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Recent Progress in the Chopper Spectrometer, INC

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Abstract

A guide tube comprising supermirrors, of which the critical wavenumber is three times as large as that of natural nickel, was installed in the primary flight path of the chopper spectrometer, INC, at KENS. Also, the characteristics of the ambient-temperature H_2O moderator, which INC is facing, was changed by renewal construction of the neutron source at KENS. We discuss here an improvement in the performance of INC by a comparison with the previous performance. We also report on the development on a goniometer for single-crystal experiments at low temperatures.

1. Introduction

The INC spectrometer [1], constructed in 1987, is the chopper spectrometer at KENS (Neutron Science Laboratory, High Energy Accelerator Research Organization). Using this spectrometer, scientific results have been obtained from studies mainly on low-dimensional magnetic excitations as well as crystalline field excitations [2]. Since the construction of INC, its performance has remained almost unchanged. However, we very recently had an opportunity to improve its performance owing to renewal construction of the KENS neutron source [3,4] and the installation of a supermirror guide tube. The renewal construction of the KENS neutron source was planned in order to recover the cold-neutron flux, which was reduced by blocking the neutron beam lines with distorted cadmium decouplers. In the renewal construction, we not only repaired the cold-neutron source, but also changed the characteristics of the ambient-temperature H_2O moderator, which INC is facing, mainly due to poisoning. Also, the target material was changed from tantalum to tungsten so as to increase the neutron yield. Therefore, an improvement in the performance of INC can be expected by renewal construction. A guide tube is known to be a device for transporting cold neutrons to an instrument installed far from the neutron source via total reflection from the guide coating. Among common materials, natural nickel has been a good choice for the coating with a large critical wavenumber. Because supermirrors with a critical wavenumber, triple that of natural nickel, have recently become commercially available, a guide tube effective for higher neutron energies can be realized for such a spectrometer for thermal-neutron experiments as INC. During the renewal construction of the neutron source, we installed a supermirror guide tube to gain neutron flux on INC. In this paper, we report on an improvement in the performance concerning these constructions. Furthermore, we also report here on the development of a goniometer with a refrigerator, which is indispensable for measuring magnetic excitations by using a single-crystal sample.

2. Supermirror Guide Tube

The primary flight path is 8.2 m, and the secondary path is 2.5 m for low angles and 1.3 m for high angles on INC. A supermirror guide tube was recently installed in the primary flight path, as shown in Fig.1. The guide tube is a straight guide with a cross section of 8 cm

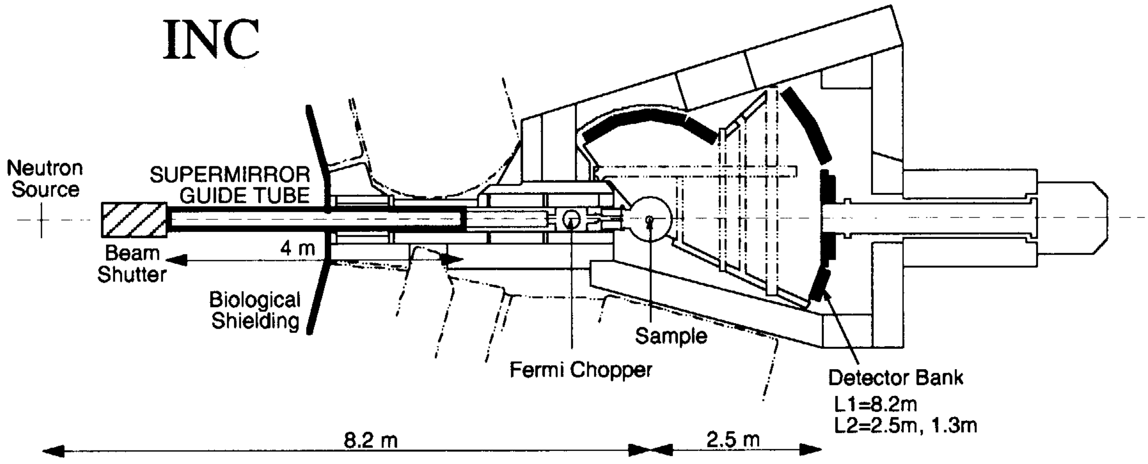

Fig.1 Layout of the chopper spectrometer, INC.

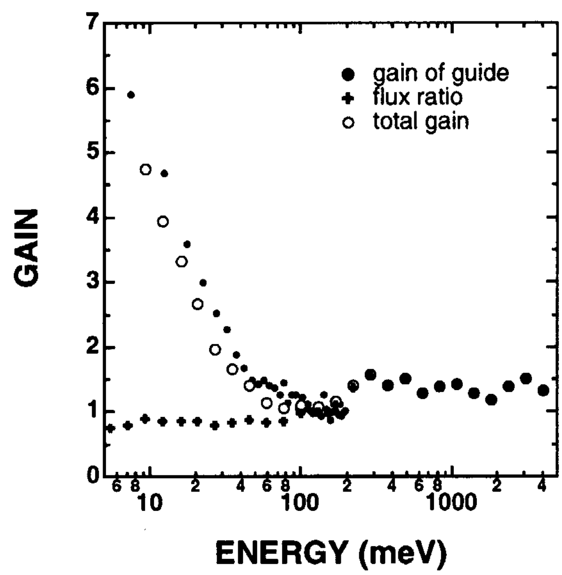

Fig.2 Calculated intensity gain as a function of the neutron energies. The gain of the supermirror guide tube, the ratio of the intensity for the present neutron source to that for the previous one, and the total intensity gain (product of the above two) are plotted. The gain of the guide tube at high energies should be 1.

× 8 cm and a length of 4 m, and located between just downstream of the shutter and the Fermi chopper. The guide tube is facing the moderator area of 10 cm × 10 cm. There is a collimator between the end of the guide tube and the sample area (6 cm × 6 cm). In the previous configuration, INC was also facing the same moderator area, and there was a collimator between the end of the shutter and the sample area (6 cm × 6 cm). Therefore, by installing the guide tube, the collimation became slightly larger. We employed NiC/Ti-supermirrors manufactured by Osmic Inc. [5]; the supermirror structure is coated on a float glass substrate. In the wavenumber (Q) dependence of the neutron reflectivity from the supermirror used in the present assembling, the reflectivity shows more than 90% at Q = 0.063Å^{-1} near to the critical point [6]. We assembled supermirror pieces with a typical coating area of 8 cm × 20 cm (thickness of glass is 2 mm or 5 mm) into a guide tube with a square cross section, as follows: SUS frames having a typical length of 40 cm of each for assembling the supermirrors were manufactured, and the SUS frames for mounting supermirrors were inserted into the existing vacuum vessel (length is 2.2 m) in the biological shielding in the upstream part of the neutron beam line and the newly manufactured vacuum vessel in the downstream part. The tolerance of the glass substrate was ±0.05 mm, and the SUS frames were manufactured with a typical tolerance of ±0.05 mm or ±0.1 mm. Consequently, the supermirrors were assembled into a guide tube with a parallelism of ±0.7 mrad between the right and left mirrors and ±0.4 mrad between the upper and lower mirrors in a SUS frame section of 40 cm with respect to the neutron beam line. The actual tolerance of the existing vacuum vessel was unknown. The SUS frames, the new vacuum vessel and some additional items were manufactured by Suzuno Giken Co., Ltd. We performed a Monte-Carlo calculation [7] to evaluate the intensity gain for installing the guide tube. Figure 2 shows the calculated intensity gain, which is the ratio of the intensity with the guide tube to that without guide tube. The guide tube is effective at neutron energies less than approximately 80 meV, a gain factor of 3 can be expected at 20 meV and of 6 at 10 meV.

3. Ambient-Temperature H_2O Moderator

INC is facing the ambient-temperature H_2O moderator. In the renewal construction, the moderator itself and its surroundings were changed as described below [3]. First, the target material was changed from tantalum to tungsten in order to increase the neutron yield. Second, we inserted a gadolinium foil at the half thickness in the moderator in order to make the pulse shape sharper by this poisoning. Third, the decoupling energy was changed from 350 eV to 100 eV at the target side and from 95 eV to 50 eV at the reflector side. Finally, in the reflector we used beryllium near to the target and moderator, and graphite for the outer region. We performed an LCS neutronic calculation [8] to describe the energy dependence of the neutron flux integrated over the emission time for the present neutron source as well as the previous one. The ratio of the integrated intensity for the present source to that for the pervious one is also plotted in Fig.2. There is an intensity gain at high energies due to the change in the target material as well as in the decoupling energy. At low energies, the integrated intensity decreases due to poisoning. The calculated total gain, which is the product of the intensity ratio and the gain of the guide tube, can be expected to be more than 1, as shown in Fig.2.

We also performed an LCS neutronic calculation for the pulse shape, i.e., the intensity against the emission time, as shown in Fig.3. At low energies, the pulse shape became sharper, and at all energies the peak height became higher. The solid lines are the fitted curves with so-called Ikeda-Carpenter function [9], as follow:

$$p(E,\tau) = \frac{\alpha}{2}(1-R)(\alpha\tau')^2 e^{-\alpha\tau'} + \frac{R\alpha^3\beta}{(\alpha-\beta)^3}\left\{e^{-\beta\tau'} - e^{-\alpha\tau'}\left(1+(\alpha-\beta)\tau'+\frac{1}{2}(\alpha-\beta)^2\tau'^2\right)\right\}, \quad (1)$$

where $\alpha=\Sigma v$ with $E = mv^2/2$ (the neutron mass, m) and $\tau'=\tau-\tau_0$ with the emission time, τ ($>\tau_0$). The calculated pulse shapes were well fitted to the Ikeda-Carpenter function in eq.(1), and the obtained parameters (β, Σ, R and τ_0) are plotted as a function of the neutron energy in Fig.4. β is the decay rate describing the storage term, which depends on the effective thickness of the moderator. In the previous neutron source, β was independent of the neutron energy because of no poisoning. In the present neutron source, a reasonable energy dependence of β has been shown for the present poisoning. Σ is the macro cross section

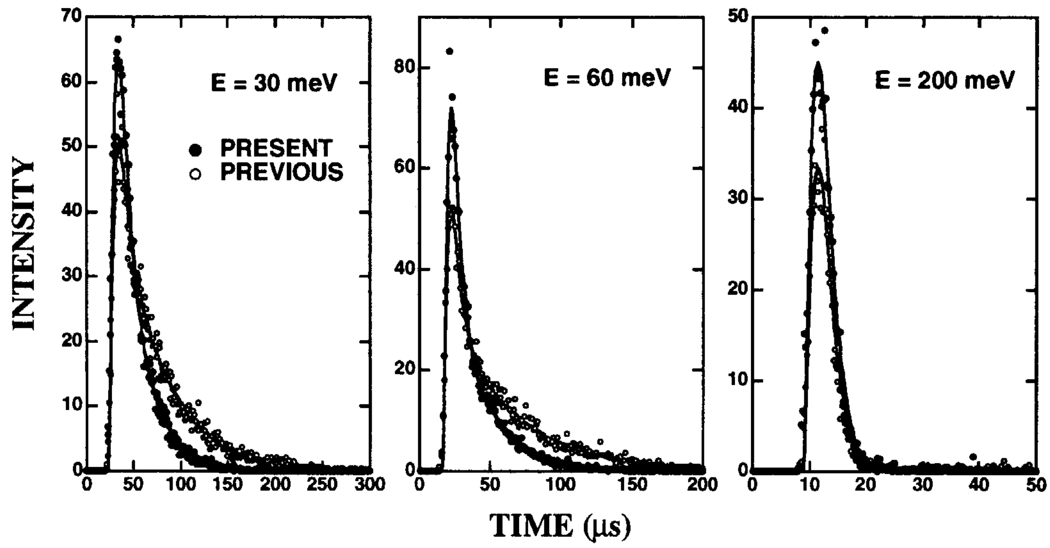

Fig.3 Pulse shape of neutrons emitted with a certain energy, i.e., emission-time dependence of neutron intensity. The solid and open circles indicate the present and previous neutron sources. The solid lines are the fitted curve with the Ikeda-Carpemter function (see text).

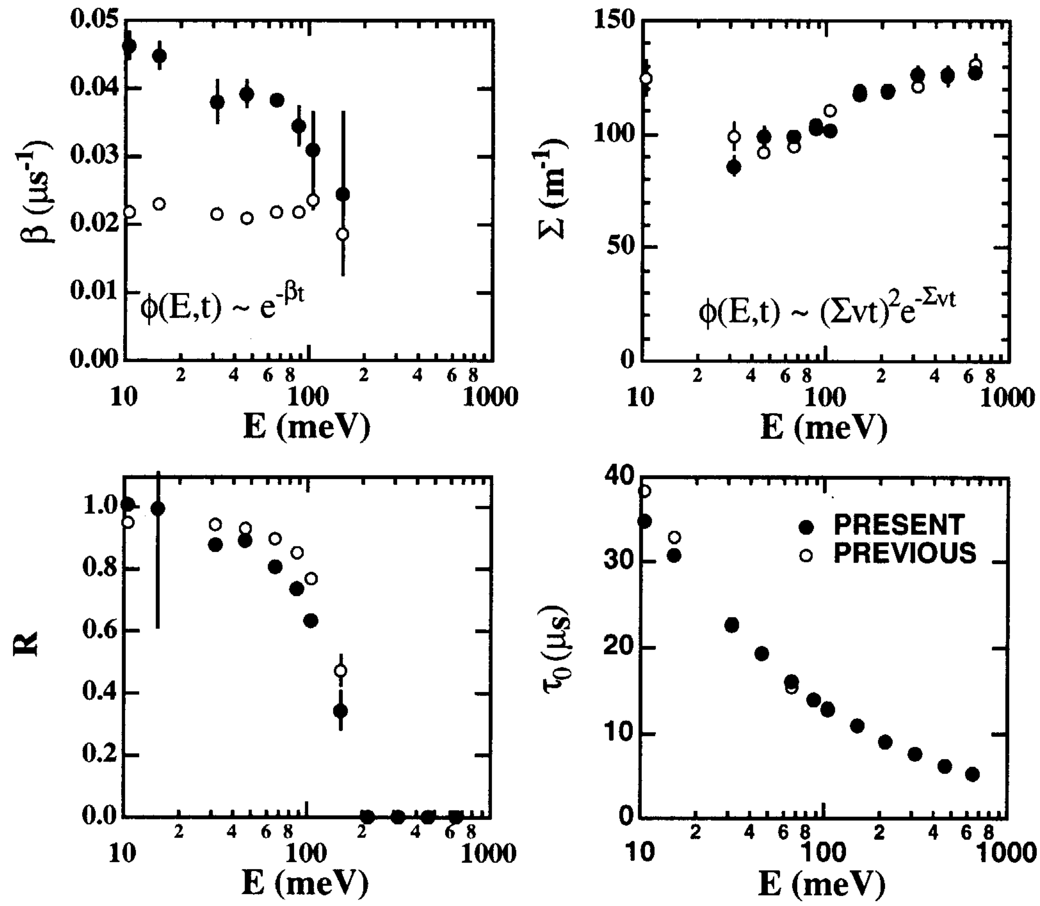

Fig.4 Energy dependence of the parameters in the Ikeda-Carpenter function, in eq. (1), for the pulse shape obtained by the fit shown in Fig. 3. The solid and open circles indicate the present and previous neutron sources. For $E \geq 200$ meV, R was fixed at 0, where β is not effective.

describing the slowing-down term. Σ was almost unchanged for changes in the neutron source. Using these parameters, we discuss the observed spectrum below.

4. Observed Performance

In order to investigate the change in the performance of INC, we performed neutron-scattering experiments: a vanadium cylindrical sample with a thickness of 1 mm, a diameter of 2.5 cm and a height of 5.8 cm was mounted at the sample position for the present configuration and the previous one, and the scattered neutrons were detected at detectors 2.5 m from the sample position. The geometrical configuration of the experiments for the present configuration was identical to that for the previous one, except for the guide tube and the collimation for the primary flight path, as described above. Figure 5 (a) shows the observed scattering intensity, which is the sum of the intensities detected at scattering angles from 5.5° to 40.4°, without a Fermi chopper. These intensities were normalized by the number of protons injected to the target. The ratio of the observed intensity for the present configuration to that for the pervious one is shown in Fig.5 (b). The calculated total gain in Fig.2 is also plotted in Fig.5 (b). The observed intensity gain was in very good agreement with the calculation up to 300 meV; in particular, a huge intensity gain due to installing the supermirror guide tube, especially at low energies, was observed.

We then observed the time-of-flight (TOF) spectrum by mounting a Fermi chopper to monochromatize the neutron beam, and the inelastic-scattering intensities from the vanadium sample were measured at scattering angles between 5.5° and 40.4°. The Fermi chopper was operated under an appropriate condition with respect to the incident neutron energy (E_i). Figure 6 shows the observed TOF spectrum of the scattering intensity as well as a calculation based on the geometrical configuration of INC, the structure of the Fermi chopper and the calculated pulse shape shown in Fig.3, where only the height of the calculated spectrum was adjusted to the observed intensity. For E_i = 60 meV, the observed TOF spectrum for both configurations was well described by

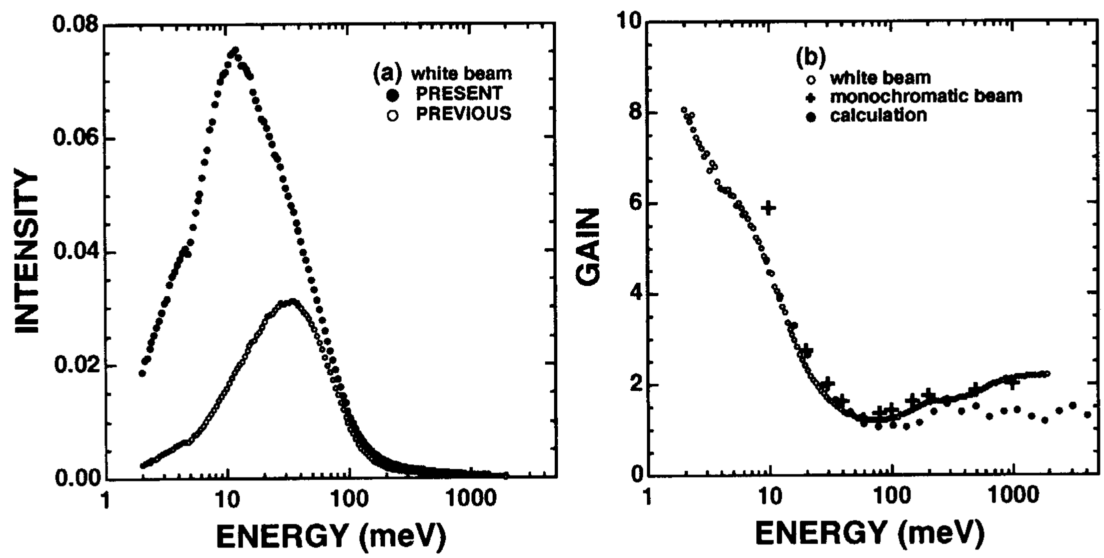

Fig.5 Observed scattering intensity from a vanadium sample with a white beam, where the solid and open circles indicate the present and previous configurations, respectively (a). The ratio of the intensity with a white beam for the present configuration to that for the previous one shown in (a) is plotted in (b). The calculated total intensity gain shown in Fig.2, and the observed intensity ratio for monochromatic beams are also plotted.

$$I(t)=\int\phi(E)p(E,t-\frac{L}{v})w(t-\frac{L_{ch}}{v_i}-\frac{L-L_{ch}}{v})dE, \tag{2}$$

where t is the TOF of the detected neutron, L is the distance between the moderator and the detector (10.71 m), L_{ch} is the distance between the moderator and the Fermi chopper (7.21 m), $E = mv^2/2$ and $E_i = mv_i^2/2$. $\phi(E)$ is the emission-time integrated neutron flux, especially in the case of the present configuration it is multiplied by the gain of the guide tube in Fig.2. $w(t)$ is the time-dependent transmission function of the Fermi chopper [10]. In the present configuration, the observed TOF spectrum became sharper than that in the previous one and the tail has been greatly reduced. In the energy-transfer spectrum, the half width was reduced to 3.0 meV for E_i = 60 meV, which is 80% of the previous width, and the tail was greatly reduced. Also for E_i= 20 meV, observed TOF spectrum has become sharper and the tail has been much reduced. For E_i = 200 meV, although the width of the observed TOF spectrum was almost unchanged, the peak became higher. For a monochromatic beam, the intensity gain, which is the ratio of the intensity integrated over TOF normalized by the number of injected protons for the present configuration to that for previous one, is also plotted in Fig.5 (b). A larger point for 10 meV comes from the poor statistics of the previous measurement.

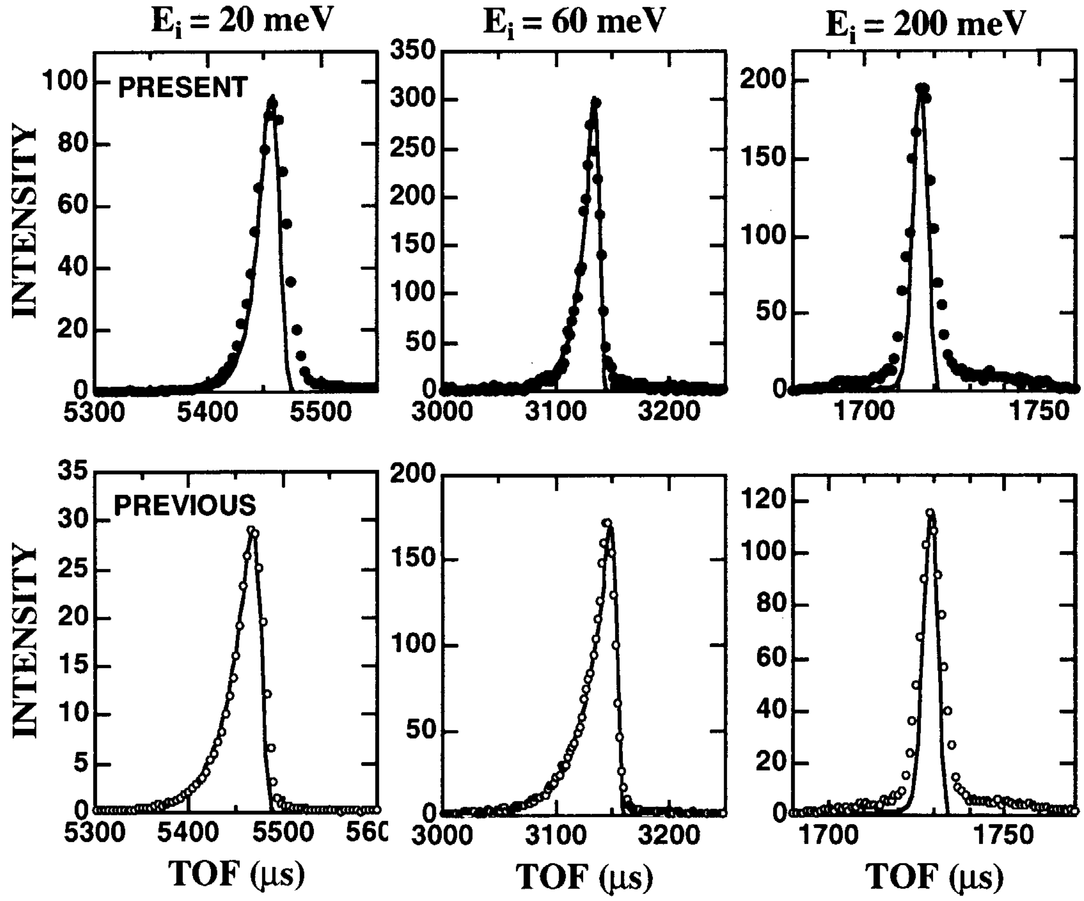

Fig.6 Observed TOF spectra with monochromatic beams. The solid and open circles indicate the present and previous configurations, respectively. The solid lines are calculated curves described in the text.

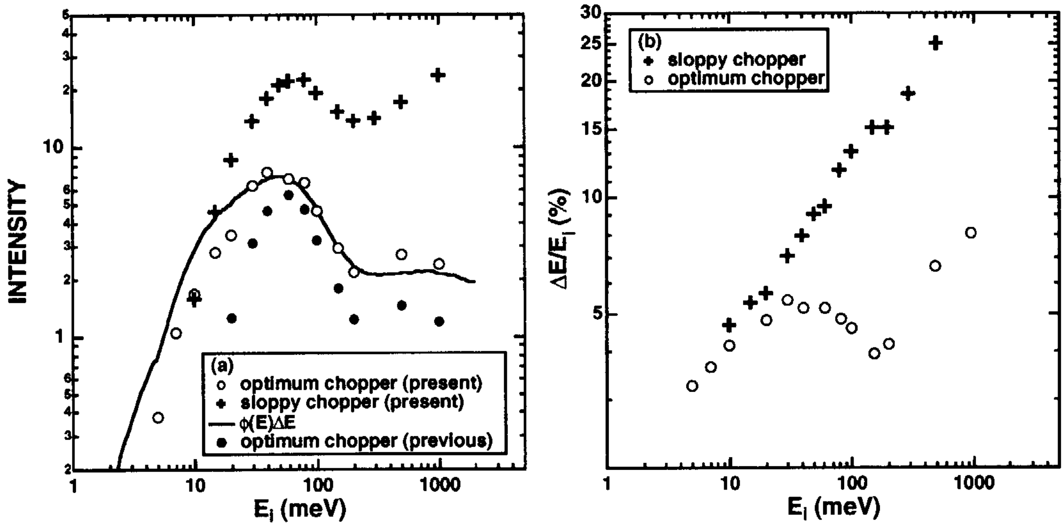

Fig.7 Observed intensities integrated over TOF with monochromatic beams (a) and corresponding energy resolution (b). The ratio of the two intensities are plotted in Fig.5 (b). The solid line is the intensity observed with the white beam multiplied by the energy resolution corresponding to the neutron energy, and scaled to the intensities of monochromatic beams. This resolution-multiplied white-beam intensity should be the maximum intensity for an appropriate operational condition of the Fermi chopper having a optimum slit package.

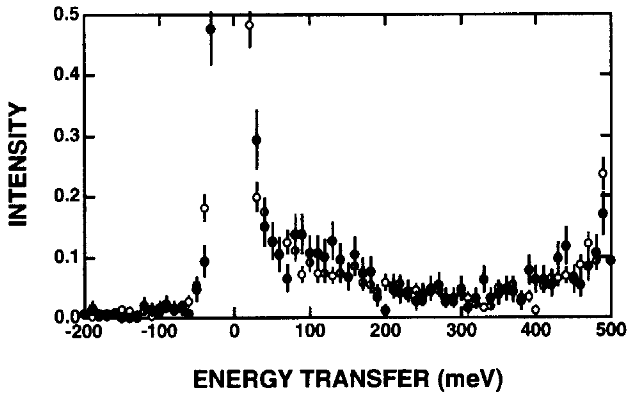

Fig.8 Inelastic spectrum from a vanadium sample measured with E_i = 500 meV at low scattering angles from 5.5° to 7.9° for the present configuration (solid circles) and the previous one (open circles). Each spectrum was normalized by the peak intensity at the elastic scattering.

This observed ratio for the monochromatic beam was in very good agreement with that observed for the white beam. This indicates that the neutrons gained by the guide tube are transmitted through the Fermi chopper, because the beam divergence increased by the supermirrors is smaller than the collimation of the slit of the Fermi chopper. For monochromatic measurements, the intensities integrated over TOF for the present configuration with the Fermi chopper having an optimum slit package, of which slit width is approximately 1 mm for high energy-resolution experiments, are plotted in Fig.7 (a). The solid line is the intensity observed with the white beam (Fig.5(a)) multiplied by an energy resolution corresponding to the neutron energy, and scaled to the intensities of monochromatic beams. This esolution-multiplied white-beam intensity should be the maximum intensity for an appropriate operational condition of the optimum chopper. The solid line almost follows the intensities of monochromatic beams for the optimum chopper,

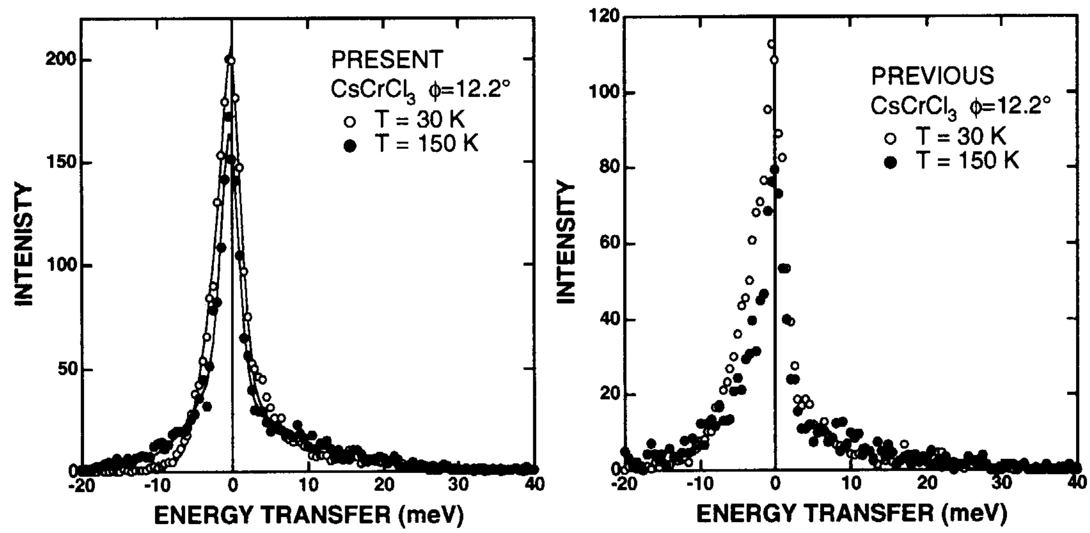

Fig.9 Inelastic scattering from a one-dimensional antiferromagnet, $CsCrCl_3$, at the magnetic zone center measured with E_i = 47 meV on INC for the present and previous configurations. The solid lins in (a) are fitted curve, where the detailed balance is included in negateive energy transfers.

except for at low energies. At low energies, the operational condition of the Fermi chopper was not optimized. In order to utilize the huge intensity gain at low energies, the Fermi chopper should operate under the optimum condition. The intensity for a sloppy chopper, which is the Fermi chopper having a slit package of which slit width is twice of that of the optimum chopper, operating with the slowest rotational frequency (200 Hz) are also plotted in Fig.7 (a). This operational condition provides the most intense neutron flux to the sample position on INC. The energy resolution measured for the corresponding condition for the optimum and sloppy choppers are plotted in Fig.7 (b). The range of the intensity and the energy resolution can be controlled between those for the optimum chopper and those for the sloppy chopper operating the slowest frequency.

The background noise is evaluated. Figure 8 shows the inelastic spectrum observed with E_i = 500 meV and at scattering angles from 5.5° to 7.9° for the present configuration and the previous one. Each spectrum was normalized by the peak intensity at the elastic scattering. The spectrum was almost unchanged. High-energy neutrons and low scattering angles are the severe condition for collimation. Therefore, the noise-to-signal ratio also remained almost unchanged after installing of the guide tube.

Finally, an example of measurements on INC is shown in Fig.9. We measured inelastic scattering from a one-dimensional antiferromagnet, $CsCrCl_3$, at the magnetic zone center at temperatures, T = 30 K and 150 K, with E_i = 47 meV. We used the same sample and applied exactly the same experimental conditions for the present and previous configurations. Each spectrum was obtained in approximately one day with one detector. The peak intensity became 1.8 times as large as that in the previous configuration. In the present configuration, a reasonable temperature dependence was clearly observed, in particular, the asymmetric line shape at the low temperature could be well explained with the detailed balance.

5. Goniometer

A goniometer is indispensable for experiments using a single-crystal sample. Further, low temperatures are required for measurements, especially of magnetic excitations. Normally, on a chopper spectrometer, there exists a large vacuum chamber consisting of a high-vacuum sample chamber and a scattering chamber; moreover, there does not exist a collimator on the secondary flight path for reducing the background noise; such collimators are always located on a triple-axis spectrometer. To reduce the background noise, the

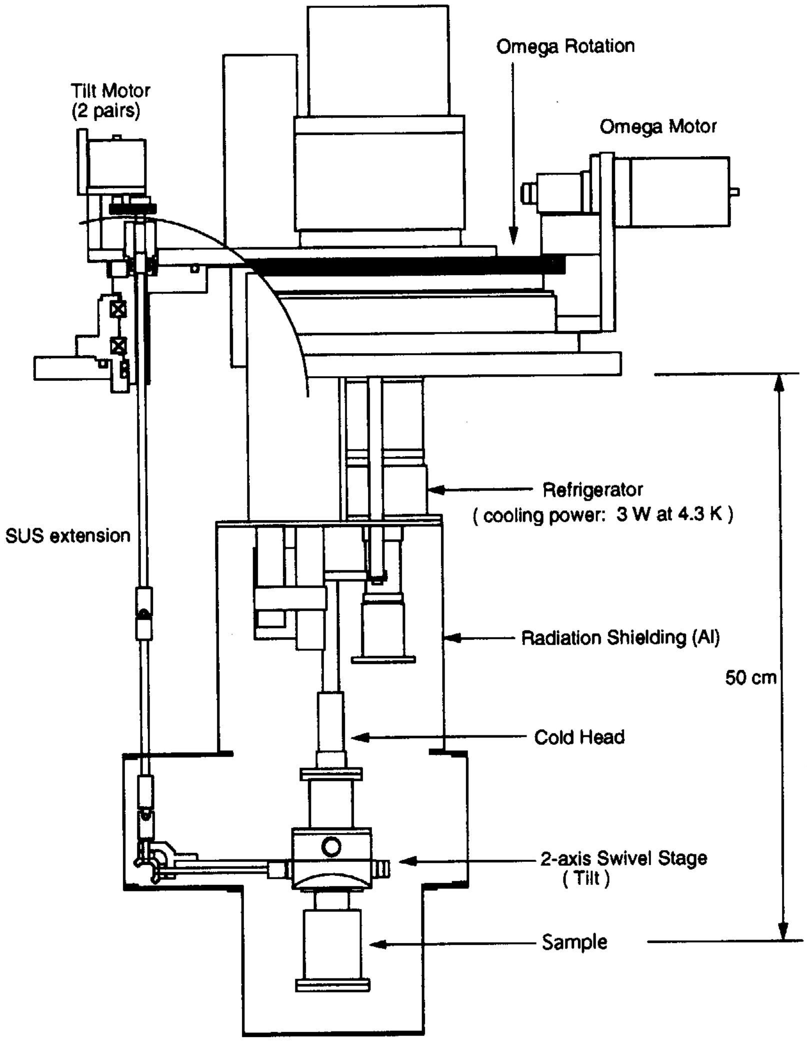

Fig.10 Schematic drawing of a goniometer with a refrigerator.

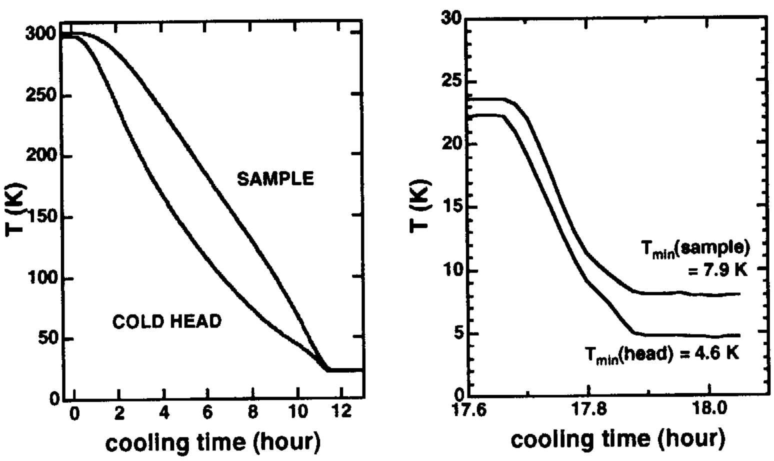

Fig.11 Cooling time in the goniometer developed at present.

thickness of all aluminum windows should be minimized on a chopper spectrometer. Therefore, a goniometer for a chopper spectrometer is required to rotate a sample crystal located in a large vacuum chamber, also to be combined with a refrigerator, where the thickness of all aluminum windows must be minimized. In this sense, we developed a goniometer combined with the refrigerator shown in Fig.10. Because the omega rotation is on the vacuum seal, the rotational motor (stepping motor) is located in the atmosphere. For a tilt scan of the two axes, two swivel stages are mounted on the cold head of the refrigerator. The rotational motion for each swivel stage is transmitted through a SUS extension from a stepping motor located outside of the vacuum. The refrigerator is a type with a closed cycle of helium gas, also with an independent Joule-Thomson circuit (CG308SC) manufactured by Daikin Industries, Ltd., of which the cooling power is 3 W at 4.3K and the lowest temperature is 4 K without any sample in the specification. The rotational angle range of the swivel stage is ±10° for each axis, and each axis can move independently of the other. The material was chosen to be phosphor bronze to obtain good thermal conductivity. A solid lubricant of MoS_2 is used in the moving part of the swivel stages so that the swivel stages can work at low temperatures. The present goniometer system was manufactured by Kohzu Seiki Co., Ltd. Figure 11 shows the cooling time in this system. It takes approximately 11 hours to cool down the sample to the lowest temperature because of the massive swivel stages; the lowest temperature was 7.9 K at the sample and 4.6 K at the cold head.

6. Summary

By installing a supermirror guide tube in the primary flight path on INC as well as the renewal construction of the neutron source at KENS, the performance of INC was drastically improved. A huge intensity gain at low energies due to installing the supermirror guide tube and a gain of factor 2 at high energies due to changing the characteristics of the neutron source were observed without any increase in the background noise. The observed gain of the guide tube was in very good agreement with a calculation. We, for the first time, have demonstrated the effectiveness of a supermirror guide tube for higher energy neutrons than cold neutrons for which a guide tube has been known to be effective. Moreover, the poisoning of the ambient-temperature H_2O moderator provided INC more symmetric energy resolution function as well as an increase in the peak intensity in the TOF spectra. The present construction resulted in a great improvement concerning all aspects of the performance. Furthermore, the development of a goniometer with three axes working at low temperatures was successful. Therefore, single-crystal experiments at low temperatures have become easier than before.

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