Measurements of Spatial Distribution of Intensity and Energy Spectrum of Neutrons from Coupled Hydrogen Moderators by using a Position Sensitive Detector (Cooperative Research)

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国際単位系（SI）

表1 国際単位系の部

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Measurements of Spatial Distribution of Intensity and Energy Spectrum of Neutrons from Coupled Hydrogen Moderators by using a Position Sensitive Detector (Cooperative Research)

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An experiment was performed by utilizing a neutron source of the Hokkaido University 45-MeV electron linear accelerator facility to confirm a peculiar spatial distribution of neutron intensities below 15 meV for a para-hydrogen moderator that has been suggested by neutron transportation calculations. For comparison, both para-hydrogen and ortho-rich-hydrogen (ortho/para ratio was 60:40∼70:30) were utilized for moderator materials. Moderator dimensions were 50 mm in thickness and 120 mm in width and height. The spatial distributions of the neutron intensity at the moderator surfaces were measured based on the pinhole camera principle by using position sensitive helium-3 detectors and by putting a cadmium plate with a pinhole at the middle of the flight-path (6m). As a result, the para-hydrogen moderator exhibits an intensity enhancement toward fringe parts nears premoderator, while the intensity decreases at the fringe parts for the ortho-rich-hydrogen moderator. These results indicated consistency of the peculiar spatial distribution obtained by the calculations.

Position dependences of neutron energy spectra on the moderator surface were measured to discuss the reason for the peculiar distribution. In the energy region between 15 meV and 100 meV, both moderators exhibit the intensity enhancements at the fringe parts. At energies below 15 meV, the para-hydrogen moderator exhibits higher intensity at the fringe parts, while the intensity decreases at the fringe parts of the ortho-rich-hydrogen moderator.

The results provide us a basis for reliability of the neutron transportation calculation used for the J-PARC spallation neutron source design.

Keywords: Spatial Distribution, Energy Spectrum, Cold Neutron, Coupled Hydrogen Moderator, Para Hydrogen, Ortho Rich Hydrogen, Position Sensitive Detector, Measurement

This research was performed by cooperative research with Hokkaido University
*Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University
中性子輸送計算によって示されたバラ水素モデレータに対する15 meV以下の中性子強度の特異な空間分布を確認するため、北海道大学45 MeV電子線形加速器施設の中性子源を利用して、実験を行った。モデレータ材料には、比較のためバラ水素とオルソリッチ水素（オルソ/バラ比は60:40〜70:30）の両者を使用した。モデレータ寸法は厚さ50 mm、縦横120 mmとした。ピンホールカメラの原理により、位置敏感型ヘリウム3検出器を用い、飛行経路（6m）の中間に直径2 mmのピンホールのあいたカドミウム板を設置し、モデレータ表面における中性子強度分布を測定した。その結果、バラ水素モデレータでは、プリモデレータが隣接するモデレータの周辺部に向かって中性子強度の増加を示していたが、オルソリッチ水素モデレータでは、周辺で強度の低下が見られた。これらの実験結果は、計算で示された特異性と矛盾のないものであった。さらに、特異な分布の原因を議論するため、モデレータ表面上の位置に対する中性子エネルギースペクトルの依存性を測定した。15 meV〜100 meVのエネルギー領域では、両モデレータとも周辺部で高い強度を示した。15 meV以下では、バラ水素モデレータでは、同様に周辺部で高い強度を示したが、オルソリッチ水素モデレータでは、周辺部で強度の減少が認められた。本研究で得られた結果は、J-PARC 核研究中性子源で使用されている中性子輸送計算の信頼性を確認する根拠の一つである。
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1 Introduction

The Japanese Spallation Neutron Source (JSNS) is one of the most important facilities at the J-PARC (Japan Proton Accelerator Research Complex) project [1] conducted by the collaboration between the Japan Atomic Energy Agency (JAEA) and the High Energy Accelerator Research Organization (KEK). At J-PARC, pulsed protons (3 GeV, 1 MW, 25 Hz) bombard a mercury (Hg) target to produce spallation neutrons, and emitted neutrons from the target are converted into cold neutrons through moderators. The neutrons are utilized mainly for neutron scattering experiments. The neutron source has one coupled and two decoupled supercritical hydrogen (H$_2$) moderators with light water (H$_2$O) premoderators. The coupled H$_2$ moderator aims at providing intense pulsed cold neutrons with maximizing time-integrated and pulse-peak intensities, while the decoupled moderators are to deliver narrower pulses for high-resolution experiments.

Extensive studies have been carried out to obtain optimal parameters (dimensions, materials, arrangement, etc.) for the moderators to attain superior neutronic performance by means of Monte Carlo calculations. Although such calculations are very useful, it is indispensable to confirm consistency between calculated results and existing experimental data. In an H$_2$ moderator, a para-H$_2$ concentration plays an important role to determine the neutronic performance, especially in the energy range below several tens meV. Figure 1 shows scattering cross sections for ortho- and para-H$_2$ at 20 K calculated for ENDF/B-VI.3 [2]. The sharp drop in the para-H$_2$ curve below 50 meV is due to spin coherence and the second drop below 3 meV is due to intermolecular interference. The main energy transfer mechanism for neutrons (neutron energy loss) at low energies is the para to ortho spin-flip transition. The neutron energy loss in the transition is 14.7 meV.

Whittemore et al.[3, 4] measured neutron energy spectra from ortho-para-H$_2$ and para-H$_2$ moderators at 20 K in an energy range between 0.2 and 100 meV. The moderators (6 inches (152 mm) in diameter and about 6 inches in height) were set beside a lead (Pb) target irradiated by about 20 MeV electrons from a Linac. Neutrons were extracted from both a reentrant hole at the center of the moderator and an outer surface of the moderator. In the case of the para-H$_2$ moderator, the neutron spectrum intensities from the reentrant hole and the outer surface were very similar, while the latter was much higher than the former in the ortho-para-H$_2$ moderator case. It was concluded that the geometrical shape of a moderator is more sensitive on the intensity at ortho-para-H$_2$ moderator than that at the para-H$_2$ moderator.

Würz [5] measured neutron energy spectra and pulse characteristics from a cylindrical H$_2$ moderator of 160 mm in height and 148 mm in diameter for various para-H$_2$ concentration between 33 and 98%, utilizing 14-MeV neutrons that was produced by the D-T reaction as a source. The para-H$_2$ concentration was determined based on the difference of heat conductivity between ortho- and para-H$_2$. In practice, difference between electric resistance of tungsten wires in the normal-H$_2$ (reference) and analyzing H$_2$ gas was measured by means of a Wheatstone
bridge. As a result, the energy spectrum measurements indicated that the spectral intensity below about 20 meV increased with the para-H\(_2\) concentration. For instance, it was reported that the 98\% para-H\(_2\) moderator exhibited 45\% higher intensity than the 45\% para-H\(_2\) moderator. Pulse characteristics were measured at the para-H\(_2\) concentration of 77 and 98\%. It was indicated that the pulse width from the 77\% para-H\(_2\) moderator was rapidly broadened below about 40 meV compared to that from the 98\% one.

Recently, Ooi et al.[6] measured neutron energy spectra and pulse shapes from a moderator of 50 mm in thickness and 120 mm in width and height in a graphite reflector, as a function of the para-H\(_2\) concentration, and compared the experimental results with calculations. At the neutron energies below 100 meV, the pulse peak intensities increased and the pulse width decreased with the increase of the para-H\(_2\) concentration. They found that the calculations were consistent with the experimental results in terms of the dependence of the para-H\(_2\) concentration on the neutronic performance although there were some discrepancies in the absolute values. It was concluded that the calculation is reliable to optimize parameters of a moderator system although there are some discrepancies between the measurements and the calculations.

In JSNS, the optimal para-H\(_2\) concentration was obtained to be 100\% together with the optimal moderator dimension as a result of calculation studies [7, 8]. The effects of these parameters on the time-integrated neutron intensity and the pulse characteristics are also consistent with the existing experimental results. In addition, a spatial distribution of low-energy (\(<15\) meV) neutron intensity was calculated on a viewed-surface of the coupled moderator. A 100\% para-H\(_2\) moderator exhibited a peculiar distribution having an intensity-enhanced region at a fringe part near premoderator, while the intensity decreased at the fringe part in a normal(25\% para)-H\(_2\) moderator. For the distribution of the normal H\(_2\) moderator, an experimental result had been reported by Ogawa et al.[9]. Ogawa measured neutron intensities on a viewed-surface at 5 Å (3.3 meV) and 10 Å (0.82 meV) from a ortho-rich-H\(_2\) moderator as a function of the vertical distance from the moderator bottom. Judging from a natural conversion speed from ortho- to para-H\(_2\) and a holding time in the experiment, the para-H\(_2\) concentration is estimated to be about 35\%. It was confirmed that the calculated distribution for normal-H\(_2\) is consistent with the measured one. There is still no experimental data exhibiting such a peculiar spatial distribution at the 100\% para-H\(_2\) moderator. Therefore, it is indispensable to measure the spatial distribution at 100\% para-H\(_2\) moderator in order to discuss a reliability of the calculated result.

In this report, the authors measured spatial distributions of neutron intensity and energy spectra on an ortho-rich- and a para-H\(_2\) moderators using position sensitive helium-3 (\(^3\)He) detectors through a pinhole. The results are to be utilized to confirm the calculation reliability.
2 Experiment

2.1 Experimental arrangement

This experiment was performed at the Hokkaido University 45-MeV electron linear accelerator facility. A lead target (80W×75H×150D mm) and a liquid hydrogen moderator (120W×120H×50T mm) with 20 mm-thick polyethylene premoderator were surrounded by a graphite reflector, the volume of about 1 m$^3$, as shown in Figs. 2 and 3. A neutron beam extraction hole, the area of 120×120 mm, was equipped in the reflector. Neutrons were detected by a position sensitive detector system located at 6 m from the moderator viewed-surface through a cadmium (Cd) plate (0.5 mm thick) with a pinhole (2 mm$^\phi$). An inverted distribution of the neutron intensity on the moderator viewed-surface was observed by the detector as shown in Fig. 4. A small piece of Cd (30×8 mm) was attached on the moderator viewed-surface for marking.

The position sensitive detector system PSD2K (Fig. 5) [10] consists of eight $^3$He gas counters (12.5$^\phi$×600L mm) and data acquisition components. As shown in Figs. 6 and 7, a Cd plate with slits of 2 mm in width was attached in front of the $^3$He counters aiming at improving vertical resolution. Figure 8 shows an example of the obtained data by one of the $^3$He counters. A higher intensity region around 4 ms between 90 and 145 ch corresponds to the Maxwellian peak of cold neutrons. Each $^3$He counter produces two-dimensional data like this.

2.2 Calibrations and corrections of detector system

In a position sensitive $^3$He counter, the produced charges by the $^3$He(n,α) reaction were collected at both ends of the counter. A relative neutron position on the $^3$He counter was determined from a ratio of the charges at both ends, and was stored as 256 channel digital data by the PSD2K module [10]. To obtain absolute position, neutrons were measured through the Cd slits plate (2 mm in width at 12.5 mm interval) perpendicular to the counters. As an example, Fig. 9 shows the neutron intensities as a function of relative horizontal position and time-of-flight (TOF) obtained by a counter, and Fig. 10 shows those integrated below 100 meV (>1.4 ms in TOF). A coefficient to convert the relative position (channel) to the absolute one was derived from the relations between the peak channel and the slit position. As shown in Fig. 11, the coefficient was obtained for each counter as a result of fitting by the least squares method. The average of the coefficients was 2.075±0.009 (mm/ch).

It is necessary to correct differences of the detection efficiency between the $^3$He counters. To obtain a flat distribution at the counters, neutrons were observed after removing the Cd plate with the pinhole in the flight-path. The corrected neutron intensity $I(X,d,E)$ was derived as follows;

$$I(X,d,E) = \frac{C(X,d,E)}{C_{ref}(X,d,E)},$$

where $X$ is the horizontal position, $d$ is the detector identification number, $E$ is the neutron
energy, $C$ is the neutron counting rate through the Cd plate with the pinhole, $C_{\text{ref}}$ is the counting rate without the Cd plate.

Background measurements were carried out by blocking up the pinhole of the Cd plate. Figure 12 compares the foreground and the background $I(X, d, E)$ integrated below 15 meV, $I_{15}(X, d)$, for a $^3\text{He}$ counter. The background was 5~13% of the foreground.

### 2.3 Para hydrogen concentration

Figure 13 shows a diagram of an H$_2$ gas supply system to the moderator. The supplied H$_2$ gas is condensed at the cold head above the moderator chamber (Fig. 2). This system consists of an H$_2$ gas bottle, flow and pressure gauges, valves and an ortho to para converter (Fig. 14), which convert ortho-H$_2$ to para-H$_2$ using an iron hydroxide (Fe(OH)$_3$) catalyst. The equilibrium para-H$_2$ concentration depends on temperature as shown in Fig. 15 cited from a reference [11]. In order to discuss effects of the para-H$_2$ concentration, both para-H$_2$ and ortho-rich-H$_2$ were filled in the moderator chamber. In the case of para-H$_2$, H$_2$ was introduced to the moderator chamber through the converter at 24 K. As shown in Fig. 15, the equilibrium para-H$_2$ concentration was expected to be $\sim$99%. In the case of ortho-rich-H$_2$, the H$_2$ gas was introduced directly to the moderator chamber without passing through the converter. The para-H$_2$ concentration is 25% at a room temperature, and increases as the following equation after H$_2$ liquefaction.

$$Q_p(t) = 1 - \frac{Q_o(0)}{1 + ktQ_o(0)},$$

where $Q_p(t)$ is the para-H$_2$ concentration at time t, $Q_o(0)$ the ortho-H$_2$ concentration at $t=0$ and $k$ the natural conversion constant. Figure 16 is a plot for $k = 0.0114$/hr [12].

The para-H$_2$ concentration was measured by the Raman spectroscopy, which used an inelastic scattering and subsequent deexcitation of a laser light. A photograph of the Raman spectrometer is shown in Fig. 17. The H$_2$ gas was sampled into a sampling bottle, and was filled into a transparent glass cell for the Raman spectroscopy as shown in Fig. 18. A Raman spectrum for 25% para-H$_2$ is shown in Fig. 19. A peak around 360 cm$^{-1}$ of Raman shift corresponds to para-H$_2$, that around 590 cm$^{-1}$ ortho-H$_2$. A peak area for para-H$_2$ ($I_p$) is defined as a product of the para-H$_2$ population ($P_p$) and the constant $C_p$ determined by such parameters as the cross section of Raman scattering, the detection efficiency for the scattered light, etc. Using those values for ortho-H$_2$ ($I_o$, $P_o$ and $C_o$), the ortho/para ratio ($r$) is obtained as follows,

$$r = \frac{P_o}{P_p} = \frac{I_o/C_o}{I_p/C_p} = \frac{I_o}{I_p} \times \frac{C_p}{C_o}. \tag{3}$$

The $C_p/C_o$ value of 1.2 $\pm$ 0.1 was obtained by measuring the Raman spectrum of the ortho-rich-H$_2$ (25% para-H$_2$) ($r=3$), which was kept at room temperature for a long time. The para-H$_2$ concentration is derived as $1/(1+r)$. 

\[\text{--- 4 ---}\]
A time table of the present experiment is shown in Fig. 20. H₂ was sampled before and after the neutron measurements for the para-H₂ moderator, and after those for the ortho-rich-H₂ one. Raman spectra of the para-H₂ moderator samples are shown in Fig. 21. Large peaks from para-H₂ and small peaks from ortho-H₂ were recognized. Expanded views of these peaks denoted by ‘view-1’ and ‘view-2’ are shown in Figs. 22 and 23, respectively. A Raman spectrum of the ortho-rich-H₂ moderator sample is shown in Fig. 24. Peaks from para-H₂ and ortho-H₂ were clearly seen. The value of \( r \) in eq.(3) and the para-H₂ concentrations were derived from integral counts corresponding to the para- and ortho-H₂ peaks as shown in Table 1. The uncertainties of the para-H₂ sample were mainly caused by statistical error of the ortho-H₂ peak counts, while those of the ortho-rich-H₂ one the error of the para-H₂ peak counts of the ortho-rich-H₂ (reference). The para-H₂ concentrations of the para-H₂ samples (sampling (1) and (2) in Fig. 20) agreed within their uncertainties. In the case of the ortho-rich-H₂ sample, the para-H₂ concentration increased during the neutron measurements due to the natural conversion as mentioned in this section. Figure 25 compares the measured para-H₂ concentration with that obtained by eq.(2). It was assumed that \( t=0 \) was the middle of the H₂ liquefaction duration (6 h), which was indicated as a horizontal error-bar in Fig. 25. The para-H₂ concentration was estimated to be between 30 to 40% during the neutron measurements for the ortho-rich-H₂ moderator.
3 Results

3.1 Spatial distribution

Due to the $^3$He counter size, spatial distribution measurements were performed by separating the moderator viewed surface into two regions where a region is near the target part of the moderator viewed surface, called as a near-target part, and is far from the target part, called as a far-target part. Figure 26 shows two-dimensional views of the spatial distribution of the neutron intensity below 15 meV, $I_{15}(X,Y)$, where $Y$ is the vertical position of the slit in front of the counter relative to the moderator center. Although $I_{15}(X,Y)$ is shown in an arbitrary unit, those from the para-H$_2$ and the ortho-rich-H$_2$ moderators can be directly compared since $I_{15}(X,Y)$ is normalized to the electron beam current of the accelerator. The horizontal distributions are shown in Figs. 27 and 28, the vertical ones are shown in Figs. 29 and 30 for the cases of the para-H$_2$ and the ortho-rich-H$_2$ moderators, respectively. An intensity depression in the upper right part of each contour map ($Y=30-60$ mm, $X\geq 40$ mm) corresponds to the small piece of Cd for marking. Through the results, it is clear that $I_{15}(X,Y)$ at the para-H$_2$ moderator is enhanced at the side and bottom fringe parts near premoderator, while $I_{15}(X,Y)$ at the ortho-rich-H$_2$ one is depressed at the fringe parts. This provides us that the calculated distribution [7] is qualitatively reasonable.

In the viewings of the far-target parts (upper figures of Figs. 26, 27, 28), lower intensity regions are observed at $Y=60$ and 72 mm in the para-H$_2$ case and only at $Y=72$ mm in the ortho-rich-H$_2$ case. This suggests that there is no liquid H$_2$ at $Y=72$ mm in both cases, referring the moderator height of 120 mm corresponds to $Y = -60 \sim 60$ mm. The para-H$_2$ case suggests that the level of liquid H$_2$ in the moderator chamber was less than that of $Y=60$ mm since the intensity at $Y=60$ mm is almost equal to that at $Y=72$ mm.

The horizontal distributions exhibit symmetrical shapes about center except the case of $Y=-38$ mm, in which $I_{15}(X,Y)$ depresses unnaturally in the region of $X<0$. Then, let define an asymmetric index that indicates the degree of the asymmetricity of the distribution as follows:

$$A_s(X) = 1 - \frac{I_{15}(-X,Y)}{I_{15}(X,Y)} \quad (X \geq 0).$$

Figure 31 shows $A_s(X)$ at $Y=-38$ mm for both moderators. From the figure, a position dependence of $A_s(X)$ is almost same. Such the depressions are not seen at the far-target viewings. Accordingly, the asymmetricity is restricted at the part very close to the target. Reviewing the preparation of the measurements, a path to the moderator center was checked by using a laser light, but the paths to the moderator fringe parts were not checked. And, as shown in Fig. 32, there are some shields inside the neutron flight tube. Therefore, it is considered that the neutron flight path was partly shaded by one of the shields. Then $I_{15}(X,Y)$ data below $X<0$ for $Y=-38$ mm should be omitted in the following discussions.

Figure 33 shows projections of the horizontal distributions of $I_{15}(X,Y)$ at the near-target part of the moderator for both the para-H$_2$ and the ortho-rich-H$_2$ cases, where the vertical
direction intensities at a horizontal position is integrated along the vertical direction and an average intensity such as \( \left\{ \left( I_{15}(-X,Y) + I_{15}(X,Y) \right) \right\}/2 \) is used at the horizontal position since the horizontal distributions exhibits the symmetrical shape about the center. In the central part \((0<|X|<\sim 30 \text{ mm})\), \( I_{15}(X,Y) \) is almost unchanged with \( X \) in both cases. From \(|X|\sim 30 \text{ mm} \) to the fringe, \( I_{15}(X,Y) \) in the para-H\(_2\) case gradually increases with \( X \) by 16\% relative to that at \( X=0 \), while \( I_{15}(X,Y) \) in the ortho-rich-H\(_2\) case decreases by 13\%. The calculated result in a reference [7] shows that \( I_{15}(X,Y) \) at the fringe is higher than that at the central part by about 50\% in a pure para-H\(_2\) moderator. The gain factors at the fringe part in the para-H\(_2\) moderators are different between the calculation (50\%) and the experimental result (16\%). One of reasons for this discrepancy is due to the moderator thickness difference such as 50 mm in this experiment and 140 mm in the calculation, respectively.

Figure 34 shows projections of vertical distributions of \( I_{15}(X,Y) \), corrected data as well as the horizontal distribution case. \( I_{15}(X,Y) \) in the para-H\(_2\) case monotonously decreases with increasing \( Y \), while \( I_{15}(X,Y) \) in the ortho-rich-H\(_2\) case has a maximum around \( Y=\sim -25 \text{ mm} \) and then decreases with increasing \( Y \). The intensity enhancement is recognized around the fringe part near premoderator of the para-H\(_2\) moderator in both vertical and horizontal projections.

### 3.2 Neutron energy spectrum

The neutron energy spectra were measured by means of the time-of-flight method. Those at the central part \((|X|=0 \text{ mm})\), the fringe parts \((|X|=42 \text{ and } 52 \text{ mm})\), and the outside part \((|X|=62 \text{ mm})\) are shown in Figs. 35 and 36 for the para-H\(_2\) and the ortho-rich-H\(_2\) moderators, respectively. The energy spectra are averaged over the data between \( Y=\sim -26 \text{ and } 25 \text{ mm} \) (see Figs. 27 and 28) where the intensity along the vertical direction exhibits stable property.

The energy spectra at the outside part are composed as mixtures of neutrons from the H\(_2\) moderator and the polyethylene premoderator that provides thermal neutrons. Therefore, the neutron intensity in the thermal energy region \((>20 \text{ meV})\) at the outside part is higher than those at the other parts, while that in the cold energy region \((<20 \text{ meV})\) is lower.

At the fringe part, both moderators have the intensity enhancements in the energy region between 15 meV and 100 meV. At energies below 15 meV, the para-H\(_2\) moderator brings about higher intensity, while the ortho-rich-H\(_2\) exhibits an intensity decrease. The intensity enhancements between 15 and 100 meV is considered to be caused by a short scattering mean-free-path of the source thermal neutrons (above 15 meV) provided from the premoderator. The scattering mean-free path is 10 mm (at 50 meV) \sim 20 mm (at 25 meV) in the para-H\(_2\) moderator, and is shorter than 10 mm in the ortho-rich-H\(_2\) one. Accordingly, the both moderators exhibit higher intensity at the fringe part at neutron energies above 15 meV. In the energy region below 15 meV, the mean-free-path for para-H\(_2\) is very long such as more than 100 mm resulting in a small probability of additional scattering. Namely, the para-H\(_2\) moderator is transparent in this region. Therefore, the neutron intensity below 15 meV also exhibits the fringe-enhanced
distribution. While in the ortho-rich-\(H_2\), the spatial distribution is approaching to a cosine like distribution getting to equilibrium with liquid \(H_2\) since the mean-free-path is much shorter, less than 6 mm below 15 meV. Therefore, the spatial distribution on the ortho-rich-\(H_2\) moderator is expressed by a combination of the fringe-enhanced distribution and a cosine like distribution. From the above consideration, it is revealed that the fringe-enhanced distribution of neutron intensity below 15 meV is caused by the unique property of the para-\(H_2\) cross section.

The energy spectra of the para-\(H_2\) and ortho-rich-\(H_2\) moderators are compared in Fig. 37 at various positions, \(|X|\). For detail comparisons, right figures show the ratios of the neutron intensities between the para- and the ortho-rich-\(H_2\) moderators. The energy dependence of the neutron intensity ratio is similar among all positions as having a intensity enhancement around 10 meV. One of the reasons for this enhancement is the neutron slowing down reaction accompanied to the para-\(H_2\) to ortho-\(H_2\) spin-flip transition. The energy of neutrons around several tens meV are more efficiently converted to about 10 meV in the para-\(H_2\) moderator. Another reason is the leaky characteristics of para-\(H_2\) due to the much smaller cross section, which decreases rapidly between 50 and 15 meV down to 1/50 comparing to ortho-\(H_2\). Therefore, the neutrons, which are slowed down to around 10 meV, are easy to be emitted. It is noted that this energy dependence of the ratio is consistent with the calculation [7].
4 Conclusion

The distributions of low-energy neutron intensity were measured for the para-H$_2$ and ortho-rich-H$_2$ moderators together with their energy spectra. The measured results demonstrate that the calculated distribution of low-energy neutrons in the JSNS design study [7] is qualitatively reasonable although the moderator dimensions are not same. This experimental study validates the JSNS design strategy in which 100% para-H$_2$ concentration is assumed.

Acknowledgement

The authors thank Prof. H. Habasaki for the measurement of para-H$_2$ concentration by Raman spectroscopy. We thank Mr. S. Sato for providing us the position sensitive detector. We thank Mr. H. Iwasa for the arrangement and operation of the cryogenic system, and Mr. K. Sato for the accelerator operation.

References


Table 1: Peak counts in Raman spectra and para $\text{H}_2$ concentration

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<tr>
<th>Sampling</th>
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Fig. 1: Scattering cross sections for liquid ortho-hydrogen (upper curve) and liquid para-hydrogen (lower curve) at 20 K calculated for ENDF/B-VI.3 [2].

Fig. 2: Experimental arrangement of target, moderator and reflector.
Fig. 3: Photograph of electron beam line, reflector and neutron beam line.

Fig. 4: Principle of distribution measurement using a pinhole.
Fig. 5: Components of position sensitive detector system, reproduced from Ref. [10]

Fig. 6: Cross sectional view of slit and detectors.
Fig. 7: Photograph of a Cd slit and $^3$He counters. $B_4C$ shielding-blocks were put in front of the $^3$He counters except the slit.

Fig. 8: An example of measured data by a $^3$He counter. Horizontal axis shows the horizontal position of neutrons, vertical one shows the time-of-flight of neutrons.
Fig. 9: Neutron intensity with vertical slits for calibration of horizontal position.

Fig. 10: Neutron intensity below 100 meV with vertical slits for calibration of horizontal position.
Fig. 11: Relations of channel number in PSD system and absolute position at each detector.

Fig. 12: Comparison of neutron intensities below 15 meV between the foreground and background measurements.
Fig. 13: Diagram of hydrogen gas supply system.

Fig. 14: Schematic view of ortho to para $\text{H}_2$ converter.
Fig. 15: Equilibrium para-H$_2$ concentration as a function of temperature [11].

Fig. 16: Para hydrogen concentration as a function of time at 20 K.
Fig. 17: Raman spectrometer

Fig. 18: Glass cell and sampling bottle.
Fig. 19: Raman spectrum for 25% para-$\text{H}_2$.

Fig. 20: Time table of experiment.
Fig. 21: Raman spectra from para-H$_2$ samples taken before and after neutron measurements.

Fig. 22: Enlarged view of Raman spectra of 'view-1 indicated in Fig. 21.
Fig. 23: Enlarged view of Raman spectra of 'view-2 indicated Fig. 21.

Fig. 24: Raman spectrum from ortho-rich-H₂ sample after neutron measurements.
Fig. 25: Time evolution of para H$_2$ concentration in the case of ortho-rich-H$_2$. 
Fig. 26: Spatial distributions of neutron intensity below 15 meV from para- (left) and ortho-rich-H$_2$ (right) moderators. Upper figures show the results viewing a far-target part of the moderator. Lower the results viewing a near-target part. Contour line is not depicted outside H$_2$. 
Fig. 27: Horizontal distribution of neutron intensity below 15 meV from para-H$_2$ moderator as a function of vertical length from moderator center.
Fig. 28: Horizontal distribution of neutron intensity below 15 meV from ortho-rich-H\textsubscript{2} moderator as a function of vertical length from moderator center.
Fig. 29: Vertical distribution of neutron intensity below 15 meV from para-H$_2$ as a function of horizontal length from moderator center.
Fig. 29: Vertical distribution of neutron intensity below 15 meV from para-H$_2$ as a function of horizontal length from moderator center. (cont’d)
Fig. 30: Vertical distribution of neutron intensity below 15 meV from ortho-rich-H$_2$ as a function of horizontal length from moderator center.
Fig. 30: Vertical distribution of neutron intensity below 15 meV from ortho-rich-H$_2$ as a function of horizontal length from moderator center. (cont’d)
Fig. 31: Asymmetricity index for the horizontal distribution of $I_{15}(X,Y)$ at $Y=-38$ mm.

Fig. 32: Photograph of components inside neutron flight tube.
Fig. 33: Comparison of horizontal distributions of neutron intensity below 15 meV between the ortho-rich- and para-H\textsubscript{2} moderators.

Fig. 34: Comparison of vertical distribution of neutron intensity below 15 meV between the ortho-rich- and para-H\textsubscript{2} moderators.
Fig. 35: Energy spectra for the para-H$_2$ moderator at various horizontal position ($|X|$).
Fig. 36: Energy spectra for the ortho-rich-H$_2$ moderator at various horizontal position (|X|).
Fig. 37: Comparison of neutron energy spectra between the para and ortho-rich-H$_2$ moderator at various |X|. Right figures show ratios of intensities.
国際単位系（SI）

表 3. 基本単位

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表 4. 基本単位を用いて定義される次元単位

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この国際単位系の定義は、科学における国際的な基準を定め、物理量を比較する際の基準として用いられる。