX simulation with this \( S(Q, \omega) \) result in perfect agreement with the spectra from one of LENS neutron beamlines for moderator temperatures of 20K and 4K. This \( S(Q, \omega) \) was also independently tested in a course of simulations conducted for a proposed UCN source based on an extracted thermal neutron beam [27].

In our simulations, we chose a 2mm-thick high-purity aluminum housing to contain the solid methane. The moderator volume has a cylindrical cup shape, as shown in Fig. 1. This geometry is designed to wrap around the UCN converter to deliver maximum cold neutron flux into the UCN production volume.

We also simulated methane clathrate hydrate at 4K as a possible medium for the “supercold” moderator. Methane clathrate hydrate is a nonstoichiometric inclusion compound of methane within the host framework of water cages in a unit cell [28]. These cages allow for nearly free rotation of methanes molecule even at low temperatures. The molecular motion is quantitatively described as a single-particle quantum rotor in a weak orientational potential. The free rotational mode of the methane molecule is known to provide a very strong down-scattering channel for neutrons [29].

For a Monte Carlo simulation of the cold neutron flux using the MCNPX simulation package, we combine a special scattering kernel of solid methane at 4K, which possesses only “free rotations” of methane molecules, with an existing scattering kernel describing heavy water (D₂O) to mimic the methane clathrate hydrate [26]. Although the \( S(Q, \omega) \) of methane clathrate hydrate has not yet been measured to the best of our knowledge, we think that this scattering kernel is a reasonable guess for \( S(Q, \omega) \) that is close enough for our purposes.
We estimated the cold neutron spectra accumulated in the UCN converter volume from the two cold moderator media types i.e., solid methane and methane clathrate hydrate. The temperature of all of the cold moderator media was assumed to be 4K. Fig. 2(a) shows the neutron spectra accumulated in the UCN converter volume when solid methane and methane clathrate hydrate are employed as the cold moderator media. The solid methane cold moderator produces a neutron spectrum with the peak spectrum energy at $\sim 1.55$ meV with $\frac{d\Phi}{d\omega} \approx 1.12 \times 10^9 \text{h/cm}^2/$s/meV of differential neutron flux. When using methane hydrate clathrate as the cold moderator, neutron flux is produced with the peak spectrum of $\frac{d\Phi}{d\omega} \approx 1.54 \times 10^9 \text{h/cm}^2/$s/meV in neutron energy at $\sim 1.02$ meV. This peak energy is very close to the energy where superfluid $^4$He has the highest intensity of the density of state, $S(\lambda)$, in the dispersion curve. Fig. 2(b) shows the neutron spectra as a function of the neutron wavelength overlapping $S(\lambda)$ of superfluid $^4$He when the UCN production rate is maximized in each case. The numerical data of $S(\lambda)$ at 0.5K in SVP(saturated vapor pressure) was sourced from the literature [17].

Using the result of cold neutron flux from this simulation, we estimated the UCN production rate as a function of the cold moderator thickness at the bottom and on the side. A detailed description of UCN production with the cold moderators will be given in the next section. The UCN production volume is filled with superfluid $^4$He at 0.8K in a container made of an aluminum tube with a total length of $\sim 1.0$ m and an inner diameter of 80 mm. The thickness of the tube is assumed to be 2 mm. The neutron optical potential for aluminum is $V_{\text{Al}} = 54$ meV. If we apply a beryllium (Be) coating on the inner surface of the aluminum tube, the optical potential of the UCN storage volume will increase to the Fermi potential of Be of $V_{\text{Be}} = 252$ meV [20]. This will not only enhance the UCN storage density significantly but will also extend the UCN storage time because the optical potential of the UCN storage volume will be increased to the Fermi potential of Be.

A lower temperature of the UCN converter volume can be achieved with a $^3$He/$^4$He refrigerator. In this case, we assume that the tube containing the $^4$He UCN converter is connected to a heat exchanger made of high-purity copper tubing with a diameter identical to that of the UCN converter. The Be coating can be also applied to the copper tubing to prevent any UCN leakage through the inner surface of the copper tube. If the temperature of superfluid He is kept at 0.8K, the storage time of the UCN is ideally very close to the neutron life time. The estimated $^4$He circulation rate is approximately $0.04 \sim 0.06$ mol/min to maintain the UCN volume at the designated temperature.

**UCN PRODUCTION AT A COMPACT NEUTRON SOURCE**

UCN production in superfluid $^4$He is based on the energy-versus-momentum relationship of the superfluid $^4$He. From the coherent inelastic scattering of the incident cold neutrons with energy $E$, and momentum $k$ down to energy $E'$, momentum $k'$, the production rate per unit volume is determined from the literature [17, 31]

\[
P_{\text{UCN}}(V_c) = \frac{\int_{0}^{\infty} dE \int_{0}^{V_c} N \frac{d\phi}{dE} \frac{d\sigma}{dE'} (E \rightarrow E') dE'}{\int_{0}^{\infty} dE dE'},
\]

where $\frac{d\phi}{dE}$ is the differential incident flux of the cold neutron, $N$ is the number density of $^4$He, and $\frac{d\sigma}{dE'}$ is the differential cross-section for inelastic neutron scattering. The critical potential energy $V_c$ of the UCN is given by the relative optical potential of the UCN container from the Fermi potential of superfluid $^4$He. The differential cross-section is given by

\[
\frac{d\sigma}{dE} = 4\pi b'^2 k' \frac{\hbar}{k} S(Q, \hbar\omega),
\]

where $b$ is the bound neutron scattering length of $^4$He, $\hbar \omega = E - E'$ is the energy transfer, $Q = k - k'$ is the momentum transfer, and $S(Q, \hbar\omega)$ is the dynamic structure function evaluated in the energy-momentum space for free neutrons. For superfluid $^4$He, one can write Eq. (2) as

\[
P_{\text{UCN}}(V_c) = N\sigma V_c \frac{k_0}{3\pi} \int_{0}^{\infty} \frac{d\phi}{d\lambda} s(\lambda) d\lambda,
\]

where $\sigma$ is the bound neutron scattering cross section of $^4$He. The scattering function of superfluid $^4$He is defined as a function of the incident neutron wavelength $\lambda$,

\[
s(\lambda) = \hbar \int S(Q, \hbar\omega) \delta(\hbar\omega - \hbar^2 k^2 / 2m_n) d\omega,
\]
where $Q = k = 2\pi/\lambda$ with the assumption of $k' \ll k$. The scattering function can be divided into two parts, single-phonon and multi-phonon parts, as $s(\lambda) = s_{\text{single}}(\lambda) + s_{\text{multi}}(\lambda)$.

The single-phonon UCN production rate found in the literature\[17, 31\] gives,

$$P_{\text{single}}(V_c) = N\sigma\left(\frac{V_c}{E^*}\right)^{3/2}\frac{\lambda^*}{3}\beta S^* \frac{d\phi}{d\lambda}|_{\lambda^*}, \tag{6}$$

where $\lambda^* = 2\pi/q^*$ is the neutron wavelength at the intersection of the dispersion curves of the free neutron and the helium ($q^* = 0.706\text{Å}^{-1}$ for SVP), and $S^* = \hbar\int S(Q, \omega)d\omega$ denotes the intensity due to single-phonon emission. In addition, $\beta = \frac{v_1}{v_2 - v_3}$ is the Jacobian factor.

For the Be coated UCN converter, the critical potential energy $V_c$ is defined as $V_c = V_{\text{Be}} - V_F(^4\text{He}) = 232\text{meV}$. This yields the single-phonon production rate as

$$P_{\text{single}}(V_c) = 4.93097 \times 10^{-8} \frac{\text{A}}{\text{cm}} \frac{d\phi}{d\lambda}|_{\lambda^*}, \tag{7}$$

where $\frac{d\phi}{d\lambda}$ is the differential cold neutron flux near $\lambda = 8.9\text{Å}$.

FIG. 3: Dimensions of the cold moderator volume, side thickness $s$ and bottom thickness $b$, varied for the maximum UCN production rate

To investigate the UCN production rate as a function of the cold moderator geometry, we varied the bottom thickness $b$ and side thickness $s$ of the cold moderator volume. As expressed by Eq\[4\] the UCN production rate is defined by the integral flux of the incident cold neutron. The proposed concept enables the feeding of cold neutrons from a broad angular distribution to the UCN production volume. In our previous study of a cold neutron moderator for LENS, it was revealed that the optimal thickness of a solid methane moderator is close to 2cm. In this study, the bottom thickness $b$ is fixed at either 1cm or 2cm. In each configuration of the bottom thickness, the side thickness $s$ varies from 0.5cm to 2.3cm to determine the optimal thickness of the side for maximum UCN production.

The geometry and position of the UCN production volume itself are fixed in this study. The inner diameter of the superfluid $^4\text{He}$ bottle is 80mm and the total length of the tube is about 1m. The total volume of the liquid $^4\text{He}$ bottle is $\sim 5320\text{cc}$. The area surrounded by the cold moderator is $\sim 26.8\text{cm}$ long from the bottom end. Therefore, the volume involved in UCN production is close to $1347\text{cc}$. The rest of the tube volume is considered as the UCN storage volume despite the absence of a geometrical change.

Fig. 4a shows the UCN production rate as a function of the bottom thickness $b$ and side thickness $s$ of the solid methane cold moderator at 4K. When the bottom thickness $b$ is fixed at 1cm, the UCN production rate is as high as $54\text{UCN/cc/s}$ with the side thickness $s$ close to 1.4cm. However, the UCN production rate can reach $56\text{UCN/cc/s}$ when the bottom thickness is fixed at 2cm and the side thickness is between 1.3 and 1.4cm. With methane clathrate hydrate cold moderator at 4K, the UCN production rate increases to $80\text{UCN/cc/s}$ when the bottom thickness $b$ is fixed at 1cm and the side thickness $s$ is between 0.7 and 0.9cm as shown in Fig\[4\]. The UCN production rate shows a similar trend, but the rate declines to $76\text{UCN/cc/s}$ when the bottom thickness $b$ is fixed at 2cm.

Fig. 5 shows the rate of UCN production from single-phonon excitation in Eq\[7\] over the total UCN production in Eq\[4\] as $\text{UCN}_{\text{ph}}/\text{UCN}_{\text{tot}}$ in both cases. When solid methane is used as a cold moderator, the contribution of the single-phonon excitation channel to UCN production varies from 85% to 90%. However, this rate increases to 93% and even to 95% when methane clathrate hydrate is used as the cold moderator. In both cases, single-phonon excitation is the dominant process for UCN production over the multi-phonon process in terms of this concept, mainly because the cold neutron spectrum produced from both cold moderators has a peak energy near $\sim 1\text{meV}$, as indicated in Fig\[2\].
After the UCNs are produced, the accumulation of UCNs for a sufficiently-long time in the superfluid $^4$He volume is in principle possible due to the zero nuclear absorption cross section of $^4$He. If the upscattering of UCNs is sufficiently suppressed by lowering the temperature of $^4$He below 0.8K, as mentioned earlier, the UCN storage time could be several hundred seconds. However, many previous experiments showed that it is quite difficult to reach several hundred seconds of UCN storage time, mainly due to the collision between the UCNs with the inner surfaces of the storage volume. If we assume a UCN storage time of $\tau \approx 50$sec for practical applications, the UCN density becomes $\rho = P \times \tau \approx P \times 50$sec. From the maximum UCN production rate, $P = 80$UCN/cc/s, the maximum UCN density we can expect from this study is approximately $\rho = 4000$UCN/cc. Because we assumed a UCN production volume of 1347cc, the total number of UCN produced in the UCN converter can be as high as $N_{\text{converter}} \sim 5 \times 10^5$UCN.

For the extraction of UCNs, a vertical extraction method introduced in the literature[30] could be applied. A vertical extraction method of UCNs from a converter was successfully demonstrated in recent experiments[32, 33]. The main components necessary to realize vertical extraction are a short vertical section of the neutron guide located on top of the UCN converter and a cold valve that causes the UCNs to accumulate in the converter before they are extracted. Those components can be installed at the end of the UCN storage volume and operated with minimal temperature fluctuation. The efficiency $\epsilon$ of UCN extraction through the vertical extraction method can be expected to be as high as 40% of UCNs accumulated in the storage volume[32]. Therefore, the total number of UCNs one can extract from this study is approximately $\rho = P \times \tau \approx P \times 50$sec. From the maximum UCN production rate, $P = 80$UCN/cc/s, the maximum UCN density we can expect from this study is approximately $\rho = 4000$UCN/cc. Because we assumed a UCN production volume of 1347cc, the total number of UCN produced in the UCN converter can be as high as $N_{\text{converter}} \sim 5 \times 10^5$UCN.

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estimate at the end of the extraction line is as high as \( N_{\text{extraction}} = \epsilon \times N_{\text{converter}} \approx 2 \times 10^6 \text{UCN} \) when using this concept.

RADIATION HEATING

The heat loads on the UCN volume and the cold moderator volume in each setup were also studied from MCNPX. With regard to the heat load on the superfluid \(^4\text{He}\), the total heat load including the heat load from charged particles was estimated with MCNPX by tallying the energy deposition from the neutrons. Decay gamma and beta heating from activated aluminum are not included in the MCNPX calculations.

Fig.6 shows the heat load on the UCN converter volume in the two different moderator cases of, solid methane and methane clathrate hydrate at 4K. Even with different thicknesses on the side and bottom of the moderator, the overall heat load on the UCN converter volume is approximately 22 mW or less in both cases. This extremely low heat load on the UCN converter volume makes it possible to operate the UCN source for longer time with reduced amounts of \(^3\text{He}\) circulation for cooling.

The heat load on the cold moderator volume is also estimated, as shown in Fig.7. As side thickness becomes thicker, the overall heat load also increases to 450mW in the case of solid methane, and to 300mW in the case of methane clathrate hydrate. For the solid methane moderator, the thermal load at the optimal thickness for maximum UCN production is as low as 350mW. In the case of methane clathrate hydrate, the thermal load drops to 200mW at the optimal thickness for maximum UCN production. Because the thermal load on the cold moderator in both cases remains well below 400 mW, it is still possible to run the cold moderator even with a refrigerator with less than 1W of cooling power at 4K.

![Heat Load on UCN Volume](image)

(a) Solid CH\(_4\) at 4K  
(b) Methane clathrate hydrate at 4K

FIG. 6: Cold moderator thickness-dependent heat load in the superfluid \(^4\text{He}\) UCN converter with solid CH\(_4\) and methane clathrate hydrate as the cold moderators

CONCLUSION

We proposed a new concept of UCN production at compact neutron sources. We established a MCNPX model for a compact UCN source with superfluid \(^4\text{He}\) as a UCN converter surrounded by a layer of cold moderator volume. The cold moderator volume is filled with examples of “advanced” and “supercold” moderator materials at 4K, sold methane and methane clathrate hydrate. The UCN production rate and the cold neutron flux were estimated for both cases from the MCNPX model.

Based on a Monte Carlo simulation with MCNPX, the UCN production rate is as high as 56 UCN/cc/sec with solid methane as a cold moderator and 80 UCN/cc/sec when methane clathrate hydrate is employed as a cold neutron moderator. More than 85\% of UCNs were produced through single-phonon excitation in superfluid \(^4\text{He}\) in both cases. The thermal load on the UCN converter volume is as low as 20mW with both cold moderator materials. The heat
FIG. 7: Cold moderator thickness-dependent heat load with solid CH\(_4\) and methane clathrate hydrate as cold moderators

The heat load on the cold moderator is less than 400mW. This very low heat load enables the operation of the UCN converter with a minimal amount of \(^3\)He circulation.

Our estimation showed that UCN production at a compact neutron source is not only competitive with other leading UCN sources around the World in terms of the UCN production rate, but is also advantageous in terms of long-term operation as well as a low operation cost.

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