Studies of Cold Neutron Sources for Spallation Targets.

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## 1. Introduction

According to our present knowledge the main region of interest for the application of cold neutron lies between 3 Å and 20 Å which corresponds to .2 meV<E<10 meV. For $\lambda$>100 Å we have the region of ultra cold neutrons whereas the intermediate region has not been used much up to now. The need for cold neutrons appears to be met optimally by a large deuterium source like the cold source installed at the HFR Grenoble. Fig. 1 shows the maximum possible neutron intensities obtained by shifting the Maxwellian distribution in a large non absorbing moderator towards lower temperatures (upper dashed line).

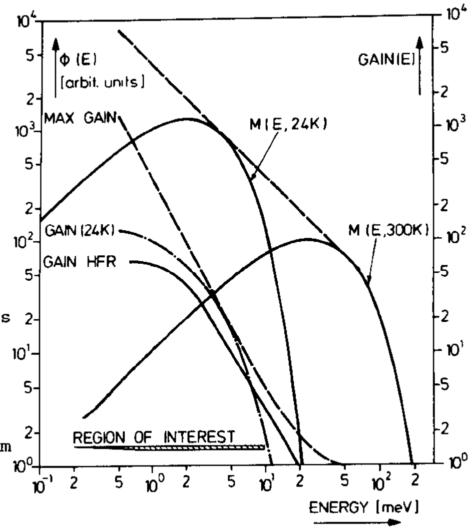


Fig. 1
Fluxes and gainfactors of cold moderators

The Maxwellian distribution for T=24 K, the boiling temperature of $D_2$, has its broad maximum right in the middle of the region of interest. The corresponding intensity gain is indicated by the dash-dotted curve. The actual gain achieved with the Grenoble source is somewhat smaller due to the following reasons:

1. finite size of the cold moderator
2. position of coldest spectrum in the center, not at the surface
3. flux depression by structural elements



4. absorption and scattering of the neutron beam in the walls
5. rethermalization of neutrons in the moderator layer between source and beam tube

The curve marked by MAX. GAIN gives the maximum possible gain if the source temperature is always adapted to the particular neutron energy used in the experiment. This curve is not very far from the actual $D_2$-result above about 2 meV. This demonstrates that there is no need for an intermediate source with a moderator temperature above that of liquid $D_2$. On the other hand it may be worth while to look into the performance of a solid $D_2$ source cooled with liquid helium by which higher intensities below 1 meV may be obtained. However, it can be foreseen, that serious cooling problems will arise for such a source.

The intensity emanating from a cold source is given by $I(E) \sim \phi_{th}(E,\vec{r}) \cdot GAIN(E)$ where $\phi_{th}(E,\vec{r})$ is the thermal flux in the moderator without the cold source. It is this quantity which has to be optimized. Fig. 2 shows a typical radial distribution of the thermal flux in a $D_2O$ moderator.

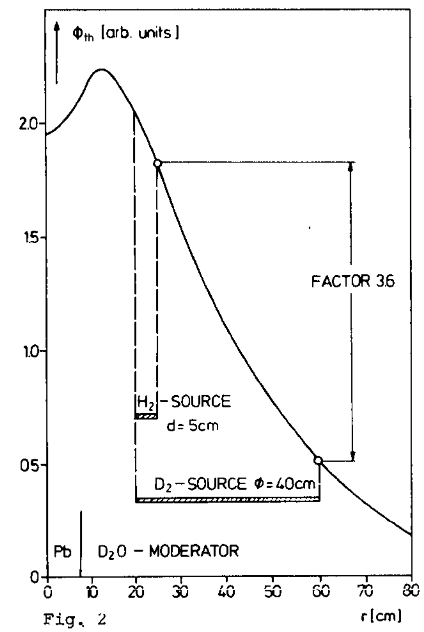


Fig. 2
Radial flux distribution in a cylindrical Pb target - $D_2O$ moderator assembly

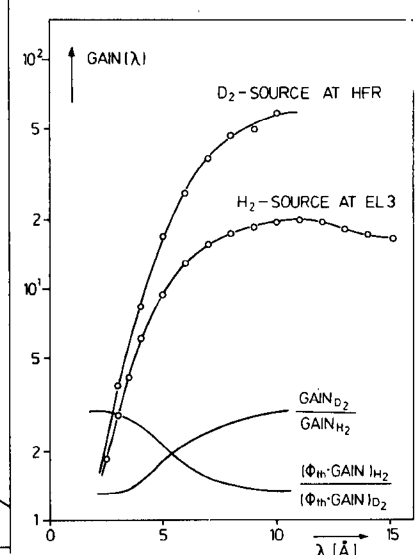


Fig. 3
Gainfactors of $H_2$ and $D_2$ sources

These calculations are based on the assumption that there are no gas bubbles in the liquid. The small difference between the two upper curves in Fig. 4 tells us that in a large vessel a considerable amount of gas bubbles (up to 50 volume %) can be tolerated without appreciable disadvantage for the efficiency of the source if these bubbles are distributed about uniformely in the liquid.

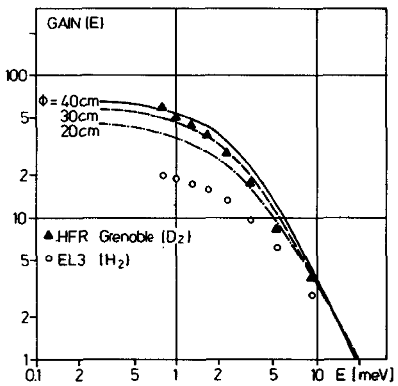


Fig. 4
Gainfactors for $D_2$ sources of various sizes

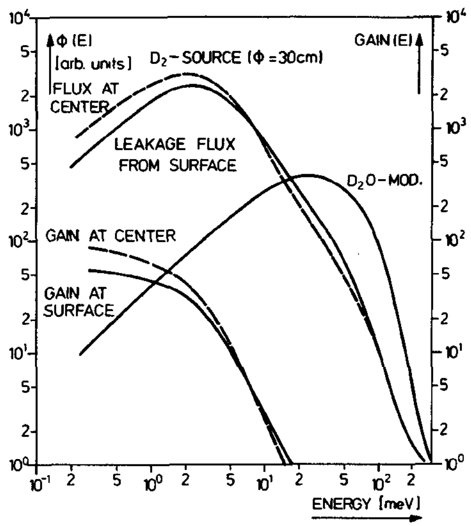


Fig. 5
Fluxes and gainfactors at the center and from the surface of a spherical $D_2$-source with 30 cm diameter

### 3.2 Reentrant Hole

The most efficient rethermalization of the neutrons occurs in the center of the cold source. Therefore, by using a reentrant hole reaching to the center of cold moderator a better performance of the cold source may be achieved. As the cross section of the reentrant hole has to be of the order at least of 200 $cm^2$ this can be done only in cases of a large $D_2$ vessels. Fig. 5 compares the leakage flux from the surface of a 30 cm Ø source with the flux at the center and shows the corresponding gain factors for a case where there is no gradient in the integrated



flux of the surrounding moderator. The small differences between the two spectra does not seem to justify the installation of a reentrant ho hole.

However, the use of a reentrant hole may be advantageous if the neutron beam is extracted in the direction of a strong flux gradient because it shifts the radiating surface to a position of higher integrated neutron flux. Plans on these lines are presently being discussed at the HFR in connection with the "deuxieme souffle". An improvement by a factor of two is expected /5/.

## 4 $H_2$-Cold Sources

### 4.1 General Aspects

Compared to the $D_2$ sources the problems in connection with $H_2$ sources are much more complex. We may distinguish between three cases according to the postulations put forward by the users as listed in Table 2.

| case | postulations | | mode of operation of accelerator | production of cold neutrons | position of the cold source |
|---|---|---|---|---|---|
| | $\phi_{av}$ | $\phi_{max}$ | | | |
| 1 | high | not of interest | steady state | rethermalization of thermal neutrons from surrounding moderator | maximum of thermal flux |
| 2 | not of interest | high | short proton pulses $\Delta t_p \approx 1 \mu s$ | moderation of fast neutrons in the source itself | as close to the target as possible |
| 3 | high | high | coarse pulsing $\Delta t_p \approx 500 \mu s$ | rethermalization of thermal neutrons + moderation of fast neutrons | intermediate between target and maximum of thermal flux (in reality: close to the target) |

Table 2: Use of $H_2$-sources at proton accelerators

The problems in connection with case 1 are similar to those encountered with hydrogen sources in reactors with the main difference that the heating by fast neutrons is more severe. In order to obtain high peak currents (case 2) the cold source has to be placed very close to the proton target. Crude estimates lead to a nuclear heating of about 2 to 3 KW per liter $H_2$ and 1 MW of proton beam power for a Pb Bi target.

In the region of the large $D_2$ source with 40 cm diameter the thermal flux drops by a factor of 4. If the cold neutrons are extracted radially i.e. from the outer surface of the source, as is done at the HFR, the flux level is small. If we use a slab hydrogen source placed in such a way that the distance to the target (or core) is the same as that for the $D_2$ container this source will have a much better performance as is seen in Fig. 3. Although the gain factors obtainable are smaller than those for $D_2$ /1/ the intensity of cold neutrons is higher in the whole energy region.

2. Nuclear Heating

| SOURCE OF HEATING | SOURCE DISTRIBUTION |
|---|---|
| 1. γ's from (n,γ) reactions in the core or proton target | $I_\gamma \sim e^{-\frac{r}{25}}/r^2$ |
| 2. γ's from the fission and/or spallation process | |
| 3. high energy protons from the target | |
| 4. fast neutrons | $\phi_f \sim e^{-\frac{r}{9}}/r^2$ |
| 5. γ's from (n,γ) reactions in the surounding moderator and structural elements (beam tubes) | $\varrho \sim \phi_{th}$ |
| 6. γ's from (n,γ) reactions in the cold moderator and structural elements of the cold source | |
| 7. β's from the β-decay after (n,γ) reactions in the structural elements of the cold source | |

Table 1: Nuclear heating in a cold source

Table 1 shows the main processes responsible for the nuclear heating of a cold cource. For a Pb-Bi target the contributions due to the γ's from the target are considerably reduced compared to the core γ's in a reactor and may be neglected in the heating calculations. This is generally considered as a particular advantage of a spallation source. However, it should be mentioned that for the HFR source only one quarter of the total nuclear heating is due to the γ's from the core /2/. Little is known about the influence of high energy protons. A Bi layer of suitable thickness between the target and the source may eliminate this contribution. The heating due to items 5 to 7 is proportional to the thermal neutron flux and therefore a common problem for both the reactor and the spallation source.

A major problem seems to be caused by the fast neutrons due to the rather hard source spectrum. In a reactor the fission spectrum has a mean energy of $\bar{E}$=2.0 MeV. According to the measurements of Cierjacks et al./3/



the average energy of the source spectrum from a Pb target is 25 MeV, which is a factor 12.5 higher than for the fission spectrum. However, in the heating calculations a factor of 2.5 instead of 12.5 corresponding to $\bar{E}$=5 MeV, seems to be more adaequate. These values can be made plausible by the following considerations:

1. In liquid hydrogen and deuterium the scattering mean free path increases beyond 50 cm for energies above 30 MeV. Thus even a large $D_2$-source with linear dimension of 30 to 40 cm becomes transparent for neutrons above 30 MeV. With 30 MeV as a cutoff energy an average energy of $\bar{E}$=5.5 MeV is obtained using the data of Cierjacks et al.
2. Calculations on the energy deposition by fast neutrons in a $H_2$-source close to the spallation target taking into account the detailed source spectrum yield the same result as a simplified calculation based on a single group of fast neutrons with $\bar{E}$=4.5 MeV.
3. Measurements of the fast neutron yield from a Pb-Bi spallation target by Gompf and Reichardt /4/ using a modified long-counter yielded an average energy of about 4.5 MeV for those neutrons of the source spectrum which are moderated in the paraffine and afterwards recorded in the detector. Thus existing calculations for cold sources in reactors may be used also for spallation source problems if we increase the energy deposition caused by fast neutron collisions by a factor of 2.5.

3. $D_2$-Sources

3.1 *Size Effects*

Due to the large dimensions of a $D_2$-source the installation of such a source is only possible in a $D_2O$ moderator where the thermal flux distribution is only slowly varying. However, we have seen before that also in $D_2O$ the thermal flux changes by a factor of four along a distance of 40 cm which corresponds to the diameter of the Grenoble cold source. This rises the question about the efficiency of smaller $D_2$-sources. Fig. 4 shows calculated gainfactors for three diameters of spherical sources (d=40,30,20 cm). Even the small source with a diameter of 20 cm yields higher gains than the $H_2$ source. Compared to the large vessel with a diameter of 40 cm the intensity is reduced only by a factor of 1.5 below 1 meV. Above this energy the intensity losses are even smaller. Therefore it may be advantageous in specific cases to use a small $D_2$ source with a diameter of about 20 cm if this allows to install the source closer to the target where the flux in the moderator is higher. This, however, will increase the heating problems.

Most of this heating is caused by the fast neutrons. If the compressor ring of the German spallation source project can make use of the full beam current of the linac, there will be about 12 to 18 KW of heat production in a hydrogen cold source of volume 1 liter if it is placed close to the target. This means that there will be only vapour in the container. A layer of $H_2O$ of suitable thickness between the target and the cold source will devrease the nuclear heating. However, it will decrease the cold flux in a similar way, as in hydrogeneous moderators the distribution of the thermal neutrons closely follows that of the fast neutron flux.

Case 3 represents the German spallation source project without compressor ring. It is hoped that stationary experiments can be performed under similar conditions as at the HFR whereas TOF experiments will profit considerably from the pulse structure. A suitable cold source seems to be a hydrogen source in a $D_2O$ moderator. Peak intensities for the energy integrated neutron flux of about $10^{16}$ ($n/cm^2$ sec) are expected if the cold source is placed close to the proton target. This, of course, leads to the same unsolvable heating problems that have been mentioned in connection with case 2. However, in the present case, the fast flux and thus the nuclear heating decreases faster than the thermal flux if we remove the cold source from the target to a position where the technical problems caused by the nuclear heating become solvable.

The short mean free path of subthermal neutrons together with the postulations for large beam cross-sections, where the height should be larger than the width, lead to the plate shaped hydrogen cold sources. Typical dimensions are: 25 cm high, 12 cm wide, 5 cm thick. Due to this shape the position of the $H_2$-source will respect to the proton target is of considerable importance. Four cases have to be considered:

1. proton beam horizontal, source in WING-geometry
2. proton beam horizontal, source in SLAB-geometry
3. proton beam vertical, source in WING-geometry
4. proton beam vertical, source in SLAB-geometry.

As in general cold neutrons are extracted via neutron guides, the background problems are less severe than with thermal beam tubes. Therefore slab-geometry seems to be preferable as the target moderator coupling is better than for wing geometry. Obviously Nr. 1 is rather unfavourable configuration for in addition to the bad target-moderator coupling the cold neutrons flux decrease rapidly with increasing distance from the



target. Therefore the upper part of the cold source does not contribute much to the extracted neutron beam. Configuration 2 cannot be realized with a target wheel and those targets where the cooling circuits are lying in a horizontal plane. More satisfactory configurations are achieved if the proton beam hits the target vertically.

## 4.2 Parahydrogen

It has been shown by Würtz /6/ that for spallation neutron sources with short proton pulses (∿1μs) the use of para-hydrogen will offer considerable advantages as the lifetime of the subthermal neutrons is considerably smaller than in all other hydrogeneous moderators. This is caused by the peculiar behavior of the neutron cross-section which drops to a rather small value of 1.5 barn below 14 meV (see Fig. 6). The corresponding mean free path is 16 cm. Thus neutrons scattered down below 14 meV have a high probability to be emitted from the moderator without further collisions. Fig. 7 shows the mean emission time as function of energy for neutrons leaking out of a cylinder (15 cm Ø, 15 cm height) of almost pure para-hydrogen.

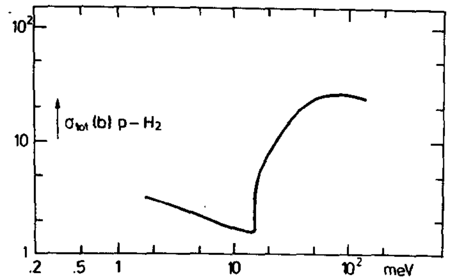


Fig. 6
Total slow neutron cross-section of para-hydrogen

The ordinate is the variance Δt which is defined by $\Delta t=\sqrt{\overline{t^2}-\overline{t}^2}$. For an exponential decay $\Delta t=1/\lambda$ where $\lambda$ is the relaxation constant. Above 30 meV we find the typical $1/\sqrt{E}$ bahvior of the slowing down region. However, also below 10 meV the curve roughly follows an $1/\sqrt{E}$ dependence. This is caused by the fact that the time for emitting a neutron from the moderator surface is essentially determined by the time elapsed between the scattering process and the arrival of the neutron at the surface of the moderator. This time behavior is very useful for time of flight experiments as it leads to a constant energy resolution.

The other 77% para-23% ortho mixture also shown in the figure is somewhat arbitrary as it does not correspond to the usual high temperatur

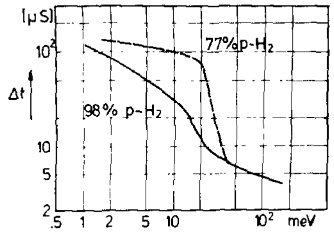


Fig. 7
Variance of the neutron emission time from liquid hydrogen

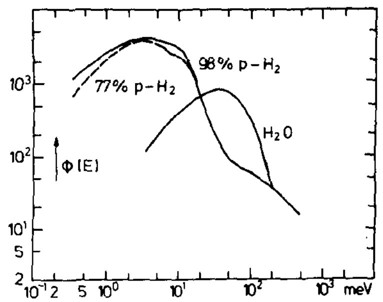


Fig. 8
Stationary leakage spectra from liquid hydrogen

equilibrium composition of 25% para-75% ortho, which is mostly conserved also in liquid hydrogen unless special efforts are undertaken using ortho-para converters. As the scattering by para-hydrogen is very small compared to that by ortho-hydrogen below 14 meV its presence can be largely neglected in this energy region. Thus the dashed curve will be representative also for the usual para-ortho composition. As can be seen from Fig. 8 the time integrated intensities $\bar{\phi}(E)$ are nearly the same for the two cases. Therefore the peak intensity $\hat{\phi}$ in para-hydrogen is considerably higher than in ordinary hydrogen according to the relation
$\hat{\phi}(E) \sim \frac{\bar{\phi}(E)}{\Delta t(E)}$ .

## 5. A $D_2$ Source for the German Spallation Source Project

Fig. 9 shows a possible arrangement for a $D_2$ source in the heavy water tank above the target wheel as proposed by G. Bauer /7/. The volume is about 30 l - similar to that of the HFR -, the midpoint is 36 cm from the midplane of the target wheel. Cold neutrons are extracted vertically at an average thermal flux level of about $3 \cdot 10^{14}$ n cm/sec.

Fig. 10 compares the thermal and fast flux distributions in the $D_2O$ tank along the cylinder axis with those of the HFR. The later data were taken from the "Yellow Book" /8/ and represent the unperturbed thermal flux. The zero point for the abszissa is the surface of the fast neutron source (core, spallation target) for both cases. The curves for the spallation source were obtained from a two dimensional multigroup diffusion



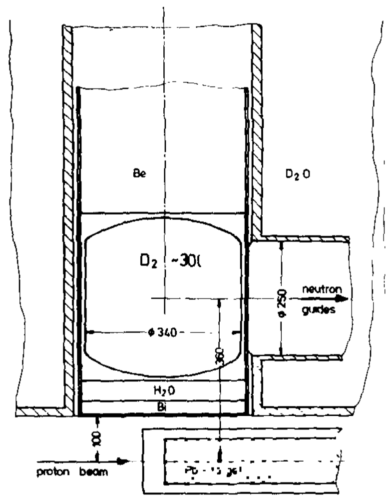


Fig. 9
$D_2$-source proposed for the German spallation source

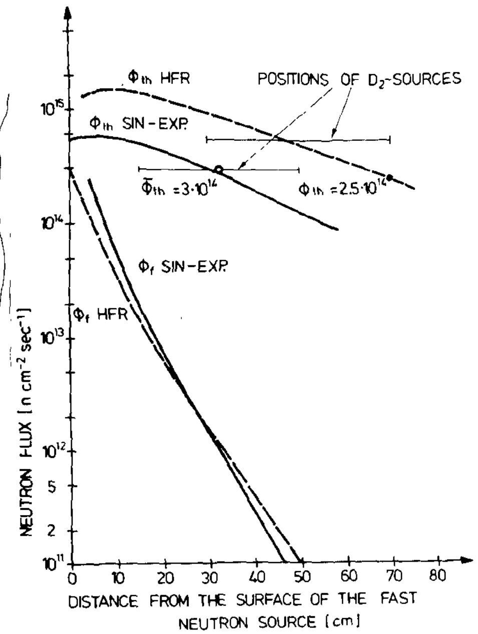


Fig. 10
Fast and thermal neutron fluxes in the $D_2O$ moderator

calculation simulating a pilot experiment performed a SIN. The height of the thermal flux was adapted to the flux values measured in the SIN experiment. It decreases somewhat faster with increasing distance from the source than the HFR flux due to the smaller size of the heavy water tank compared to the vessel of the HFR. The fast fluxes do not differ much in the region of interest. (In the calculations the fast neutron spectrum was truncated at 10 MeV). Also indicated are the positions of the $D_2$ sources and the average thermal fluxes at the points of beam extraction. Based on the data for the HFR source we have estimated the heat production in the cold source under the assumption that the structural materials are the same for both cases (inner vessel 1.5 mm Al. outer vessel 8 mm zircaloy.) The results are shown in Table 3. The quoted figures can be considered only as very rough estimates due to the fact that detailed information about the

| source | volume | $\bar{\Phi}_{therm}$ at position of beam extraction | heating [Watt] by | | | total [Watt] |
|---|---|---|---|---|---|---|
| | | | core γ's | fast neutrons | (n,γ) β· | |
| HFR Grenoble | 30 l | $2.5\cdot10^{14}$ | 1460 | 140 | 4200 | 5800 |
| spallation source | 30 l | $3\cdot10^{14}$ | - | 3000 | 2400 | 5400 |

Table 3: Nuclear heating of $D_2$-sources

amount of structural material in the environment of the cold source is not yet available. However, we learn from these figures that the nuclear heating in the source considered here has a similar magnitude as that in the HFR source. Therefore the cooling should not cause particular problems.

More serious problems may arise from the radiation damage caused by the fast neutrons in the Al-vessel. The side close to target views a fast neutron flux that is about 20 times larger than that impinging on the HFR source.

The time behavior of the cold neutron flux will closely follow that of the surrounding $D_2O$ moderator. Therefore a peak intensity of the energy integrated flux of $2\cdot10^{15}$ n/cm$^2$ sec is expected. A time of flight spectrometer placed at this source will have an intensity that is 8 times higher than at the IN5 in Grenoble.

## References

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/8/ Neutron Beam Facilities at the HFR Available for Users