A consideration of cold neutron source for KENS-II

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ABSTRACT: The importance of a coupled cold moderator for small angle neutron scattering experiments with pulsed neutrons is discussed in connection with a cold neutron source for KENS-II.

Introduction

All the cold neutron sources presently in operation at pulsed spallation neutron facilities are decoupled moderators for relatively short pulse uses. Small angle scattering (SANS) of polarized and unpolarized cold neutrons is one of the most important fields of research using cold neutrons–not only in steady sources, but also in pulsed ones. However, it is believed that such experiments with a pulsed neutron source are not as favorable as with a high flux reactor. In these experiments the pulse width from such moderators is short enough for the required wavelength resolution, but the time-averaged intensity of cold neutrons is not adequate compared with that from a high flux reactor.

Table 1 compares some important parameters of cold neutron sources at the spallation neutron facilities with those at the ILL. Time-averaged cold neutron fluxes from the existing pulsed spallation neutron sources are more than two orders of magnitude smaller than that from the ILL, and therefore it seems to be difficult for those sources to compete with experiments at a high flux reactor in such fields, even though we take into account a gain factor (10~20 as discussed later) in pulsed sources, which comes from time structure. As a measure of the efficiency of a cold neutron source, here we introduce the conversion efficiency, which is defined as time-averaged 4π-equivalent cold neutron flux on a moderator surface per fast neutron emitted from a neutron generating target or a reactor core. It may be obvious from the table that the conversion efficiency of a decoupled cold moderator in a large spallation neutron source as ISIS is much smaller than that of the ILL, while that of a small source as KENS-I' is higher than that of a high flux reactor. The higher efficiency in KENS-I' is due to the use of solid methane as moderator material and a larger coupling efficiency between target and moderator, which is only possible in a smaller system.

As far as neutronics is concerned, it was already proved that solid methane is the best moderator material for a pulsed cold neutron source due to higher hydrogen density and superior low energy modes compared to liquid hydrogen (Inoue et al., 1983).

Table 1. Comparison of world's cold-neutron-source efficiency

Neutron source	Type	Power	Fast neutron yield(n_f/s)	Cold source	Maxwellian integral flux	Conversion efficiency	Remarks
ILL	Reactor	58 MW	$1.8 \times 10^{18**}$	Liq. D_2 in D_2O reflector	5.4×10^{14}	3×10^{-4}	Achieved
KENS-I'	Pulsed spallation	500 MeV 3 μA U-target	3×10^{14}	Solid CH_4 decoupled to Be reflector	1.4×10^{11}	4.8×10^{-4}	Achieved
ISIS	Pulsed spallation	800 MeV 200 μA U-target	3.5×10^{16}	Liq. H_2 decoupled to Be reflector	2.1×10^{12}	6×10^{-5}	Calc. value present $I_P = 100$ μA
SNQ Mock-up	Quasi-continuous spallation	1.1 GeV 5 mA	6.87×10^{17}	Liq. H_2 coupled to premoderator in C reflector	3.1×10^{14}	5×10^{-4}	SIN Exp. $E_T \sim 80$ K (?)
KENS-II	Pulsed spallation	1 GeV 200 mA W-target	2.5×10^{16}	?	1.25×10^{13}	if same as KENS-I'	Relative merit is close to ILL in D17-like exp.

*for simplicity we calculated (Maxwellian integral/n_f) instead of (cold neutrons/n_f)

**assuming one useful neutron per fission

This moderator, however, cannot be used at intense spallation neutron sources because it suffers from serious radiation damage (a so-called "burp" phenomena). ISIS has proved that liquid methane is still useful even at a beam current, 100 μA of 800 MeV protons. This moderator, however, is not for providing higher flux of cold neutrons but just narrow pulses of thermal and epithermal neutrons.

There is no doubt that liquid hydrogen is at the present time the only proved material for a cold moderator which can be used as an intense cold neutron source, but the conversion efficiency of a decoupled liquid hydrogen moderator is too low. Kiyanagi, et al., studied various decoupled liquid hydrogen moderators and compared those with a reference decoupled solid methane moderator (5 cm thick) (Kiyanagi, et al., 1986). The conversion efficiency was increased up to 50% of that of the reference moderator by increasing the thickness of liquid hydrogen to 15 cm, but still not enough.

It is strongly desired that SANS experiments in KENS-II, which may not be as favorable as epithermal neutron scattering, must be a close second to D 17 at the ILL, Grenoble, even if we cannot catch up to them. This requires that the conversion efficiency in KENS-II must be, at least, as large as that of the present KENS-I', or hopefully much better, since the total number of fast neutrons expected from KENS-II is the same order of magnitude of ISIS. A composite moderator, which consists of the mixture of solid methane and liquid hydrogen, has been proposed but it is still in the stage of idea. A coupled moderator, especially a heterogeneous moderator that consists of a relatively small (or thin) liquid hydrogen moderator and a premoderator at room temperature, will be the shortest and most promising way to obtain higher efficiency.

Coupled moderator

A coupled moderator has the following advantages compared to a decoupled moderator:

(i) higher time-averaged flux of cold neutrons;
(ii) lower energy deposition in the moderator (lower power density as well as lower total power);
(iii) consequently, lower cost for cryogenic system;
(iv) no need of super critical hydrogen (less severe safety regulation and higher safety factor);
(v) lower leakage of fast and high-energy neutrons from neutron beam tube due to larger distance between target and moderator; consequently, lower cost for shielding around neutron beam lines and spectrometers;
(vi) better signal to background ratio.

Longer pulse width from such a moderator is still short enough for SANS experiments but gives poor energy resolution in some classes of spectroscopy as those with LAM-80 at KENS-I' and IRIS at ISIS, where the resolution is directly determined by the pulse width. This is only one disadvantage of a coupled moderator. On the other hand, in other classes of high-resolution experiments, the longer pulse width becomes an advantage. For example in an inverted geometry back-scattering spectrometer with a pulse-shaping chopper, the resolution is determined by chopper pulse width, but the dynamic range of energy transfer covered by a spectrometer becomes wider proportionally to the pulse width of source neutrons. Another example is a direct-geometry Doppler instrument where the longer pulse width but higher time-averaged flux gives higher luminosity at sample position for a given energy resolution.

Kley proposed a heterogeneous cold moderator consisting of ZrH_2 or H_2O at room temperature and of liquid parahydrogen at 20 K as a cold neutron source of a repetitive fast pulsed reactor SORA (Kley, 1971). Bauer, et al., performed measurements on such moderators as a part of an experimental program for optimizing the cold moderator for SNQ, the German spallation source, and showed that coupled moderators of liquid hydrogen (both normal and para) with H_2O- premoderator in a graphite reflector provide fairly large efficiency as shown in Table I (Bauer, et al., 1985). The value is about 10% lower than that of liquid hydrogen in a D_2O reflector, but the peak flux is higher than the latter.

Their results encouraged our developing program on a coupled moderator for KENS-II. However, they found a serious problem, that the effective neutron temperatures from those coupled moderators are unexpectedly high, T_N~80K. We cannot understand the reason why, but it seems to be a fatal disadvantage to this kind of moderator if it is true because the gain factor relative to a decoupled moderator becomes lower at longer wavelength. They suggested that experiments on a coupled liquid deuterium moderator in a large D_2O moderator-reflector will give a larger gain factor at longer wavelength region.

Preliminary experiments on coupled moderator

We have performed preliminary experiments on a coupled moderator. The results are reported in a separate contribution in this workshop (Watanabe, et al., 1988). Our results are very encouraging and summarized as follows:

(i) Effective neutron temperature T_N is reasonably low and almost the same as those of a bare liquid hydrogen moderator and of a decoupled one in a graphite reflector. The results are essentially different from those by Bauer, et al.
(ii) Gain factor of the coupled moderator increases at lower wavelength.
(iii) Gain factors of coupled liquid hydrogen moderators, especially with polyethylene premoderator, are significantly (more than 5 times) higher than a decoupled one.
(iv) Pulse widths in full width at half maximum from coupled moderators are not so broad compared to those from a decoupled one; about two times. The values are by only 1.5 times as long as those of the present solid methane decoupled moderator at KENS-I'.
(v) Consequently, the peak height of the neutron pulses is significantly higher than that from a decoupled one.

In the present preliminary experiment, the fast neutron source was not a spallation one but an electron-induced photo-neutron source, and the top parts of the premoderator and the graphite reflector were missing due to the use of a relatively large cryostat that was not optimized for this purpose. Therefore, the estimation of the absolute conversion efficiency of the present coupled moderator is difficult, but we can discuss the relative gain. The relative gain factor of the present coupled liquid-hydrogen moderator with premoderator to the 5-cm-thick decoupled liquid-hydrogen moderator was more than five. On the other hand, the previous experiment (Kiyanagi, et al., 1986) showed that the relative gain factor of a 5-cm-thick decoupled liquid-hydrogen moderator to a reference decoupled moderator of 5-cm-thick solid methane at 20 K was about one third. This suggests that the gain factor of the present coupled liquid-hydrogen moderator with premoderator is superior to that of the reference solid methane, i.e., there may be a possibility that we can realize higher conversion efficiency than that of the present KENS-I', even taking into account a lower coupling efficiency between target and moderator in a larger system of KENS-II.

Relative merit for SANS

Here we discuss the relative merit of a pulsed cold neutron source to a high flux reactor reactor in SANS experiments. The intensity I of a neutron beam at a sample position is proportional to the phase space density (Maier-Leibnitz, 1966), and for a Maxwellian distribution given by

$$I \propto \frac{\phi k_z}{2\pi k_T^4} \exp\{-(k_z/k_T)^2\}\, \Delta k_z\,,$$

$$\text{with } k_T = \sqrt{2mk_BT_N}\,/\hbar,$$

where ϕ is the time-averaged neutron flux in the Maxwellian at the moderator, m the neutron mass, k_z the z component (beam direction) of the momentum of interest, k_B the Boltzman constant, T_N the neutron effective temperature.

Although T_N in a pulsed cold neutron source is different from that in a high flux reactor, we assume for simplicity that the T_N's for both sources are the same. This assumption is not so bad when we compare the measured energy spectrum in our preliminary experiment on a coupled cold moderator for KENS-II (preceding section) with that of the ILL cold neutron source. In a reactor experiment, the data acquisition rate is proportional to I at a fixed k, while in a pulsed experiment it is proportional to the integral of I over the useful band width $\Delta\lambda$ of incoming neutrons. The non-overlapping useful band width in angstroms is, as well known, given by

$$\Delta\lambda = 3.96 \times 10^3/(fL),$$

where f is the repetition rate, L the flight path length between source and detector in meters. If we assume that we can realize a conversion efficiency in KENS-II as high as that in the present KENS-I', we have a time-averaged cold neutron flux of $\phi = 1.25 \times 10^{13}\ n_c/cm^2{\cdot}sec$ as listed in Table I, which is about a factor of 40 smaller than that of the ILL high flux reactor.

On the other hand, in a pulsed source we have an extra gain that comes from time structure (useful band width). Here we consider a D17-like experiment at the ILL or a SANS-like experiment at KENS (a D11-like experiment with a pulsed source seems to be difficult). We concluded that the total flight path length of 13 m or hopefully 10 m will be possible, which gives the useful band width 6 Å or 7.9 Å for $f = 50\ s^{-1}$. The gain is given by

$$\text{Gain} = [\int_{\lambda_{min}}^{\lambda_{max}} d\lambda/\lambda]/(\delta\lambda/\lambda)_{\text{reactor}}.$$

The denominator is the wavelength resolution in a reactor experiment, which is about 0.1.

If we assume that neutrons in the wavelength region between 1 and 7 Å (corresponds to $\Delta\lambda = 6$ Å) or 1 and 8.9 (corresponds to $\Delta\lambda = 7.9$ Å) are useful, we have

$$\begin{aligned} \text{Gain} = &\ \ln(7/1)/0.1 = 19.5 \\ \text{or} &\ \ln(8.9/1)/0.1 \sim 22. \end{aligned}$$

If we assume that neutrons only in a longer wavelength region, for example, between 4 and 10 Å or 4 Å and 11.9 Å, are useful, we have a gain of 9.2 or 10.9. Thus the gain from pulse structure is 10 -20. This means that the relative merit of KENS-II to the ILL in a D17-like experiment is 1/2 or 1/4, assuming that time-averaged 4π-equivalent flux of KENS-II is about a factor of 1/40 smaller than that of the ILL.

Since our preliminary experiment on a coupled moderator has given indication of higher conversion efficiency than the present KENS-I', a D17-like experiment with KENS-II is expected to be a close second to that with D17 at the ILL. It may be well recognized that there exists another merit in a pulsed neutron experiment–much wider momentum range simultaneously covered by larger $\Delta\lambda$.

Relative merit of a coupled cold moderator in an application other than SANS will be discussed elsewhere.

Moderator configuration

The total number of useful cold neutrons that can be extracted from one cold moderator or total number of cold neutron beam lines (direct beam holes and neutron guide tubes) that can view one cold moderator will be another important figure of merit of a cold neutron source. The maximum angular opening of one cold neutron moderator in a target-moderator-reflector assembly will be limited to a certain value, typically about 0.5 radian, because a much larger opening removes a significant part of the reflector and, consequently, sacrifices the beam intensity. The total number of

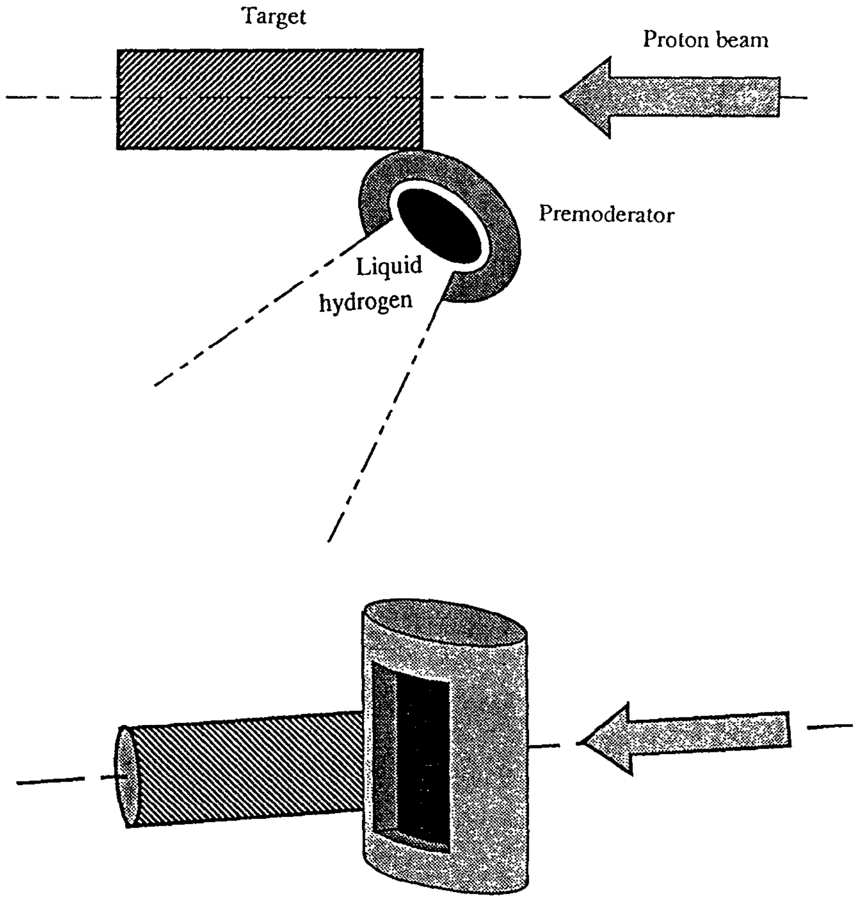

Fig. 1 A modified slab geometry for KENS-II cold neutron source.

neutron guide tubes accessible within this angle is, therefore, limited to about 10, assuming the distance between the moderator and the beginning of the guides to be about 1.5 m and the inner (outer) width of the guide about 5 cm (7.5 cm). This number is to be compared with that in a high flux reactor, where the number of guides extracted from a cold moderator is typically 5, but ultimately increased by about 3 times in the experimental hall. The growth in number is possible only in the case that the height of the moderator view-surface as well as the height of the guides at the inlet is as high as those in the high flux reactor at the ILL (about 15 cm). In pulsed spallation facilities the height is limited to about 5 cm because the cold moderators are coupled to the target in the wing geometry where the spatial distribution of cold neutrons has a peak at about 3 cm from the target-side end with rapid exponential decrease towards the oposite end.

A slab geometry in target moderator configuration will be a possible way to increase the bright zone on the view surface of the moderator. Generally, the slab geometry is susceptible to background fast neutrons and brings an extremely high dose equivalent rate around a neutron beam line. In order to improve this shortcoming, a modified slab geometry as illustrated in Fig. 1 shall be studied further. In this geometry no beam tube within the opening angle of about 30° views the target directly and a bright area about 10 cm wide by 15 cm high may be realized. Such a configuration will increase the capability for cold neutron usage in a pulsed spallation neutron facility.

We are thinking to adopt decoupled moderators for short pulse uses as usual which may be a liquid methane moderator and light water moderator(s). An optimal target-moderator-reflector configuration including a coupled moderator as shown in Fig.1 is under consideration.

References

Bauer G., Conrad, H., Fischer, W., Grunhagen;, K. and Spitzer, H., 1985, Proc. ICANS-VIII, RAL-85-110, p. 344

Kiyanagi, Y., Inoue, K., Watanabe, N. and Iwasa, H., 1986, KENS Report-VI, KEK Progress Report 86-2, p. 270

Kley, W., 1971, Proc. the Joint Meeting on Pulsed Neutrons and Their Utilization, EUR 4954e, p. 379

Maier-Leibnitz, H., 1966, Nukleonik 8, p. 61

Watanabe, N., Kiyanagi, Y., Inoue, K., Furusaka, M., Ikeda, S., Arai, M. and Iwasa, H., 1988, to be published in these proceedings.